Streamflow

Identification

1. Indicator Description

This indicator describes trends in the magnitude and timing of streamflow in rivers and streams across the United States. Streamflow is a useful indicator of climate change for several reasons. More precipitation is expected to cause higher average streamflow in some places, while heavier storms could lead to higher peak flows. More frequent or severe droughts may reduce streamflow in some areas. Changes in the amount of snowpack and earlier spring melting have been found to alter the size and timing of peak streamflows (Dudley et al., 2017).

Components of this indicator include trends in four annual flow statistics from 1940 through 2014:

- Magnitude of annual seven-day low streamflow (Figure 1).
- Magnitude of annual three-day high streamflow (Figure 2).
- Magnitude of annual mean streamflow (Figure 3).
- Timing of winter-spring center-of-volume date (Figure 4).

2. Revision History

December 2012:	Indicator published.
May 2014:	Updated indicator with data through 2012. Added Figure 3 to show annual mean streamflow and renumbered original Figure 3 (winter-spring center of volume) as Figure 4.
August 2016:	Updated indicator with data through 2014.

Data Sources

3. Data Sources

Mike Kolian of EPA developed this indicator in partnership with Michael McHale, Robert Dudley, and Glenn Hodgkins at the U.S. Geological Survey (USGS). The indicator is based on streamflow data from a set of reference stream gauges specified in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES-II) database, which was developed by USGS and is described in Lins (2012). Daily mean streamflow data are stored in the USGS National Water Information System (NWIS).

4. Data Availability

EPA obtained the data for this indicator from Michael McHale, Robert Dudley, and Glenn Hodgkins at USGS. Similar streamflow analyses had been previously published in the peer-reviewed literature (Burns et al., 2007; Hodgkins and Dudley, 2006). USGS provided a reprocessed data set to include streamflow trends through water year 2014.

Streamflow data from individual stations are publicly available online through the surface water section of NWIS at: http://waterdata.usgs.gov/nwis/sw. Reference status and watershed, site characteristics, and other metadata for each stream gauge in the GAGES-II database are available online at: http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Methodology

5. Data Collection

Streamflow is determined from data collected at stream gauging stations by automated devices that record the elevation (or stage) of a river or stream at regular intervals each day. Intervals vary from station to station—typically every 15 minutes to one hour. USGS maintains a national network of stream gauging stations, including more than 7,000 stations currently in operation throughout the United States (http://pubs.usgs.gov/fs/1995/0066/report.pdf). USGS has been collecting stream gauge data since the late 1800s at some locations. Gauges generally are sited to record flows for specific management goals or legal mandates, typically in cooperation with municipal, state, and federal agencies.

Streamflow (or discharge) is measured manually at regular intervals by USGS personnel (typically every four to eight weeks). The relation between stream stage and discharge is determined, and a stage-discharge relation (rating) is developed to calculate streamflow for each recorded stream stage (Rantz et al., 1982). These data are used to calculate the daily mean discharge for each day at each site. All measurements are made according to standard USGS procedures (Rantz et al., 1982; Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010).

This indicator uses data from USGS stream gauges that are part of the Hydro-Climatic Data Network 2009 (HCDN-2009) network (Lins, 2012), which is a subset of the USGS GAGES-II network. HCDN-2009 gauges have been carefully selected to reflect minimal interference from human activities such as dam construction, reservoir management, wastewater treatment discharge, water withdrawal, and changes in land cover and land use that might influence runoff. The subset of HCDN-2009 gauges was further examined on the basis of length of period of record (75 years) and completeness of record (greater than or equal to 80 percent for every decade). Figures 1, 2, and 3 are based on data from 192 stream gauges. Figure 4 relies on 56 stream gauges largely because it is limited to stream basins that receive 30 percent or more of their total annual precipitation in the form of snow. This additional criterion was applied because the metric in Figure 4 is used primarily to examine the timing of winter-spring runoff, which is substantially affected by snowmelt-related runoff in areas with a large annual snowpack. All of the selected stations and their corresponding basins are relatively independent—that is, the analysis does not include stations with watershed areas that overlap by more than 30 percent.

All watershed characteristics, including basin area, station latitude and longitude, and percentage of precipitation as snow were taken from the GAGES-II database. GAGES-II basin area was determined through EPA's National Hydrography Dataset Plus and supplemented by the USGS National Water-Quality Assessment Program and the USGS Elevation Derivatives for National Applications.

6. Indicator Derivation

Figures 1, 2, and 3. Seven-Day Low (Figure 1), Three-Day High (Figure 2), and Annual Average (Figure 3) Streamflow in the United States, 1940–2014

Figure 1 shows trends in low-flow conditions using seven-day low streamflow, which is the lowest average of seven consecutive days of streamflow in a year. Hydrologists commonly use this measure because it reflects sustained dry or frozen conditions that result in the lowest flows of the year. Seven-day low flow can equal zero if a stream has dried up completely.

Figure 2 shows trends in very wet conditions using three-day high streamflow, which is the highest average of three consecutive days of streamflow in a year. Hydrologists use this measure because a three-day averaging period has been shown to effectively characterize runoff associated with large storms and peak snowmelt over a diverse range of watershed areas.

Figure 3 shows trends in average conditions using annual average streamflow, which is the average of all daily mean streamflow values for a given year.

Rates of change from 1940 to 2014 at each station on the maps in Figures 1–3 were computed using the Sen slope, which is the median of all possible pair-wise slopes in a temporal data set (Helsel and Hirsch, 2002). The Sen slope was then multiplied by the number of years in the period (74 years: the last year minus the starting year) to estimate total change over time. Trends are reported as percentage increases or decreases, computed from the value for the last year of the regression line relative to the value of the first year of the regression line.

Figure 4. Timing of Winter-Spring Runoff in the United States, 1940–2014

Figure 4 shows trends in the timing of streamflow in the winter and spring, which is influenced by the timing of snowmelt runoff in areas with substantial annual snowpack. The timing of streamflow also can be influenced by the ratio of winter rain to snow and by changes in the seasonal distribution of precipitation. Figure 4 shows trends in the winter-spring center-of-volume (WSCV) date, which is defined for this indicator as the date when half of the total streamflow between January 1 and July 31 for sites in the western United States, or half of the total streamflow between January 1 and May 31 for sites in the eastern United States, has passed by the gauging station. These regionally different time periods were selected to best represent the period during which snowmelt occurs in each region, based on snowmelt-related streamflow interpreted from long-term average seasonal hydrographs. Trends in this date are computed in the same manner as the other three components of this indicator, and the results are reported in terms of the number of days earlier or later that the WSCV date is occurring. For more information about WSCV-date methods, see Dudley et al. (2017), Hodgkins and Dudley (2006), and Burns et al. (2007).

Indicator Development

For the 2016 update to this indicator, EPA and USGS adjusted the analysis in two ways:

- The analysis of all four metrics changed from calendar years (January 1 to December 31) to water years (October 1 to September 30). Water years are defined such that "water year 2014" runs from October 2013 through September 2014.

- The seasonal window for the timing of winter-spring flows changed from January through June for all gauges to January through July for western gages and January through May for eastern gauges.

EPA and USGS made these adjustments to harmonize this indicator with other publications based on the same data, including Dudley et al. (2017), and to reflect best practices for characterizing WSCV.

7. Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) procedures are documented for measuring stream stage (Sauer and Turnipseed, 2010), measuring stream discharge (Turnipseed and Sauer, 2010), and computing stream discharge (Sauer, 2002; Rantz et al., 1982). Stream discharge is typically measured and equipment is inspected at each gauging station every four to eight weeks. The relation between stream stage and stream discharge is evaluated following each discharge measurement at each site, and shifts to the relation are made if necessary.

The GAGES-II database incorporated a QC procedure for delineating the watershed boundaries acquired from the National Hydrography Dataset Plus. The data set was cross-checked against information from USGS's National Water-Quality Assessment Program. Basin boundaries that were inconsistent across sources were visually compared and manually delineated based on geographical information provided in USGS's Elevation Derivatives for National Applications. Other screening and data quality issues are addressed in the GAGES-II metadata available at: https://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Analysis

8. Comparability Over Time and Space

All USGS streamflow data have been collected and extensively quality-assured by USGS since the start of data collection. Consistent and well-documented procedures have been used for the entire periods of recorded streamflows at all gauges (Corbett et al., 1943; Rantz et al., 1982; Sauer, 2002).

Trends in streamflow over time can be strongly influenced by human activities upstream, such as the construction and operation of dams, flow diversions and abstractions, and land-use change. To remove these non-climatic influences to the extent possible, this indicator relies on a set of reference gauges that were chosen because they represent least-disturbed (though not necessarily completely undisturbed) watersheds. The criteria for selecting reference gauges vary from region to region based on land use characteristics. Therefore, a modestly impacted watershed in one part of the country (e.g., an area with agricultural land use) might not have met the data quality standards for another less impacted region. The reference gauge screening process is described in Lins (2012) and is available in the GAGES-II metadata at: https://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Analytical methods have been applied consistently over time and space.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. This analysis is restricted to locations where streamflow is not highly disturbed by human influences, including reservoir regulation, diversions, and land cover change. Changes in land cover and land use over time, however, could still influence trends in the magnitude and timing of streamflow at some sites.

2. Reference gauges used for this indicator are not evenly distributed throughout the United States, nor are they evenly distributed with respect to topography, geology, elevation, or land cover, due to variations in the availability of long-term data.

3. Some streams in northern or mountainous areas have their lowest flows in the winter due to water being held in snow or ice for extended periods. At these sites, low flow trends could be influenced by climate factors other than reduced precipitation or otherwise dry conditions, such as long stretches of cold weather.

10. Sources of Uncertainty

Uncertainty estimates are not available for this indicator as a whole. As for the underlying data, the precision of individual stream gauges varies from site to site. Accuracy depends primarily on the stability of the stage-discharge relationship, the frequency and reliability of stage and discharge measurements, and the presence of special conditions such as ice (Novak, 1985). USGS has published a general online reference devoted to the calculation of error in individual stream discharge measurements (Sauer and Meyer, 1992).

11. Sources of Variability

Streamflow can be highly variable over time, depending on the size of the watershed and the factors that influence flow at a gauge. USGS addresses this variability by recording stream stage many times a day (typically 15-minute to one-hour intervals) and then computing a daily average streamflow. Streamflow also varies from year to year as a result of variation in precipitation and air temperature. Trend magnitudes computed from Sen slopes provide a robust estimate of linear changes over a period of record, and thus this indicator does not measure decadal cycles or interannual variability in the metric over the time period examined.

While gauges are chosen to represent drainage basins relatively unimpacted by human disturbance, some sites may be more affected by direct human influences (such as land-cover and land-use change) than others. Other sources of variability include localized factors such as topography, geology, elevation, and natural land cover. Changes in land cover and land use over time can contribute to streamflow trends, though careful selection of reference gauges strives to minimize these impacts.

Although the WSCV date is driven by the timing of the bulk of snow melt in areas with substantial annual snowpack, other factors also will influence the WSCV date. For instance, a heavy rain event in the winter could result in large volumes of water that shift the timing of the center of volume earlier. Changes over time in the distribution of rainfall during the WSCV measurement period could also affect the WSCV date.

12. Statistical/Trend Analysis

The maps in Figures 1, 2, 3, and 4 all show trends through time that have been computed for each gauging station using a Sen slope analysis by USGS. Because of uncertainties and complexities in the interpretation of statistical significance, particularly related to the issue of long-term persistence (Cohn and Lins, 2005; Koutsoyiannis and Montanari, 2007), significance of trends is not reported. Future updates of this indicator will likely also include details on the significance of the reported trends.

References

Burns, D.A., J. Klaus, and M.R. McHale. 2007. Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. J. Hydrol. 336(1–2):155–170.

Cohn, T.A., and H.F. Lins. 2005. Nature's style: Naturally trendy. Geophys. Res. Lett. 32:L23402.

Corbett, D.M., et al. 1943. Stream-gaging procedure: A manual describing methods and practices of the Geological Survey. U.S. Geological Survey Water-Supply Paper 888. https://pubs.er.usgs.gov/publication/wsp888.

Dudley, R.W., G.A. Hodgkins, M.R. McHale, M.J. Kolian, and B. Renard. 2017. Trends in snowmelt-related streamflow timing in the conterminous United States. J. Hydrol. 547:208–221.

Helsel, D.R., and R.M. Hirsch. 2002. Statistical methods in water resources. Techniques of water resources investigations, Book 4. Chap. A3. U.S. Geological Survey. https://pubs.usgs.gov/twri/twri4a3.

Hodgkins, G.A., and R.W. Dudley. 2006. Changes in the timing of winter-spring streamflows in eastern North America, 1913–2002. Geophys. Res. Lett. 33:L06402. https://water.usgs.gov/climate_water/hodgkins_dudley_2006b.pdf.

Koutsoyiannis, D., and A. Montanari. 2007. Statistical analysis of hydroclimatic time series: Uncertainty and insights. Water Resour. Res. 43(5):W05429.

Lins, H.F. 2012. USGS Hydro-Climatic Data Network 2009 (HCDN-2009). U.S. Geological Survey Fact Sheet 2012-3047. https://pubs.usgs.gov/fs/2012/3047.

Novak, C.E. 1985. WRD data reports preparation guide. U.S. Geological Survey Open-File Report 85-480. https://pubs.er.usgs.gov/publication/ofr85480.

Rantz, S.E., et al. 1982. Measurement and computation of streamflow. Volume 1: Measurement of stage and discharge. Volume 2: Computation of discharge. U.S. Geological Survey Water Supply Paper 2175. https://pubs.usgs.gov/wsp/wsp2175.

Sauer, V.B. 2002. Standards for the analysis and processing of surface-water data and information using electronic methods. U.S. Geological Survey Water-Resources Investigations Report 01-4044. https://pubs.er.usgs.gov/publication/wri20014044.

Sauer, V.B., and R.W. Meyer. 1992. Determination of error in individual discharge measurements. U.S. Geological Survey Open-File Report 92-144. https://pubs.usgs.gov/of/1992/ofr92-144.

Sauer, V.B., and D.P. Turnipseed. 2010. Stage measurement at gaging stations. U.S. Geological Survey Techniques and Methods, Book 3. Chap. A7. U.S. Geological Survey. https://pubs.usgs.gov/tm/tm3-a7.

Turnipseed, D.P., and V.B. Sauer. 2010. Discharge measurements at gaging stations. U.S. Geological Survey Techniques and Methods, Book 3. Chap. A8. U.S. Geological Survey. https://pubs.usgs.gov/tm/tm3-a8.