Climatic Change (2021) 165: 36
https://doi.org/10.1007/s10584-021-03057-5

Indicators of climate change impacts on the water cycle and water management

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Received: 9 December 2016 / Accepted: 9 March 2021 / Published online: 29 March 2021

Abstract
Managing water is a top social and economic responsibility and is expected to become even more critical as climate change, in addition to other human activities, alters water availability and quality. Robust indicators reflecting the effects of climate change on the US and global water cycles are needed in order to appropriately manage water resources. Here, we describe a suite of seventeen water cycle and management indicators, which are based on synthesis of available datasets. These indicators include average and heavy precipitation, standardized precipitation index, annual, 7-day low and 3-day high streamflow volume, streamflow timing, snow cover, snow water equivalent, groundwater level, lake water temperature, stream water temperature, dissolved oxygen, salinity, Palmer Drought Severity Index, water withdrawals, and water use. We also identify three indicators that could be included in the suite of water cycle and management indicators with some additional, directed work: snowfall, evapotranspiration, and soil moisture. Our conceptual framework focuses on known water cycle changes in addition to potential effects on management and addresses water quantity and quality, as well as water use and related interactions with freshwater ecosystems, societal impacts, and management. Water cycle indicators are organized into three categories: (1) hydrologic processes, (2) water quality processes, and (3) water quality and quantity impacts. Indicators described here are recommended to serve as critical references for periodic climate assessments. As such, these indicators support analyses of the effects of global change on the natural environment, agriculture, energy, and water resources, among other sectors. Additionally, we identify research gaps and needs that can be addressed to advance the development of future indicators.

Keywords Water cycle · Water quality · Water quantity · Precipitation · Hydrology · Snow cover · Drought · Indicators

This article is part of a topical collection on "National Indicators of Climate Changes, Impacts, and Vulnerability" edited by Anthony C. Janetos and Melissa A. Kenney

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1 Introduction

Water is vital to all aspects of life on our planet. Managing water is a primary component of human economic activities and is expected to become even more critical as changes in demand and climate alter its availability and quality. As noted in the Fourth Climate Assessment report, “The quality and quantity of water available for use by people and ecosystems across the country are being affected by climate change, increasing risks and costs to agriculture, energy production, industry, recreation, and the environment” (USGCRP 2018, p. 27). Documenting observed changes in the water cycle is critical for understanding feedbacks in the climate system as well as for managing the impacts of these changes in many economically important sectors.

Numerous prominent examples of changes in the water cycle have been documented in the scientific literature. For example, climate change is driving global increases in the amount and variability in precipitation, including extreme events (Durack et al. 2012; Kunkel et al. 2013), and these water-related impacts affect agriculture, municipal supply, forestry, energy demand, and production, among other sectors. In some regions such as the northeastern US, heavy precipitation events have increased by as much as 55% for 99th percentile 1-day events and as much as 92% for 5-year 2-day events between 1958 and 2016 (USGCRP 2017), while other regions in the USA are experiencing more extreme droughts (Trenberth et al. 2014). Beyond precipitation, changes in streamflow, snow, groundwater, and water quality have been well documented and are expected to continue (Georgakakos et al. 2014; Lall et al. 2018).

Accordingly, this paper is intended to describe a system of water-related indicators that document observed changes in the water cycle as well as those that quantify impacts that are experienced in ecosystems and the water management sector. These indicators are intended to inform a larger conceptual system of indicators (Kenney et al. 2018).

As noted in the summary by Kenney et al. (2018, p. 3), the indicator system is “based primarily on the need to establish consistent baselines against which change and variability can be measured.” The primary purpose is to support the sustained U.S. National Climate Assessment (NCA) (Buizer et al. 2013) by providing long-term information that is regularly updated about key US impacts in systems and sectors, such as water cycle and water management, that are required by the 1990 Global Change Research Act or of broad concern to the US public (Kenney et al. 2018).

The process and decision criteria for the overall indicator system, as well as input on the scientific integrity and utility of specific indicators, were provided by the Indicator Work Group, a work group established for the third National Climate Assessment Advisory Committee. Several indicator teams were formed to focus on elements of the global climate system or sectors that may be impacted by climate change. Our indicator team was focused on the water cycle and water management. Each indicator technical team was asked to develop a conceptual framework describing the system they focused on, provide recommendations of indicators that could be implemented with no additional research, and identify research priorities (Kenney et al. 2016, 2018). The initial recommendations informed the development of the proof-of-concept indicator system released by the U.S. Global Change Research Program (USGCRP) in 2015. This paper revisits the conceptual framework and recommendations to envision what we believe are indicators that are important representations of water cycle and water management while also supporting the vision for an indicator system described in Kenney et al. (2018). We also describe possible extensions to that indicator suite to improve the information available for identifying and understanding changes to the water system.

Water quantity and quality are not only sensitive to climate phenomena on multiple spatial and temporal scales, water is also an integral part of the climate system. Water management issues vary on multiple time scales, from minutes to hours (e.g., flash floods) to years to decades (e.g., drought, desertification). The impact of climate-scale changes on water management may be expressed as changes in the frequency, magnitude, timing, or duration of extreme events (Milly et al. 2002).

The indicators recommended in this paper are intended to be nationally and regionally relevant and support analysis of the effects and impacts of global change on the natural environment, agriculture, energy, and water resources, among other sectors. Our indicator choices were influenced by analyses carried out as part of the Third and Fourth National Climate Assessments, particularly the water chapters (Georgakakos et al. 2014; Lall et al. 2018), as well as existing indicator publications such as EPA's *Climate Change Indicators in the United States* report (EPA 2016) and USGCRP's Indicator Platform (https://www.globalchange.gov/browse/indicators). Our goal is not to replicate all of these efforts; rather, we seek to build upon these efforts including the scientific literature to select the most important indicators that answer the questions:

1. How does climate change impact the water cycle and water management?
2. How are these impacts changing over time?
3. Where are these impacts most apparent?

2 Climate change impacts on the water cycle and water management

The scope of the water cycle and management indicators described here includes water quantity and quality, as well as water use and the related interactions with freshwater and coastal/marine ecosystems, societal impacts, and management. Given that the water cycle is part of the larger indicator framework as shown in Kenney et al. (2018, Figure 2), we developed a conceptual framework for water cycle and water management that focused on defining system boundaries, interactions with other systems, and internal system dynamics. As shown in Fig. 1, our conceptual framework describes the key interactions of the water cycle with the physical climate system, which provides forcing through changes in precipitation, radiation, wind speed, temperature, and humidity, and feedbacks such as changes in evapotranspiration due to soil moisture limitation and changing radiation budgets due to albedo changes related to snowpack and landcover changes. Non-climate factors that moderate the water cycle include geology, soils, phenology, and topography, which partly control partitioning of precipitation into surface runoff and infiltration and groundwater recharge, as well as societal factors including changes in water demand and land use. Together, these interactions and moderating factors regulate the water cycle and influence the impacts of extreme events or baseline conditions that affect freshwater ecosystems and water resources.

Variability across multiple space and time scales is an important characteristic of the climate and non-climate factors that impact the water cycle and water resources management. Accordingly, the ability to illustrate variability across space and time scales, data availability, maturity, changes in averages as well as extremes, and societal importance were all taken into consideration in the choices of metrics and datasets that make up the water cycle and management indicator suite. This results in a diverse set of measurements that can be used

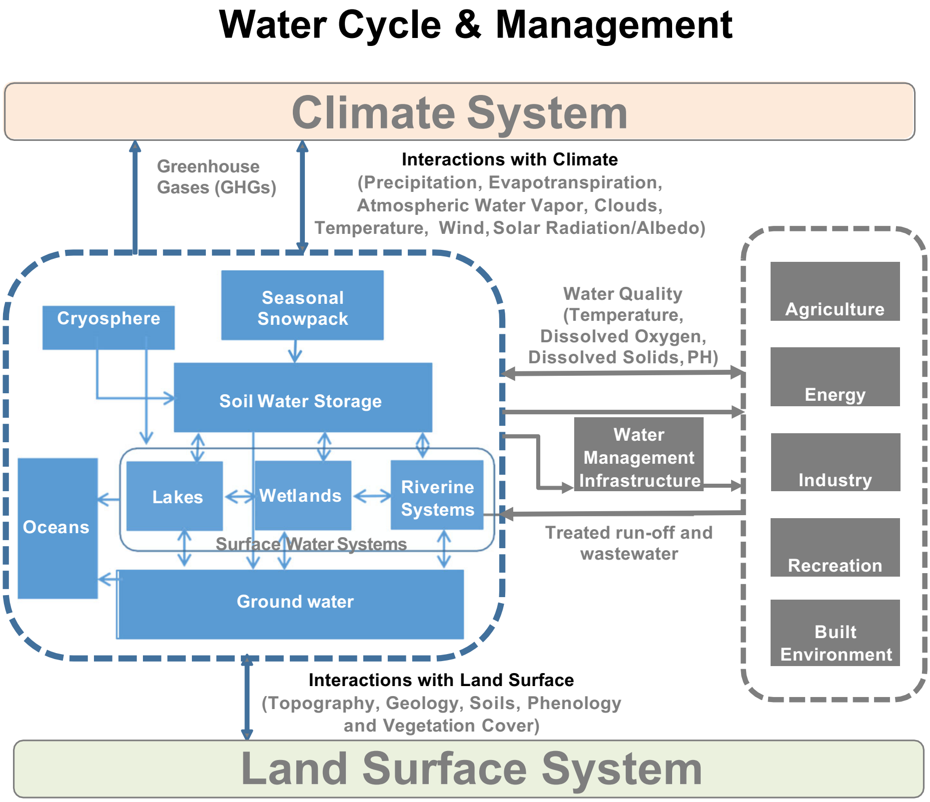


Fig. 1 Conceptual framework for identification of water cycle and management indicators

as indicators of hydrologic processes, water quality processes, the state of our natural and engineered water systems, and their inter-related impacts.

We organize the suite of water cycle and water management indicators using the conceptual framework shown in Fig. 1. This framework is intended to identify the major processes and water management sectors for which indicators may be needed. *Hydrologic process indicators* are based on measurements of hydrologic processes such as precipitation, streamflow, snow, and groundwater, indicated in Fig. 1 on the left-hand side in blue. *Water quality process indicators*, noted in the connection of the hydrologic processes to water management objectives, describe important aspects of the quality of habitat in both lakes and streams for organisms and human uses, and indicators include measurements of water temperature, sediments in streams, dissolved oxygen, and salinity. In addition, concentrations or total maximum daily loads of high-impact constituents such as nitrogen and phosphorous play an important role in water quality and water management. Finally, impacts and use indicators that connect climate and water resources management shown on the right of Fig. 1 are grouped in the following manner. *Water system impacts* such as floods and droughts are indicated by extreme values of precipitation and streamflow, as well as composite indices that reflect extreme water deficits such as droughts. Within the water system, *water use indicators* describe the total water used by various sectors including agricultural, industrial, human, and ecological. *Water quality impacts* include terrestrial and aquatic ecosystem health (e.g., harmful algal blooms), increased costs and implications of water treatment, water supply and recreational use disruptions, and public health impacts. Together, this indicator system describes the status and trends in the water cycle and its management under a changing climate.

3 Indicators

We present a selection of indicators (Table 1) represented in three categories: hydrologic processes, water quality processes, and water system impacts, as shown in the conceptual framework (Fig. 1). Because water quality impacts are primarily addressed in other indicator teams (e.g., freshwater, coastal, ecosystems), our team chose not to propose new indicators here. Note that some indicators were deemed important by multiple technical teams. The Team Lead that was responsible for describing the indicator is listed in the table, along with other teams that endorsed the same indicator. Table 1 also includes a Status column that indicates whether the indicator is "Current," "Available," or "Needs development."

3.1 Hydrologic process indicators

Among the many hydrologic processes, precipitation, streamflow, snow cover and snow water equivalent, and groundwater levels are indicators that are the most readily available, data-mature, and societally important. These indicators are well suited to quantifying changing average conditions as well as extremes, as we observe that distributions are changing in response to climate change (Milly et al. 2008, 2015).

Annual and seasonal precipitation, heavy precipitation, and anomalously high and low precipitation (represented by the Standardized Precipitation Index) were chosen as precipitation indicators. Annual and seasonal precipitation are already well-established NCA indicators (Easterling et al. 2017), so we provide only a brief discussion here. Average, high, and low streamflows and the timing of streamflow were chosen as streamflow indicators. Snow-covered area and date of maximum snow water equivalent are two snow indicators ready for implementation. Finally, groundwater levels round out the hydrologic processes indicators. Further description and discussion of these indicators are provided below.

3.1.1 Heavy precipitation

Precipitation is one of the most easily recognizable and essential of the basic climate variables. "Heavy precipitation" refers to instances during which the amount of precipitation experienced in a location substantially exceeds what is normal for that location, season, and duration. An increase in heavy precipitation does not necessarily mean the total amount of precipitation at a location has increased—just that precipitation is occurring in more intense events. However, changes in the intensity of precipitation, when combined with changes in the interval between precipitation events, can also lead to changes in overall precipitation totals (EPA 2016). The potential impacts of heavy precipitation include crop damage, soil erosion, and an increase in flood risk. In addition, runoff from precipitation can impair water quality as pollutants deposited on land wash into water bodies.

Trends in heavy precipitation, particularly in the Northeast US, have been identified in the NCA Third Assessment Report (Walsh et al. 2014), the Climate Science Special Report (USGCRP 2017), and the NCA Fourth Assessment Report (USGCRP 2018). In recent years,

Table 1 Recommended water cycle and management indicators**.** The name and a short description of each recommended indicator is listed alongside the indicator technical team that led the work on that indicator. The last column provides the status of the indicator as "Current," "Available," or "Needs Development," along with source, if applicable. Note that all indicators can be represented as spatial maps and as time series. See text and figures for more details and examples

Name	Description	Team Lead	Status
Hydrologic processes			
Heavy precipitation	Total precipitation delivered in the top 1% of all days with precipitation	Water	Current USGCRP Indicator
Standardized Precipitation Index	The Standardized Precipitation Index describes abnormally low or high precipitation over a certain period	Water	Available from NIDIS drought.gov
Precipitation	Daily and monthly gridded precipitation in the contiguous 48 states	Physical climate (endorsed by water)	Available from NOAA NCEI Climate at a Glance https://www.ncdc.noaa.gov/cag/
Annual mean streamflow volume	Normalized annual mean streamflow, or runoff, in the USA	Water	Current EPA Climate Indicator
Seven-day low streamflow	Minimum 7-day average daily streamflow each year in the USA	Water	Current EPA Climate Indicator
Three-day high streamflow	Maximum 3-day average daily streamflows in the USA for each year (Current EPA Climate Indicator)	Water	Current EPA Climate Indicator
Snowmelt timing	Date representing the center of volume (COV) of streamflow each year in the USA. The COV for this indicator is defined as the date when half of the streamflow between January 1 and May 31 of each year passes a particular gage (January 1 and July 31 for western sites)	Water (endorsed by phenology)	Current EPA Climate Indicator
Snow water equivalent	Date and magnitude of maximum snow water equivalent	Water	Current EPA Climate Indicator
Snow cover	Snow-covered area in North America from optical remote sensing	Physical climate (endorsed by water)	Available from NOAA Climate Data Record (CDR) program, based on original work at Rutgers University, Global Snow Lab (doi: https://doi.org/10.7289/V5N014G9)
Annual average groundwater levels	Annual average groundwater levels as recorded by the USGS Climate Response Network	Water	Needs development. Data Available from USGS Climate Response Network. https://waterdata.usgs.gov/networks/CRN/

Table 1 (continued)

Name	Description	Team Lead	Status
Water quality processes			
Lake water temperature	Lake water temperature	Freshwater ecosystems (endorsed by water)	Available from Global Lake Temperature Collaboration (http://www.laketemperature.org/) and the Environmental Data Initiative (https://environmentaldatainitiative.org/)
Stream water temperature	Stream water temperature	Freshwater ecosystems (endorsed by water)	Available from USGS Spatial hydro-ecological decision system (SHEDS; http://db.ecosheds.org/)
Dissolved oxygen	Dissolved oxygen	Freshwater ecosystems (endorsed by water)	Available from Water Quality Portal (https://www.waterqualitydata.us/) and the Environmental Data Initiative (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.624.1).
Salinity	Salinity	Water	Needs development. Was originally recommended by Freshwater Team, but later removed due to data record limitations[1]
Water system impacts			
Palmer Drought Severity Index (PDSI)	Palmer Drought Severity Index (PDSI)	Physical climate/water (jointly developed)	Available from NOAA NCEI Climate at a Glance https://www.ncdc.noaa.gov/cag/
Annual Average Water Withdrawals by Source	Annual average rate of water withdrawals from surface water and groundwater, as estimated by the USGS National Water Use Science Project	Water	Needs development. Data available from USGS Water Use in the United States. https://water.usgs.gov/watuse/data/
Annual Average Water Use by Sector	Annual average rate of water withdrawals from surface water and groundwater, as estimated by the USGS National Water Use Science Project	Water	Needs development. Data available from USGS Water Use in the United States. https://water.usgs.gov/watuse/data/

[1] The Water Quality Portal (WQP; https://www.waterqualitydata.us/) has in total across US EPA, USGS, and other organizations, over 1000 freshwater ecosystem sites with over 10 years of salinity data, but less than 200 with over 25 years of data, and most sites are concentrated along the Eastern seaboard and Southeast US

a larger percentage of precipitation has come in the form of intense single-day events, and therefore, we recommend two heavy precipitation indicators—one related to the percent increase of daily extreme precipitation for a given region and one related to the area over which extreme precipitation is increasing.

Heavy precipitation is currently an indicator in the USGCRP Indicator Platform, as well as the EPA Climate Change Indicator suite (EPA 2016). This indicator measures the relative

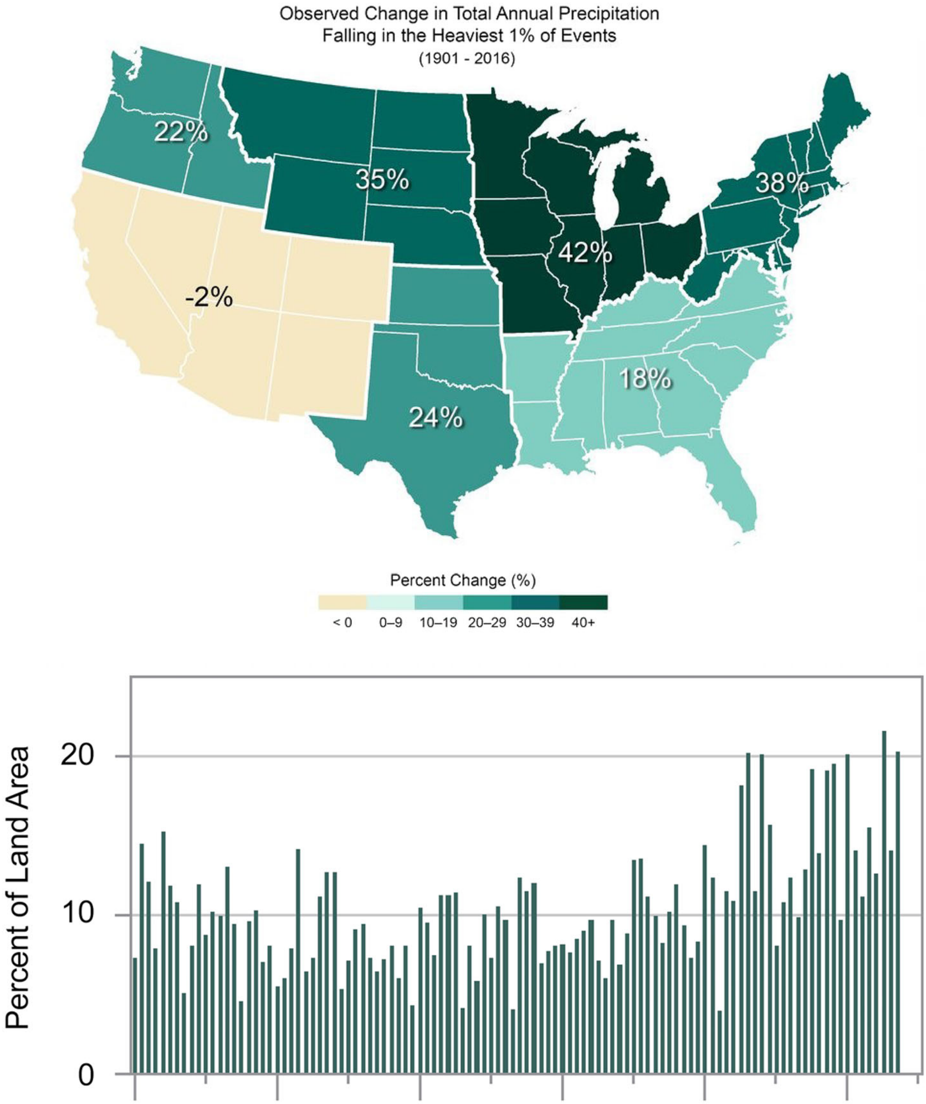


Fig. 2 (Top) This figure shows the observed change in total annual precipitation falling in the heaviest 1% of events for the continental US for the period 1901–2016 (source: USGCRP, 2017). (bottom) This figure shows the percentage of the land area of the contiguous 48 states where a much greater than normal portion of total annual precipitation has come from extreme single-day precipitation events. The bars represent individual years (source: USGCRP, 2017)

amount of annual rainfall delivered by large, single-day precipitation events. Extreme precipitation events are defined as days with precipitation in the top 1% of all days with precipitation. The first heavy precipitation indicator is a map showing percent increase of heavy precipitation by region relative to a reference period (Fig. 2, top). Another indicator shows the percentage of the land area of the contiguous 48 states where a much greater than normal portion of total annual precipitation has come from extreme single-day precipitation events (Fig. 2, bottom) following the Climate Extremes Index methodology (Gleason et al. 2008).

As shown in Fig. 2 (top), heavy precipitation is becoming more intense and more frequent across most of the USA, particularly in the Northeast and Midwest. The percentage of land area with high contributions of extreme events (90th percentile) to precipitation totals increased between 1910 and 2016 (Fig. 2, bottom). While this indicator is focused on areal coverage, it does not quantify the number of heavy precipitation events or indicate trends in total precipitation, and therefore, one must interpret changes with caution. Our vision for the indicator system is that this heavy precipitation indicator could be accessed and presented at scales as small as county, climate division, or watershed to address issues and answer questions about local-scale changes in the water cycle.

3.1.2 Standardized Precipitation Index

The Standardized Precipitation Index (SPI) (McKee et al. 1993, 1995) is another precipitation-related indicator that is commonly used to characterize the unusualness of the observed precipitation over a given time (e.g., 6 months or 12 months; Figure S1) relative to the historical record for a given station or aggregation of stations. Its multi-scalar nature allows for the discrimination between “short term” drought (often considered as on the weeks-to-months scale) and “long term” drought (often considered as on the seasons-to-years scale). While it is commonly used to track dry spells or drought, it can also be used to track wet periods. A full explanation of the SPI is available online at http://www.wrcc.dri.edu/spi/explanation.html.

Trends in SPI have been widely noted, for example, by Zhai et al. (2010) in China and Ganguli and Ganguly (2016) for the conterminous US (CONUS). Ganguli and Ganguly show strong drying trends in 6-month SPI in the western US, with wetting trends in the eastern US. When you average across CONUS (e.g., Figure S1), these trends are not apparent. Therefore, we recommend an SPI indicator that is calculated at the climate division level, which is similar to the approach used to calculate SPI for the U.S. Drought Monitor (Svoboda et al. 2002). We recommend displaying SPI aggregated by region in a manner similar to Fig. 2 for heavy precipitation, with the longer term vision of a web mapping service that can display multiple spatial scales.

3.1.3 Annual and seasonal precipitation

Annual and seasonal precipitation indicators have been discussed in detail in the NCA4 Climate Science Special Report (Easterling et al. 2017). There are documented trends in both annual and seasonal precipitation that can influence not only the water cycle and water management but also critical sectors such as agriculture and energy production.

The recommended indicators are trends in annual and seasonal precipitation, as shown in Figure S2. These figures are based on a NOAA National Centers for Environmental Information (NCEI) gridded precipitation dataset known as nCLIMDIV (Vose et al. 2014a, b). An alternate dataset considered by the team is PRISM (Daly et al. 1994), although the developers of the PRISM dataset state on their website that their data are not suitable for trend analysis because of the temporal heterogeneity of data sources. To further emphasize the regional patterns, annual and seasonal precipitation can be aggregated by region in a manner similar to Fig. 2 for heavy precipitation. As with heavy precipitation and SPI, we also have the longer term vision of a web mapping service that can display multiple spatial scales.

3.1.4 Streamflow indicators

Streamflow is essential to meeting water demand for human and ecological purposes, and both the volume and timing of flow can be extremely important. In addition, extremes in streamflow (floods and droughts) create hazards that require considerable planning and expense to mitigate. Several separate indicators are recommended that characterize multiple aspects of streamflow, including annual flow volume, annual high flow, annual low flow, and the timing of flow.

Streamflow indicators can be calculated from the USGS Hydro-Climatic Data Network (HCDN) (Slack et al. 1993; Lins and Slack 1999; Lins 2012) set of stream gages, which have been selected as those that reflect minimal interferences from human activities. Variability in streamflow trends across the country can be clearly visualized by mapping these indicators at individual stream gages.

The EPA has published a set of streamflow indicators based on select long-term USGS stream gage records from HCDN (EPA 2016) that can be used as a starting point. As shown in Fig. 3, each streamflow indicator reflects a different climatically important aspect of the water cycle. The maximum 3-day high flows in rivers can indicate more flood risk due to changes in heavy precipitation. Seven-day low flows can reflect dry spells that challenge our ability to meet competing demands for water. Acute low flows can result in shortages and environmental impacts even if the total annual flow is sufficient. The minimum 7-day average daily flow is commonly used for regulatory purposes. The annual mean flow at each stream gage is a measure of all water available for a year and can reflect large-scale changes in the water cycle such as precipitation or evaporation. Changes in timing, as reflected in changes of the center of volume (COV) of flow each year, can indicate changes in snowfall or snowmelt (Knowles et al. 2006; Berghuijs et al. 2014). The COV is defined as the date when half of the streamflow in a specified period of each year passes a particular gage. The EPA "winter-spring center of volume" indicator presently specifies periods of Jan 1 to May 31 for eastern sites and Jan 1 to July 31 for western sites. The Freshwater Indicators group (Rose et al., this special issue) is also supportive of the COV indicator due to its ecological significance.

To improve upon this indicator in the future, the ability to zoom in and look at detailed information for individual stream gages would be desirable.

3.1.5 Snow indicators

Snow plays a key role in water availability and management in many areas of the USA and particularly the western US, where high-elevation snowpack accounts for the majority of the annual water supply (Bales et al. 2006). In these regions, snow builds up in the mountains over the winter and melts in the spring to provide streamflow through the spring and summer months supporting municipal and agricultural uses, hydroelectric power

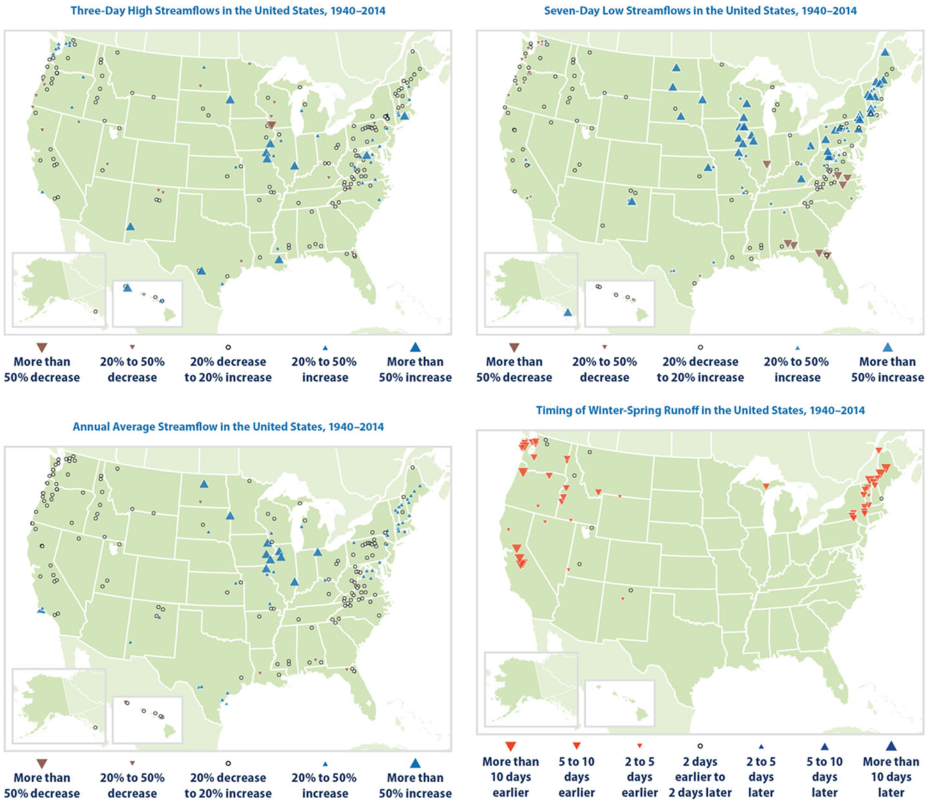


Fig. 3 Trends in 7-day annual low streamflows (top left), and 3-day annual high streamflows (top right), annual average streamflow (bottom left), and timing of winter-spring runoff (bottom right) from 1940 to 2012 (figure source: EPA 2016)

generation, recreation, and aquatic habitat systems, among other needs. Warmer temperatures are expected to shift the rain-snow transition zone upward in elevation and decrease the area and volume of snow cover, with implications for the amount and timing of runoff and consequently water management.

We recommend two types of snow indicators. The first set focuses on snow water equivalent (SWE) and the second is snow-covered area (SCA). SWE is a key water management metric in the western USA. It is responsive to climate because changes in precipitation and/or temperature can lead to changes in snowpack, including melt, compaction, and other factors affecting density. The EPA currently includes a snowpack indicator showing long-term trends in SWE using a consistent date (April 1, Figure S3). It may be beneficial to add an indicator based on the dates and magnitudes of peak SWE. Historically, the peak in SWE occurs somewhere around or after April 1 (Regonda et al. 2005) and water management activities, such as reservoir operations, use this date for storage limit decisions (Mote et al. 2005), so the basis of the EPA indicator is sound. However, many sites that have long-term SWE measurements have seen peaks occurring earlier than April 1. Variations in this date relate to the size of the snowpack and year-to-year variability in weather conditions. Concurrent with increasing air temperatures, it is expected that this date will move earlier in the year and the peak magnitude of SWE will decrease, thereby reducing this natural water reservoir

(Mote 2003; Mote et al. 2016). Therefore, we recommend two SWE indicators: date and magnitude of peak SWE, with a focus on the western US.

One limitation of using SWE as a measurable indicator is regional variability in snow processes and monitoring. In the western US, there is an extensive in situ network of automated stations and monthly manual measurements that directly quantify SWE such as the Natural Resources Conservation Service (NRCS) manual snow surveys at over 1100 cooperative measurement sites; automated snow monitoring Snow Telemetry (SNOTEL; https://www.wcc.nrcs.usda.gov/snow/) stations (over 800 stations); and the California Cooperative Snow Surveys (https://info.water.ca.gov/snow/). Combining satellite observations of snow cover with these on-the-ground SWE measurements supports a consistent assessment of both SWE and snow cover extent. The difficulty is in the rest of the USA, where satellite coverage does assess snow cover, but the processes related to snow hydrology are quite different.

For these reasons, we recommend an additional SCA snow indicator (Figure S4), which is derived from satellites (Robinson et al. 2012; Estilow et al. 2015) and available in a gridded format suitable for spatial analysis. The Physical Climate indicator technical team was the lead for this indicator. Snow cover is valuable in identifying how temperature impacts the form of precipitation (Knowles et al. 2006). In the mountain west, increasing temperatures would ultimately limit the spatial extent of snow cover through fluctuations in the intermediate zone of rain/snow mix, changes in snowmelt rates, and/or snowpack reaching isothermal conditions earlier (Mote 2003; Mote et al. 2005). Therefore, a SCA indicator could be shown as percent cover over time (comparing dates and maximum extent over time related to temperatures).

3.1.6 Groundwater indicators

Groundwater provides a vast natural reservoir for water storage. Groundwater is pumped to meet water supply needs (e.g., municipal, agricultural) and also naturally discharges to rivers, streams, and other water bodies, sustaining base flows during otherwise dry periods. Changes to groundwater availability can have impacts on activities relying either on groundwater aquifers directly or on baseflow.

Climate affects groundwater storage through changes in the processes leading to recharge and discharge from aquifers. Groundwater levels, as measured in observation wells, can be used as an indicator of changes in groundwater storage over time. Changes to the annual average, annual maximum, and annual minimum groundwater levels can be calculated at individual wells, allowing users to assess the spatial variability in groundwater levels locally, regionally, and across the country.

Accordingly, groundwater levels can be tracked from individual wells identified in the USGS Climate Response Network (CRN). Water level changes from the USGS CRN groundwater wells have been determined to better reflect climatic variability rather than human influences (Cunningham et al. 2007). The National Groundwater Monitoring Network provides a web portal to access groundwater well data collected by state and federal agencies (see https://www.ngwa.org/what-is-groundwater/groundwater-issues/national-groundwater-monitoring-network). Wells in this network that respond mainly to climate could be used to supplement those in the USGS CRN. As with streamflow, the trends in groundwater levels can be mapped directly to visualize changes across the country. Extending the visualization to allow viewing of data at individual wells would be a useful add-on.

To provide an overview of conditions in the Nation’s principal aquifers, the USGS has experimented with composite hydrographs showing water level composited from multiple wells located within a single aquifer (Evenson et al. 2018). Additional work on this concept may allow its use as a future indicator. At a much coarser scale, data from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) satellites can be used to estimate changes in overall water storage, much of which can be attributed to groundwater (Rodell et al. 2009; Castle et al. 2014). Gridded water storage data from GRACE and GRACE-FO can be evaluated on a year-over-year basis to explore where water is accumulating or being depleted. Further evaluation would be required to determine if changes were climate-induced or human-induced (which could in turn be driven by climate change).

3.2 Water quality processes indicators

Changes in water quality may reflect changes in climate forcing as well as anthropogenic impacts and use. A key message from Lall et al. (2018) is that “Surface water quality is declining as water temperature increases and more frequent high-intensity rainfall events mobilize pollutants such as sediments and nutrients.” Reduced dissolved oxygen can result from decreases in low flow volume, and the risk of harmful algal blooms could increase due to the aforementioned water temperature increases and additional nutrient loading. Further, sea level rise brings with it the risk of saltwater intrusion and increasing salinity. In addition to direct impacts on water quality, Lall et al. note that “indirect impacts on water quality are also possible in response to an increased frequency of forest pest/disease outbreaks, wildfire, and other terrestrial ecosystem changes” in addition to land-use change.

Our indicator suite contains four water quality indicators that were originally proposed by the Freshwater Ecosystems team: lake water temperature, stream water temperature, dissolved oxygen, and salinity. While there is strong interest in tracking changes in salinity, the Freshwater Ecosystems team subsequently removed salinity as a recommended climate indicator because studies show that increases in salinity in many places may be driven more by road salt application than by climate change. Given the potential impacts of saltwater intrusion on groundwater and surface water salinity, our team chose to retain salinity as an indicator, although as shown in Table 1, the indicator needs development. The remaining three indicators are described in a companion manuscript submitted to this special issue authored by Rose et al. (personal communication, 2021).

In the future, additional water quality indicators based on other water quality monitoring data could be considered. For example, the USGS National Water Quality Assessment Program (NAWQA) shows trends in numerous water quality constituents in an online mapper (https://nawqatrends.wim.usgs.gov/swtrends/). Additional work could be undertaken to estimate the degree to which these trends are affected by climate versus other factors. Where a strong climate influence is known or suspected, the specific water quality constituent could be developed as a new indicator.

3.3 Water system impact indicators

Two important water quantity impacts are floods and droughts. Precipitation and streamflow extremes were covered as hydrologic process indicators. An additional drought indicator, the Palmer Drought Severity Index, is also included here. Two other indicators that address this topic include the total water withdrawals by source and the water withdrawals by sector of use. These indicators are described in detail, below.

3.3.1 Drought indicators

Drought is one of the costliest natural disasters, and tracking changes in the area covered by drought is an important indicator of water quantity impacts. Dozens of drought indicators are in common use (e.g., Heim Jr. 2002; Keyantash and Dracup 2002; Svoboda and Fuchs 2017). The Palmer Drought Severity Index (PDSI) (Palmer 1965) was created with the intent to describe the total moisture status as the cumulative departure (relative to local mean conditions) in atmospheric moisture supply and demand at the surface (Fig. 4). PDSI is routinely calculated by NOAA for climate divisions throughout the USA. The index has also been calculated for discrete points, geographical regions, and gridded fields for the past beginning in 1870 in the USA (Dai et al. 2004) and for the future using climate projections as inputs (Dai 2011). Due to its wide availability and use, the PDSI is recommended as an indicator of drought.

Supporting its use as a climate indicator, trends in PDSI have been examined by numerous authors (e.g., Burke et al. 2006; Zhai et al. 2010). Although the PDSI was a landmark in the development of drought indices, it is not without limitations (Heim Jr. 2002; Sheffield et al. 2012). The index was specifically designed to treat the drought problem in semiarid and dry subhumid climates where local precipitation is the sole or primary source of moisture and was originally calibrated for those areas; extrapolation beyond these conditions may lead to unrealistic results.

As discussed by Sheffield and Wood (2008), land surface models may be used to overcome some of the limitations of PDSI for tracking drought through soil moisture-based duration, intensity, and severity analysis. Although NOAA's North American Land Data Assimilation

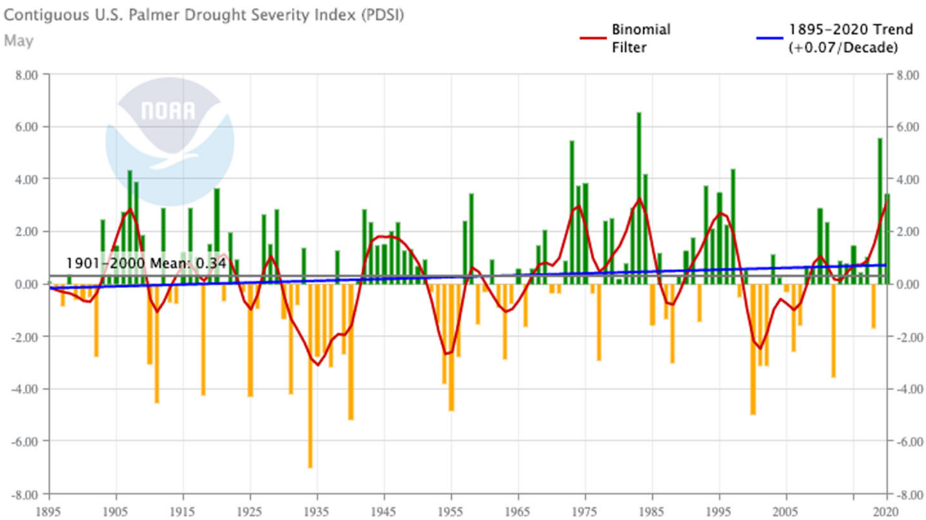


Fig. 4 This chart shows annual values of the Palmer Drought Severity Index, averaged over the entire area of the contiguous 48 states. Positive values represent wetter-than-average conditions, while negative values represent drier-than-average conditions. A value between −2 and −3 indicates moderate drought, −3 to −4 is severe drought, and −4 or below indicates extreme drought. The red line is a binomial filter and the blue line is a trend from 1895 to 2020 (figure source: NOAA NCEI Climate at a Glance https://www.ncdc.noaa.gov/cag/national/time-series)

System NLDAS (Xia et al. 2012) provides the required variables to support an alternative drought indicator for CONUS and is used in the US Drought Monitor (USDM; Figure S5), the USDM only goes back to 2000. Recently, a team at NASA's Goddard Space Flight Center completed a new LDAS reanalysis, including assimilation of multiple satellite datasets on the same 1/8 degree grid and time period as NLDAS, called the National Climate Assessment LDAS (NCA-LDAS; Jasinski et al. 2019; Kumar et al. 2019). The NCA-LDAS merges data and models to provide the best estimate of trends in critical water cycle variables. As shown in that work, there are clear trends in air temperature, radiation, soil moisture, and evapotranspiration, all of which could be used to develop more physically meaningful drought trend indicators free from the water balance approximations of PDSI. Similarly, a new drought reconstruction developed by the University of California, Los Angeles (Su et al., personal communication, 2020) extends the record back to cover the last century. Further, we expect that the demand for finer spatial scales of information related to the availability of newer data types will drive the development of finer scale (~ 1 km) land reanalysis. Accordingly, the PDSI could be revisited as an indicator in the future.

3.3.2 Water use indicators

Water use information complements the study of surface water and groundwater availability, and is essential to understanding how future societal water demands will be met while maintaining adequate water quality and quantities for ecosystems. Water supplies and their uses are affected by factors such as demographics, economic trends, legal decisions, and climatic fluctuations. For example, from 1950 to 2010, the population of the USA doubled and shifted from rural to urban areas and from the North and East to the South and West (Hobbs and Stoops 2002; Mackun et al. 2011). Today, many regions with burgeoning populations are also quite dry, and increasing demands pose important challenges to water supplies and resource managers.

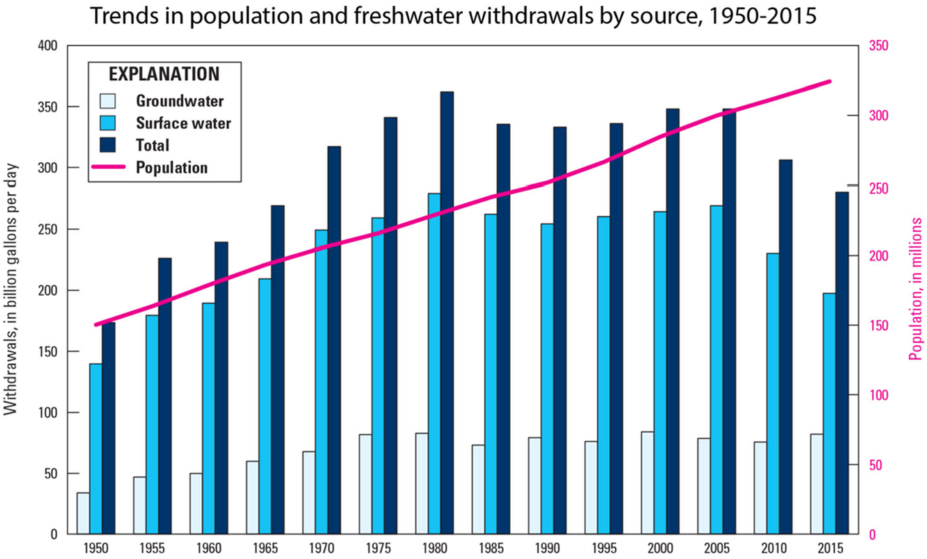
Beginning in 1950 and repeated every 5 years, the USGS has compiled and estimated water use information in cooperation with local, state, and federal agencies to document how the Nation's water resources are used (Fig. 5). The most recent publication in this series includes data through 2015 (Dieter et al. 2018). The data in these compilations allow development of the following recommended water use indicators at the regional and national scales:

1. The total annual average water use, including source (surface water or groundwater); and
2. The total annual average water use by major sector of use, as defined in the USGS reports.

As much as possible, additional details on consumptive water use and water use by additional sectors of users are desirable. These additional indicators could be developed with sufficient data. While the focus here is on total water use and changes related to climate change, per capita water use has decreased in many regions due in part to water use efficiency programs (Donnelly and Cooley 2015). These types of derived indicators could be useful for a future update to the indicator system.

3.4 Water quality impact indicators

As noted above, and discussed in more detail in the Third and Fourth National Climate Assessment Report water chapters (Georgakakos et al. 2014; Lall et al. 2018), water quality



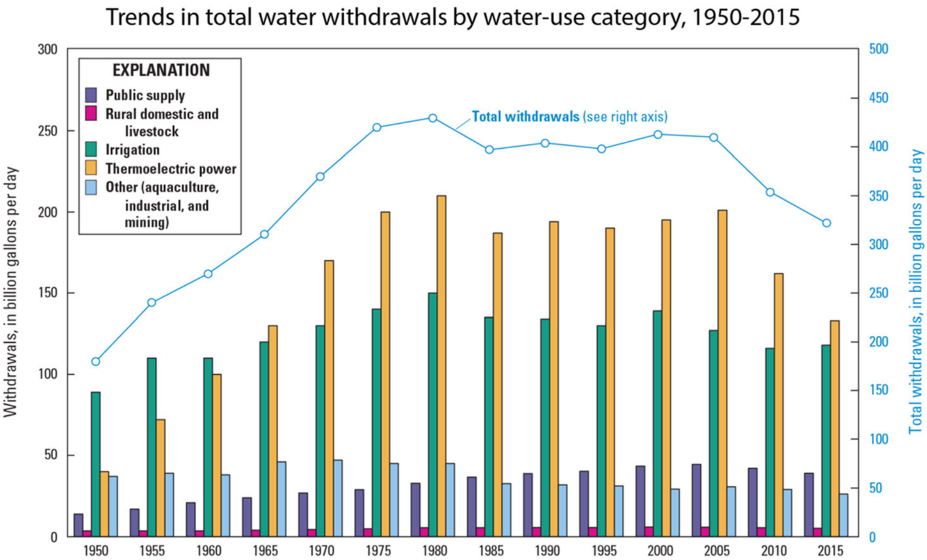


Fig. 5 Trends in population and freshwater withdrawals by source (top) and by water use sector (bottom), 1950–2015, as shown in a recent USGS water use report (figure source: Dieter et al. 2018)

impacts include degradation of terrestrial and aquatic ecosystem health, increased costs and implications for water treatment, water supply and recreational use disruptions, and public health challenges. Beyond these direct impacts, indirect impacts on infrastructure coupled with multiple stressors that reduce ecosystem services (e.g., water purification by oysters) may further degrade water quality. While the team recognizes the importance of water quality impact indicators, we did not identify indicators that could be implemented with no additional research. Further, most of these impacts are within other sectors and are partially covered by other indicator suites referenced in Kenney and Janetos (2020) such as freshwater ecosystems, ocean and coastal, agriculture, forests, rangelands, and built environment. Additional focus on cross-sectoral water quality impacts could be the subject of future research and indicator development.

4 Additional future indicators

Key indicators missing from our proposed initial indicator suite include soil moisture, snowfall, and evapotranspiration. Each variable has its own set of issues that prevent it from immediate inclusion in the indicator suite. However, with some additional, directed work, all three of these critical climate-impacted variables could become part of the comprehensive suite of water cycle and management indicators. Specific needs for each variable are discussed below.

4.1 Soil moisture percentiles

The importance of soil moisture in the global climate system has been underlined by the Global Climate Observing System (GCOS), which endorses soil moisture as an Essential Climate Variable. Soil moisture is directly connected to vegetation productivity and soil health. Measuring soil moisture content and identifying trends at both the spatial and temporal scales as related to changes in climate would provide a valuable tool for assessing impacts related to drought, runoff, and groundwater recharge.

Measuring soil moisture in the USA is approached using a variety of in situ measurement networks that monitor soil moisture and soil temperature at different depths (Quiring et al. 2016), as well as remote sensing through satellite observations, e.g., the Soil Moisture Active Passive (SMAP) mission (Entekhabi et al. 2010) and modeling (Xia et al. 2015). The U.S. Drought Portal (www.drought.gov) provides an overview to many sources of soil moisture information. In general, in situ networks provide accurate measurements of soil moisture and soil temperature at depths up to 100 cm for specific sites, but methods often vary. There are many differences between the measurements such as measurement depth, units of soil moisture, sampling interval, and precision.

A recommended soil moisture-based indicator is the soil moisture percentile. This could be computed at individual in situ sites as well as through integration with land surface models. Land surface models provide spatially and temporally continuous soil moisture estimates at multiple depths that are especially useful for monitoring agricultural drought (Mo 2008; Mo et al. 2011). As discussed above, the NASA NCA-LDAS (Jasinski et al. 2019; Kumar et al. 2019) now provides a pathfinder for a national soil moisture analysis. Merging soil moisture in situ observations with remote sensing and models is also the goal of an effort by the National Integrated Drought Information System (NIDIS) to develop a coordinated national soil moisture network (NSMN). The NSMN completed a pilot study in 2015 focused on northern Texas and Oklahoma and will be moving forward with expanding this effort for the entire USA in coming years. A sustained and authoritative soil moisture analysis effort is required before a soil moisture percentile indicator can be developed.

4.1.1 Snowfall

As described above, although in situ measurement of snowfall and snowpack in near real time is covered in the western US through the NRCS Snow Survey and Water Supply Forecasting

Program, data availability is severely limited in the central and eastern parts of the USA. Furthermore, the NRCS SNOTEL and manual snow course sites are typically at higher elevations and therefore do not always capture data in the rain/snow transition zone and at lower elevations where many observations indicate that climate change is having a significant impact on snowfall. Information on snowfall can help to fill these gaps.

The U.S. Historical Climatology Network (USHCN) operates rain gages that measure precipitation as both rain and snow (http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html). The USHCN is comprised of 1221 stations from the U.S. Cooperative Observing Network within the 48 contiguous United States and 46 stations in Alaska. However, there are concerns that the measurement of snowfall is complicated by the inability of heated or shielded rain gages to accurately measure snowfall, particularly during high snowfall rates (Kunkel et al. 2007).

While there has been some analysis of trends in snowfall using a special quality-controlled dataset (Kunkel et al. 2009), to include snowfall as a national-scale indicator requires an expansion of the SNOTEL network to capture snowfall measurements in lower-to-mid elevations in the Western US coupled with an effort to combine these measurements with USHCN and CRN data for the rest of the USA. Combining this with remote sensing data from radar or satellites and modeled data such as PRISM (Daly et al. 1994), as well as leveraging and integrating newer gridded snow depth measurements (Lundquist et al. 2015), could allow for future adoption of snowfall as a water indicator. Important requirements for a snowfall indicator would be the ability to display spatial patterns, particularly with respect to elevation, as well as changes in timing and intensity, similar to heavy precipitation.

4.1.2 Evapotranspiration

Evapotranspiration (ET) is the second largest component of the water cycle after precipitation. While only limited land-based measurements of ET are available, there are three remotely sensed products that are supported by federal agencies for continuous ET monitoring. These are the following: the USGS Earth Resources Observation and Science (EROS) Operational Simplified Surface Energy Balance SSEBop (Senay et al. 2011); the USDA Agricultural Research Service (ARS) and NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Atmosphere Land Exchange Inverse (ALEXI) (Anderson et al. 2011); and the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) MOD16 (Mu et al. 2011) Global Evapotranspiration Product. Each of these methods is a candidate for further study towards a future ET indicator. A new effort known as OpenET (https://etdata.org/) will provide a platform that supports inter-comparison and evaluation of these products for future use as indicators. ET estimates from the aforementioned NLDAS and NCA LDAS systems could also be considered. Key requirements for an ET indicator include sustained support, the ability to resolve scales from national to climate division, a record length of 30 years or more, and peer-reviewed evaluation against reference data.

5 Summary and future work

We have developed a conceptual model for water cycle and management indicators that considers both natural and engineered water systems and their interactions with the climate system and the land surface system. We have recommended a suite of 17 indicators, some developed in collaboration with other technical teams such as Freshwater and Physical Climate. These indicators provide an initial synoptic assessment of the current state, availability, and quality of water in its many forms as well as estimates of changes in the water cycle and management.

Our indicator suite is focused primarily on selected state- and national-scale summaries of annual statistics for data that are collected at much finer spatial and temporal scales. To be most useful for water management, these data need to be able to be stratified by watershed and/or management units of interest where appropriate. Hence, investment is needed to enable these indicators to be fully scalable and mappable, so that the indicator can be accessed and presented at scales as large as national and scales as small as county/climate division or watershed. Being able to visualize the indicator information at different scales will better enable their use to address issues and answer questions about local-scale changes in the water cycle. Generating gridded datasets from the observations will facilitate this effort.

Beyond the 17 recommended indicators, additional efforts to explore future indicators for soil moisture, snowfall, and evapotranspiration would provide a more complete set of indicators for the water cycle. Closing some cross-cutting technical gaps could support enhanced indicators in the future with focused effort by sponsoring agencies. Efforts to address the gaps include merging multi-sensor information and enhanced spatial analysis and display capabilities.

As described above with respect to snow water equivalent and soil moisture, merging (spatially or temporally) sparse in situ observations with remote sensing and models can provide a mechanism to maximize the information content obtained from diverse networks. Further investment in methodologies and systems that can optimally integrate information from multiple sources and produce interpolated estimates when appropriate could make the indicator system more useful for water resource management.

We should emphasize the conclusions of Kenney and Janetos (2020) that there are gaps in this recommended indicator suite, particularly with respect to human dimensions' indicators as well as leading indicators. In our suite, water use is the most direct indicator of human dimensions, although we recognize that there are human dimensions in every aspect of the water cycle and water management. Better connections with other sector teams as well as with socioeconomic experts would help develop indicators that quantify the impacts of changes in water quantity and quality.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-021-03057-5.

Acknowledgements The authors acknowledge the support provided by A.C. Janetos, chair of the Indicator Work Group under the National Climate Assessment and Development Advisory Committee (NCADAC), and M.A. Kenney, director of the Indicator Research Team. Kenney's research team provided research and coordination support to the technical team, which was supported by National Oceanic and Atmospheric Administration grant NA09NES4400006 and NA14NES4320003 (Cooperative Climate and Satellites-CICS) at the University of Maryland/ESSIC. Members of the Indicators Technical Teams, NCADAC Indicators Working Group, and Kenney's Indicator research team are included in Kenney et al. (2016). C.P-L. acknowledges support from NASA. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Availability of data and material (data transparency) All data are publicly available.

Code availability (software application or custom code) Not applicable

Authors' contributions All authors contributed to the study conception and design. The first draft of the manuscript was written collaboratively by all authors, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding All authors were supported by their respective agencies/institutions.

Declarations

Conflict of interest The authors declare no competing interests.

References

Anderson MC, Kustas WP, Norman JM et al (2011) Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. Hydrol Earth Syst Sci 15:223–239. https://doi.org/10.5194/hess-15-223-2011

Bales RC, Molotch NP, Painter TH, et al (2006) Mountain hydrology of the western United States. Water Resour Res 42:. https://doi.org/10.1029/2005WR004387

Berghuijs WR, Sivapalan M, Woods RA, Savenije HHG (2014) Patterns of similarity of seasonal water balances: a window into streamflow variability over a range of time scales. Water Resour Res 50:5638–5661. https://doi.org/10.1002/2014WR015692

Buizer JL, Fleming P, Hays SL, et al (2013) Report on Preparing the Nation for Change: Building a Sustained National Climate Assessment Process

Burke EJ, Brown SJ, Christidis N (2006) Modelling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. J Hydrometeorol 7:1113–1125. https://doi.org/10.1175/JHM544.1

Castle SL, Thomas BF, Reager JT et al (2014) Groundwater depletion during drought threatens future water security of the Colorado River Basin. Geophys Res Lett 41:5904–5911. https://doi.org/10.1002/2014GL061055

Cunningham WL, Geiger LH, Karavitis GA (2007) U.S. Geological Survey Ground-water Climate Response Network: USGS Fact Sheet 2007-3003

Dai A (2011) Drought under global warming: a review. Wiley Interdiscip Rev Clim Chang 2:45–65

Dai A, Trenberth KE, Qian T (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130. https://doi.org/10.1175/JHM-386.1

Daly C, Neilson RP, Phillips DL et al (1994) A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J Appl Meteorol 33:140–158. https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2

Dieter CA, Maupin MA, Caldwell RR, et al (2018) Water Availability and Use Science Program: estimated use of water in the United States in 2015

Donnelly K, Cooley H (2015) Water use trends in the United States. In: Pacific Inst. http://pacinst.org/publication/water-use-trends-in-the-united-states.

Durack PJ, Wijffels SE, Matear RJ (2012) Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Science (80-) 336:455–458. https://doi.org/10.1126/science.1212222

Easterling DR, Kunkel KE, Arnold JR, et al (2017) Precipitation change in the United States. In: Wuebbles DJ, Fahey DW, Hibbard KA, et al. (eds) Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA, pp. 207–230

Entekhabi D, Njoku EG, O'Neill PE et al (2010) The soil moisture active passive (SMAP) mission. Proc IEEE 98:704–716. https://doi.org/10.1109/JPROC.2010.2043918

EPA (2016) Climate Change Indicators in the United States (Fourth Edition). In: Environmental Protection Agency, Washington, DC. Office of Atmospheric Programs. 430-R-16-004. pp 1–96

Estilow TW, Young AH, Robinson DA (2015) A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth Syst Sci Data 7:137–142. https://doi.org/10.5194/essd-7-137-2015

Evenson EJ, Jones SA, Barber NL, et al (2018) Continuing progress toward a national assessment of water availability and use. USGS Circular. Reston, VA. https://doi.org/10.3133/cir1440

Ganguli P, Ganguly AR (2016) Robustness of meteorological droughts in dynamically downscaled climate simulations. J Am Water Resour Assoc 52:138–167. https://doi.org/10.1111/1752-1688.12374

Georgakakos A, Fleming P, Dettinger M, et al (2014) Chapter 5: Water resources. U.S. Global Change Research Program, Washington, D.C.
Gleason KL, Lawrimore JH, Levinson DH et al (2008) A revised U.S. Climate Extremes Index. J Clim 21:2124–2137. https://doi.org/10.1175/2007JCLI1883.1
Heim RR Jr (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165. https://doi.org/10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2
Hobbs F, Stoops N (2002) Demographic Trends in the 20th Century. U.S. Census Bureau, Census 2000 Special Reports, Series CENSR-4, Washington, DC https://www.census.gov/prod/2002pubs/censr-4.pdf
Jasinski MF, Borak JS, Kumar SV et al (2019) NCA-LDAS: overview and analysis of hydrologic trends for the national climate assessment. J Hydrometeorol 20:1595–1617. https://doi.org/10.1175/JHM-D-17-0234.1
Kenney MA, Janetos AC (2020) National indicators of climate changes, impacts, and vulnerability. Clim Chang 163:1695–1704. https://doi.org/10.1007/s10584-020-02939-4
Kenney MA, Janetos AC, Gerst MD (2018) A framework for national climate indicators. Clim Chang:1–14. https://doi.org/10.1007/s10584-018-2307-y
Kenney MA, Janetos AC, Lough GC (2016) Building an integrated U.S. National Climate Indicators System. In: Jacobs K, Moser S, Buizer J (eds) The US National Climate Assessment: innovations in science and engagement. Springer International Publishing, Cham, pp 85–96
Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. Bull Am Meteorol Soc 83:1167–1180. https://doi.org/10.1175/1520-0477-83.8.1167
Knowles N, Dettinger MD, Cayan DR (2006) Trends in snowfall versus rainfall in the western United States. J Clim 19:4545–4559. https://doi.org/10.1175/JCLI3850.1
Kumar SV, Jasinski M, Mocko DM et al (2019) NCA-LDAS land analysis: development and performance of a multisensor, multivariate land data assimilation system for the National Climate Assessment. J Hydrometeorol 20:1571–1593. https://doi.org/10.1175/JHM-D-17-0125.1
Kunkel KE, Karl TR, Easterling DR et al (2013) Probable maximum precipitation and climate change. Geophys Res Lett 40:1402–1408. https://doi.org/10.1002/grl.50334
Kunkel KE, Palecki M, Ensor L et al (2009) Trends in twentieth-century U.S. snowfall using a quality-controlled dataset. J Atmos Ocean Technol 26:33–44. https://doi.org/10.1175/2008JTECHA1138.1
Kunkel KE, Palecki MA, Hubbard KG et al (2007) Trend identification in twentieth-century U.S. snowfall: the challenges. J Atmos Ocean Technol 24:64–73. https://doi.org/10.1175/JTECH2017.1
Lall U, Johnson T, Colohan P, et al (2018) Chapter 3 : Water. Impacts, risks, and adaptation in the United States: The Fourth National Climate Assessment, Volume II. Washington, DC
Lins HF, Slack JR (1999) Streamflow trends in the United States. Geophys Res Lett 26:227–230. https://doi.org/10.1029/1998GL900291
Lins HF (2012) USGS Hydro-Climatic Data Network 2009 (HCDN–2009). U.S. Geol. Surv. Fact Sheet 2012–3047, 4 p. https://pubs.usgs.gov/fs/2012/3047/
Lundquist JD, Hughes M, Henn B et al (2015) High-elevation precipitation patterns: using snow measurements to assess daily gridded datasets across the Sierra Nevada, California. J Hydrometeorol 16:1773–1792. https://doi.org/10.1175/JHM-D-15-0019.1
Mackun PJ, Wilson S, Fischetti TR, Goworowska J (2011) Population distribution and change: 2000 to 2010. U.S. Census Bureau, 2010 Census Briefs C2010BR-01, Washington, DC https://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf,
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society, Anaheim, CA, pp 179–186
McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. In: Proceedings of the 9th Conference on Applied Climatology. American Meteorological Society, Dallas TX, pp. 233–236
Milly PCD, Betancourt J, Falkenmark M, et al (2008) Stationarity is dead: whither water management? Science (80-) 319:573–574. https://doi.org/10.1126/science.1151915
Milly PCD, Betancourt J, Falkenmark M et al (2015) On critiques of "stationarity is dead: whither water management?". Water Resour Res 51:7785–7789. https://doi.org/10.1002/2015WR017408
Milly PCD, Wetherald RT, Dunne KA, Delworth TL (2002) Increasing risk of great floods in a changing climate. Nature 415:514
Mo KC (2008) Model-based drought indices over the United States. J Hydrometeorol 9:1212–1230. https://doi.org/10.1175/2008JHM1002.1
Mo KC, Long LN, Xia Y et al (2011) Drought indices based on the climate forecast system reanalysis and ensemble NLDAS. J Hydrometeorol 12:181–205. https://doi.org/10.1175/2010JHM1310.1
Mote PW (2003) Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophys Res Lett 30. https://doi.org/10.1029/2003GL017258

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005) Declining mountain snowpack in western north America. Bull Am Meteorol Soc 86:39–49. https://doi.org/10.1175/BAMS-86-1-39
Mote PW, Rupp DE, Li S et al (2016) Perspectives on the causes of exceptionally low 2015 snowpack in the western United States. Geophys Res Lett 43:10,980–10,988. https://doi.org/10.1002/2016GL069965
Mu Q, Zhao M, Running SW (2011) Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens Environ 115:1781–1800. https://doi.org/10.1016/j.rse.2011.02.019
Palmer WC (1965) Meteorological drought. U.S. Weather Bur. Res. Pap. No. 45 58
Quiring SM, Ford TW, Wang JK et al (2016) The North American Soil Moisture Database: development and applications. Bull Am Meteorol Soc 97:1441–1459. https://doi.org/10.1175/BAMS-D-13-00263.1
Regonda SK, Rajagopalan B, Clark M, Pitlick J (2005) Seasonal cycle shifts in hydroclimatology over the western United States. J Clim 18:372–384. https://doi.org/10.1175/JCLI-3272.1
Robinson D, David A, Estilow T, Program NC (2012) NOAA Climate Date Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE), Version 1. NOAA Natl Clim Data Cent:137–142. https://doi.org/10.7289/V5N014G9
Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460:999–1002
Senay GB, Budde ME, Verdin JP (2011) Enhancing the Simplified Surface Energy Balance (SSEB) approach for estimating landscape ET: validation with the METRIC model. Agric Water Manag 98:606–618. https://doi.org/10.1016/j.agwat.2010.10.014
Sheffield J, Wood EF (2008) Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. J Clim 21:432–458. https://doi.org/10.1175/2007JCLI1822.1
Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491:435–438. https://doi.org/10.1038/nature11575
Slack JR, Lumb AM, Landwehr JM (1993) Hydro-Climatic Data Network (HCDN) Streamflow Data Set, 1874-1988
Svoboda M, Fuchs B (2017) Handbook of Drought Indicators and Indices*. In: Integrated Drought Management Tools and Guidelines Series, pp 155–208
Svoboda M, LeComte D, Hayes M et al (2002) The Drought Monitor. Bull Am Meteorol Soc 83:1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181
Trenberth KE, Dai A, Van Der Schrier G et al (2014) Global warming and changes in drought. Nat Clim Chang 4:17–22. https://doi.org/10.1038/nclimate2067
USGCRP (2018) Impacts, risks, and adaptation in the United States: The Fourth National Climate Assessment, Volume II. Washington, DC
USGCRP (2017) Climate Science Special Report: Fourth National Climate Assessment, Volume I. Washington, DC, USA
Vose RS, Applequist S, Squires M et al (2014a) Improved historical temperature and precipitation time series for U.S. climate divisions. J Appl Meteorol Climatol 53:1232–1251. https://doi.org/10.1175/JAMC-D-13-0248.1
Vose RS, Applequist S, Squires M et al (2014b) NOAA's Gridded Climate Divisional Dataset (CLIMDIV). NOAA NCDC. https://doi.org/10.7289/V5M32STR
Walsh J, Wuebbles D, Hayhoe K, et al (2014) Chapter 2: Our Changing Climate. Washington, DC, USA
Xia Y, Ek MB, Wu Y et al (2015) Comparison of NLDAS-2 simulated and NASMD observed daily soil moisture. Part I: comparison and analysis. J Hydrometeorol 16:1962–1980. https://doi.org/10.1175/JHM-D-14-0096.1
Xia Y, Mitchell K, Ek M, et al (2012) Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. J Geophys Res Atmos 117:n/a-n/a. https://doi.org/10.1029/2011JD016048
Zhai J, Su B, Krysanova V et al (2010) Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China. J Clim 23:649–663. https://doi.org/10.1175/2009JCLI2968.1

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