

Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States

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[1] Both climate change and human activities are known to have induced changes to hydrology. Consequently, quantifying the net impact of human contribution to the streamflow change is a challenge. In this paper, a decomposition method based on the Budyko hypothesis is used to quantify the climate (i.e., precipitation and potential evaporation change) and direct human impact on mean annual streamflow (MAS) for 413 watersheds in the contiguous United States. The data for annual precipitation, runoff, and potential evaporation are obtained from the international Model Parameter Estimation Experiment (MOPEX), which is often assumed to only include gauges unaffected by human interferences. The data are split into two periods (1948–1970 and 1971–2003) to quantify the change over time. Although climate is found to affect MAS more than direct human impact, the results show that assuming the MOPEX data set to be unaffected by human activities is far from realistic. Climate change causes increasing MAS in most watersheds, while the direct human-induced change is spatially heterogeneous in the contiguous United States, with strong regional patterns, e.g., human activities causing increased MAS in the Midwest and significantly decreased MAS in the High Plains. The climate- and human-induced changes are found to be more severe in arid regions, where water is limited. Comparing the results to a collection of independent data sets indicates that the estimated direct human impacts on MAS in this largely nonurban set of watersheds might be attributed to several human activities, such as cropland expansion, irrigation, and the construction of reservoirs.

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1. Introduction

[2] Climate change and human activities have altered the hydrologic cycle and have exerted global-scale impacts on our environment with significant implications for water resources [Barnett *et al.*, 2008; Milly *et al.*, 2008; Wagener *et al.*, 2010; Vogel, 2011]. Climate change includes the redistribution of precipitation and temperature change, which together affect streamflow discharge [Karl *et al.*, 1996; Vörösmarty *et al.*, 2000]. Human activities can alter the streamflow directly by affecting the hydrological processes or indirectly by disturbing the climate variables. The direct human impacts on streamflow include land use change [Schilling *et al.*, 2010; Arrigoni *et al.*, 2010], dam construction and reservoir operation [Rossi *et al.*, 2009], and surface water and groundwater withdrawal and return flow [Weiskel *et al.*, 2007; Wang and Cai, 2010]. Human impacts on climate can operate at various spatial scales. For example, at the global scale, human-induced elevated

CO₂ emissions contribute to global warming, while at the regional scale, irrigation in the U.S. High Plains increases the rainfall and streamflow during the summer season in the Midwest [Kustu *et al.*, 2011]. An example of local-scale impact is the urban heat island effect related to human development and urbanization.

[3] Precipitation and streamflow trends in the contiguous United States have been investigated in several recent studies. Increases in precipitation across the United States during the twentieth century have been reported by Karl and Knight [1998] and Groisman *et al.* [2004]. Streamflow has been increasing in the United States since at least 1940 [Lins and Slack, 1999; McCabe and Wolock, 2002]. On the basis of 400 sites in the conterminous United States measured during 1941–1999, McCabe and Wolock [2002] identified noticeable increases in annual minimum and median daily streamflow around 1970, especially in the eastern United States. They attributed streamflow increases to a step change that coincided with an increase in precipitation [McCabe and Wolock, 2002]. By developing maps of annual streamflow anomalies over the contiguous United States using streamflow records selected to reflect minimum direct impacts from human land disturbances and water diversion, Krakauer and Fung [2008] found a similar trend, i.e., increased streamflow around 1970 in concert with an increase in precipitation. Annual average flow and

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annual total precipitation have increased during the period of 1948–1997 across the eastern United States, and the trends appear to arise primarily from the increase in autumn precipitation [Small *et al.*, 2006]. More recently, Luce and Holden [2009] examined changes to the distribution of annual streamflow from 43 gauges in the Pacific Northwest of the United States between 1948 and 2006, and they found that the mean annual flow exhibited a decreasing trend in 25 gauges and no significant trend in the remaining 18 gauges.

[4] In all of these studies, streamflow was assumed to be unaffected by human activities; detected trends of streamflow discharge were attributed to climate change alone. However, the flow of water in most rivers in the United States reflects some level of human activities [National Research Council, 2002]. Dams and diversions for irrigation may be the most cited activities, but groundwater pumping and land use change are also important factors. Recently, Arrigoni *et al.* [2010] found that direct anthropogenic modifications (i.e., irrigation, damming, and urbanization) of the river basins across the northern Rocky Mountains have altered the flow regimes to a much greater extent than climate change over the past 59 years. To secure a complete picture of future water resources, it is necessary to consider climate change, human systems, and hydrology in an integrated framework [Vörösmarty *et al.*, 2000]. The separation and quantification of climate change and human impacts on streamflow is a challenge because of the complexity and interaction of climate, human, and hydrologic processes. Several recent studies have estimated the contributions of climate and human impacts on mean annual streamflow (MAS) for specific watersheds using distributed hydrologic models [Wang *et al.*, 2009; Ma *et al.*, 2010] and climate sensitivity or elasticity methods [Li *et al.*, 2007; Zhang *et al.*, 2008; Ma *et al.*, 2008; Zhao *et al.*, 2009]. Tomer and Schilling [2009] studied the relative effects of climate change and land use change on hydrology in the Midwest on the basis of ecohydrologic plots of water versus energy use efficiency indices. Particularly, in the Upper Mississippi River Basin, Schilling *et al.* [2010] found that the runoff coefficient increased 32% because of land use change, i.e., increasing soybean acreage.

[5] In this paper an attempt is made to categorize streamflow change into climate-induced and direct human-induced streamflow change. The climate-induced streamflow change is caused by the alterations of precipitation and potential evaporation, which can be due to natural climate variability, global climate change, and the regional and local climate effects of human activities. The human impact on the climate includes the interdependence between evaporation (E) and potential evaporation (E_p) and the contribution from E to the recycle of precipitation (P) [Brutsaert and Parlange, 1998; Roderick and Farquhar, 2002; Szilagyi, 2007]. The direct human-induced streamflow change is the alteration of precipitation portioning into evaporation and runoff. On the basis of historical data during the period of 1948–2003 for 413 gauge stations across the contiguous United States, the climate-induced and direct human-induced changes of MAS are quantified, and the quantification is based on a proposed decomposition method in the Budyko framework. An order of magnitude estimate of model uncertainty is obtained through sensitivity analysis. The estimation of the direct human impact is compared with independent data such as

population density, percent of urban, crop, and irrigated lands, and storage of reservoirs. The spatial patterns of climate- and direct human-induced changes to streamflow are analyzed and discussed. The results provide a comprehensive view on the climate- and direct human-induced MAS changes over the contiguous United States in the past 60 years.

2. Methodology

2.1. Budyko Curves

[6] To quantify the relative contributions of climate and direct human impacts on MAS, a hydrologic model is needed to link both climatic forcing and human impact on hydrological response. In this study, instead of applying a detailed hydrologic model to over 400 watersheds, which can be a very tedious exercise, a simple conceptual model based on the Budyko hypothesis [Budyko, 1974] is used to quantify the impact of climate and humans on MAS. Thus, this study is focused on the long-term MAS change.

[7] The water-energy balance at the watershed scale over a long-term temporal scale describes the partitioning of precipitation into evaporation and runoff. Budyko [1958] postulated that mean annual evaporation from a watershed could be determined, to first order, from rainfall and net radiation. On the basis of worldwide data on a large number of watersheds, Budyko [1974] demonstrated that the ratio of mean annual evaporation to mean annual precipitation (E/P , evaporation ratio) is primarily controlled by the ratio of mean annual potential evaporation to mean annual precipitation (E_p/P , climatic dryness index), as shown in Figure 1. For watersheds with E_p/P less than 1, the energy supply is the limiting factor for evaporation, while for watersheds with E_p/P larger than 1, the water supply is the limiting factor. Watersheds in different climatic regions fall at different points along the Budyko curve depending on the values of E_p/P . Observations from real watersheds are scattered around the Budyko curve because in addition to the dryness index other factors can also affect the partitioning of mean annual precipitation, such as soil water storage [Milly,

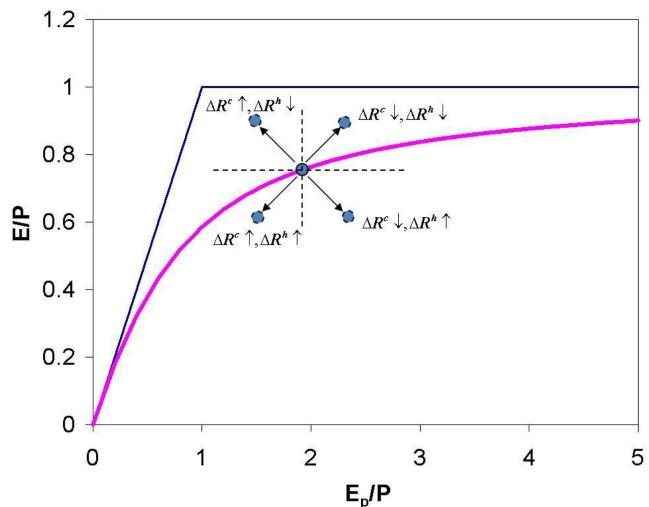


Figure 1. Budyko curve and diagram to show the direct human and climate impacts on runoff coefficient ($R = Q/P$).

1994], vegetation [Zhang *et al.*, 2001; Donohue *et al.*, 2007, 2010; Yang *et al.*, 2009], infiltration capacity and slope [Yang *et al.*, 2007], and rainfall seasonality and characteristics [Gerrits *et al.*, 2009; Jothityangkoon and Sivapalan, 2009].

[8] Many researchers have studied the mean annual water balance and proposed different functional forms to represent the Budyko hypothesis [Schreiber, 1904; Ol'dekop, 1911; Turc, 1954; Pike, 1964; Fu, 1981; Milly, 1993; Zhang *et al.*, 2001; Sankarasubramanian and Vogel, 2002; Porporato *et al.*, 2004; Yang *et al.*, 2008]. The sensitivity of various Budyko-type curves has been assessed by other studies [e.g., Potter and Zhang, 2009]. In this paper, the Fu [Fu, 1981] and Turc-Pike [Turc, 1954; Pike, 1964] equations are used, and both of them are single-parameter Budyko-type curves, as shown in Table 1.

2.2. Decomposition Method for Separating the Climate and Direct Human Impacts on MAS Change

[9] In this paper, the direct human impact represents the change of precipitation partitioning given climate conditions, and it does not include indirect human-induced climate change. The climate change represents the contribution of mean annual potential evaporation and precipitation to the streamflow change. As a result, in Figure 1 the movement of a watershed along the horizontal direction (i.e., the change of E_p/P) is only driven by climate change or variability. The movement of a watershed along the vertical direction can be driven by both climate change and direct human impacts since human activities can affect runoff generation and evaporation, and climate change can affect actual evaporation and precipitation. The challenge becomes how to separate the effects of climate change and direct human impact on the vertical movement.

[10] The proposed decomposition method assumes that for a watershed without direct human impact, if the climate (E_p/P) moves to a drier or wetter region because of climate change, the evaporation ratio (E/P) will also change to a new region but will still follow the same Budyko-type curve as the prechange period. The rationale for this assumption is based on the concept of geographic zonality; that is, at less than the geological time scales, the soil and vegetation properties are dependent only on the long-term P and E_p [Dooge, 1992]. The original Budyko hypothesis is that natural watersheds follow the Budyko curve [Budyko, 1974]. The catchment properties, especially vegetation, will respond to climate variability and change through evaporation [Jones, 2011]. Therefore, with the change of climate (i.e., E_p/P), a watershed will evolve to a new state (i.e., change of evaporation ratio) but is still on the Budyko curve. Moreover, a watershed can move along the Budyko-type curve because of climate change only, and direct human interferences can push the watershed to move on the vertical direction, i.e., change of E/P due to change of E . On the basis of this assumption, vertical movement of the watershed from the

Budyko-type curve can be divided into climate- and direct human-induced changes. As shown in Figure 1, there are four possible movement directions for a watershed. If the watershed moves to the top right corner, the climate and direct human interferences affect the streamflow in the same direction by decreasing the runoff coefficient ($R = Q/P$); if the watershed moves to the bottom left corner, climate and humans cause increased and decreased runoff coefficients, respectively.

[11] The proposed decomposition method is described in Figure 2. Suppose a watershed has shifted over time from point A (prechange period) to point B (postchange period) because of both climate change and direct human interferences (Figure 2). The dryness index and the evaporation ratio in the prechange period are denoted as E_{p1}/P_1 and E_1/P_1 , respectively. These two ratios are changed to E_{p2}/P_2 and E_2/P_2 in the postchange period (point B). Under climate change only, the watershed will evolve from $(E_{p1}/P_1, E_1/P_1)$ to $(E_{p2}/P_2, E_2/P_2)$ along the Budyko-type curve (point C). Since the climate at points B and C is same, the precipitation at point C is P_2 . Thus, climate change causes both horizontal and vertical shifts, i.e., from E_{p1}/P_1 to E_{p2}/P_2 on the horizontal direction and from E_1/P_1 to E'_2/P_2 on the vertical direction; direct human interferences cause a vertical change from E'_2/P_2 to E_2/P_2 . For the case shown in Figure 2, the contribution of the direct human impact counteracts the vertical component attributed to the climate change impact, and the overall vertical change caused by both climate and direct human impacts is from E_1/P_1 to E_2/P_2 .

[12] The climate change impact can induce both horizontal and vertical components, and both components can affect streamflow, but direct human interferences only can induce a vertical component. Thus, the contribution of direct human interferences to streamflow change is computed first. For long-term annual average, the soil water storage change can be ignored, and the streamflow is a function precipitation and evaporation ratio:

$$Q = P(1 - E/P). \quad (1)$$

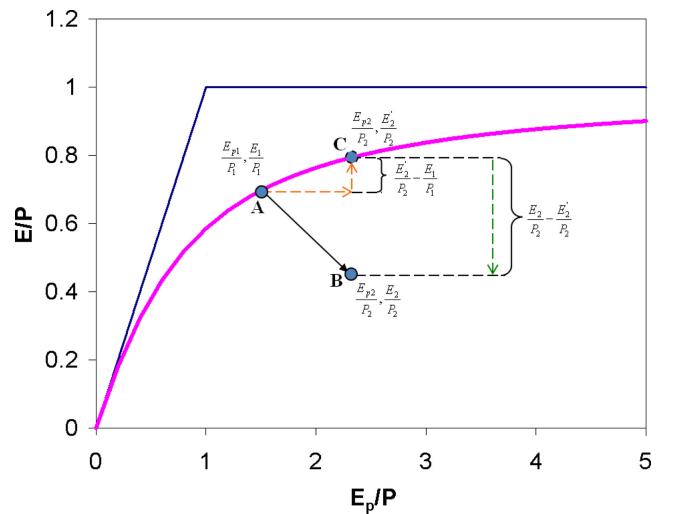


Figure 2. Decomposition method to quantify the direct human and climate contributions to the mean annual streamflow change.

Table 1. Functional Forms of Two Budyko-Type Curves

Name of Model	Functional Forms of Budyko-Type Curves
Fu	$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P} \right)^w \right]^{-1/w}$
Turc-Pike	$\frac{E}{P} = \left[1 + \left(\frac{E_p}{P} \right)^{-v} \right]^{-1/v}$

Similarly, the direct human contribution to streamflow change can be computed by

$$\Delta Q^h = P_2(E'_2/P_2 - E_2/P_2), \quad (2)$$

where ΔQ^h is the magnitude of the direct human-induced change of streamflow. The climate change contribution to streamflow change can be obtained by subtracting the human-induced change from the total streamflow change:

$$\Delta Q^c = \Delta Q - \Delta Q^h, \quad (3)$$

where ΔQ^c is the climate-induced change of streamflow. Both ΔQ^h and ΔQ^c can be positive or negative. ΔQ is the total streamflow change and is computed by

$$\Delta Q = Q_2 - Q_1. \quad (4)$$

[13] Given annual precipitation, streamflow, and potential evaporation data, the procedures for computing the contribution of climate change and direct human interferences to the MAS change are as follows.

[14] 1. The mean annual evaporation is calculated by assuming zero storage change, i.e., $E_1 = P_1 - Q_1$ and $E_2 = P_2 - Q_2$. The mean annual values of E_1/P_1 and E_{p1}/P_1 for the prechange period and E_2/P_2 and E_{p2}/P_2 for the postchange period are computed.

[15] 2. This study is focused on the change between the two periods. The watersheds in the prechange period are not natural. Thus, the prechange watersheds are not on the same Budyko-type curve. Recall that the shapes of Budyko-type curves depend on the physical properties of watersheds, such as soil properties, vegetation type and coverage, and topography [e.g., Milly, 1994; Zhang et al., 2001; Yang et al., 2007; Yokoo et al., 2008]. Therefore, a single-parameter Budyko-type curve is used, and the parameter is calibrated to the prechange period; that is, separate Budyko curves are fitted for each watershed.

[16] 3. The evaporation ratio due to climate change only (E'_2/P_2) is computed on the basis of the calibrated Budyko-type curve in step 2 corresponding to the observed dryness index under the postchange condition (E_{p2}/P_2). For the Budyko curve that is fixed, E_1/P_1 may not be on the curve exactly, but E'_2/P_2 is assumed to be on the Budyko curve corresponding to E_{p2}/P_2 in the decomposition method.

[17] 4. The streamflow change due to direct human interferences is computed by equation (2).

[18] 5. The climate-induced change of streamflow (ΔQ^c) can be computed by equation (3). It can also be computed directly from the postchange condition without direct human interferences, i.e., $\Delta Q^c = Q'_2 - Q_1$. Given negligible storage change for mean annual water balance, $Q'_2 = P_2 - E'_2 = P_2 \left(1 - \frac{E'_2}{P_2}\right)$. Therefore, one obtains

$$\Delta Q^c = P_2(1 - E'_2/P_2) - Q_1. \quad (5)$$

[19] Recently, several related studies have quantified the climate and direct human contributions to the streamflow change on the basis of the Budyko framework [Li et al.,

2007; Zhang et al., 2008; Ma et al., 2008; Zhao et al., 2009]. In these studies, the climate contribution to the streamflow change is computed by the sensitivity or elasticity method, which is based on the perturbations in precipitation and potential evaporation. The climate-induced change on MAS is determined by

$$\Delta Q^c = \beta \Delta P + \gamma \Delta E_p, \quad (6)$$

where β and γ are the sensitivity coefficients of streamflow to precipitation and potential evaporation, respectively, i.e., $\beta = \partial Q / \partial P$ and $\gamma = \partial Q / \partial E_p$. The two sensitivity coefficients can be obtained by the partial derivatives on the basis of the functional form of Budyko curve. For example, if Fu's equation is used, $\beta = P_1^{w-1} (E_{p1}^w + P_1^w)^{(1/w)-1}$ and $\gamma = E_{p1}^{w-1} (E_{p1}^w + P_1^w)^{(1/w)-1} - 1$ [Ma et al., 2008]; then

$$\begin{aligned} \Delta Q^c &= P_1^{w-1} (E_{p1}^w + P_1^w)^{\frac{1}{w}-1} (P_2 - P_1) \\ &\quad + \left[E_{p1}^{w-1} (E_{p1}^w + P_1^w)^{\frac{1}{w}-1} - 1 \right] (E_{p2} - E_{p1}). \end{aligned} \quad (7)$$

After computing ΔQ^c , the direct human impact is the difference between the total observed change in streamflow and streamflow change attributed to climate change, i.e., $\Delta Q^h = \Delta Q - \Delta Q^c$.

[20] For the decomposition method, if Fu's equation is used, substituting Fu's equation into equation (5), one obtains

$$\Delta Q^c = (P_2^w + E_{p2}^w)^{\frac{1}{w}} - E_{p2} - Q_1. \quad (8)$$

The decomposition method treats the climate dryness index as one component in equation (5), while in the sensitivity method the individual sensitivities of precipitation and potential evaporation to streamflow are computed separately. Comparing equations (7) and (8) for the case of Fu's equation, for the sensitivity method, ΔQ^c is a function of precipitation and potential evaporation during prechange and postchange periods, while for the decomposition method, ΔQ^c is a function of streamflow during the prechange period and the precipitation and potential evaporation during the postchange period. It also should be noted that both direct human and climate contributions to streamflow change can be estimated independently in the decomposition method, i.e., equations (2) and (5), respectively, while for the sensitivity method, the direct human impact results from the residual after subtracting the climate impact.

2.3. Comparing the Results from the Decomposition Method With Published Data

[21] The climate- and direct human-induced percentage changes of annual streamflow have been estimated for specific watersheds in several studies [Zhao et al., 2009; Wang et al., 2009; Zhang et al., 2008; Ma et al., 2008; Li et al., 2007] using the climate sensitivity method:

$$\begin{aligned} C &= 100(\Delta Q^c / \Delta Q), \\ H &= 100(\Delta Q^h / \Delta Q). \end{aligned} \quad (9)$$

The watersheds and their estimated climate (C) and direct human (H) impacts on mean annual streamflows from these studies are shown in Table 2. Both climate and direct

Table 2. Human- and Climate-Induced Percentage Change on Annual Streamflow Compared Between Published Data and the Decomposition Method^a

Watershed	Zhao et al. [2009]		Decomposition		
	H	C	H	C	ΔH
Huangheyan	93	7	94.9	5.1	1.9
Jimai	85	15	87.0	13.0	2.0
Maqu	51	49	54.1	45.9	3.1
Jungong	44	56	46.4	53.6	2.4
Tangnaihai	42	58	44.5	55.5	2.5
Guide	47	53	49.9	50.1	2.9
Xunhua	48	52	50.5	49.5	2.5
Xiaochuan	49	51	52.0	48.0	3.0
Lanzhou	52	48	54.8	45.2	2.8
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Watershed	Zhang et al. [2008]		Decomposition		
	H	C	H	C	ΔH
Huangfu	79	21	80.5	19.5	1.5
Gushan	61	39	60.0	40.0	-1.0
Kuye	78	22	72.4	27.6	-5.6
Jialu	63	37	62.3	37.7	-0.7
Wuding	57	43	60.7	39.3	3.7
Shiwang	43	57	33.0	67.0	-10.0
Xinshui	45	55	28.5	71.5	-16.5
Sanchuan	70	30	63.6	36.4	-6.4
Weifen	43	57	50.4	49.6	7.4
Zhujia	55	45	57.7	42.3	2.7
CSHC	54	46	51.8	48.2	-2.2
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Watershed	Ma et al. [2008]		Decomposition		
	H	C	H	C	ΔH
Huangfu	12.1	87.9	12.0	88.0	-0.1
Gushan	35.5	64.5	35.7	64.3	0.2
Kuye	22.1	77.9	22.7	77.3	0.6
Jialu	23.1	76.9	23.8	76.2	0.7
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Watershed	Li et al. [2007]		Decomposition		
	H	C	H	C	ΔH
Wuding	84.3	15.7	62.8	37.2	-21.5
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Watershed	Wang et al. [2009] ^b		Decomposition		
	H	C	H	C	ΔH
Chao	68.6	31.4	64.7	35.3	-3.9
Bai	70.4	29.6	52.8	47.2	-17.6

^a $H = 100(\bar{Q}^h/\Delta\bar{Q})$, and $C = 100(\Delta\bar{Q}^c/\Delta\bar{Q})$. ΔH is the difference of human- and climate-induced percentage change.

^bOn the basis of simulation models. Other methods from the literature are based on the climate sensitivity method.

human interferences reduce streamflow for all of the watersheds in Table 2. Fu's equation [Fu, 1981], shown in Table 1, is used for the decomposition method for these watersheds, and the estimated percentage of climate and direct human contributions to streamflow change by the decomposition method is also shown in Table 2.

[22] From Table 2, the results based on the decomposition method are close to the estimation by Zhao et al. [2009] for nine watersheds, and the difference of direct human contribution ranges between 1.9% and 3.1%. For the 11 watersheds in the work of Zhang et al. [2008], the values of H are -10% for Shiwang watershed, -16.5% for

Xinshui watershed, and 7.4% for Weifen watershed. In the estimation by Zhang et al. [2008], the climate contribution to the reduced streamflow in the Weifen watershed is estimated as 57%, which is the highest among all the 11 watersheds, but the precipitation decrease in the Weifen watershed (-1.1 mm yr^{-1}) is much more modest compared to the Shiwang and Xinshui watersheds (-2.9 and -4.3 mm yr^{-1} , respectively). The authors recognized this puzzling result but did not give an explanation. On the basis of the decomposition method, the climate contribution is 49.6% in the Weifen watershed but 67.0% and 71.5% for the Shiwang and Xinshui watersheds, respectively, suggesting that the estimation by the decomposition method is more reasonable. Both the decomposition method and the sensitivity method of Ma et al. [2008] are based on Fu's equation, and the difference between them is minimal. The difference of direct human contribution (ΔH) is between -0.1% and 0.7% . The difference of direct human contribution between the decomposition method and the estimation by Li et al. [2007] is -21.5% , the highest among all the selected watersheds. Compared with the results from the water balance model by Wang et al. [2009], the direct human contribution by the decomposition method is 3.9% less for the Chao River and 17.6% less for the Bai River.

3. Application to the Watersheds in the Contiguous United States

[23] In this section, the proposed decomposition method is utilized to assess the climate and direct human impacts on MAS at selected watersheds in the contiguous United States. The data sets for the assessment and validation are described first, then the results are presented, and the assessed contribution of direct human impact is compared with independent data sets of human activities, such as population density, urbanization, cropland area, irrigation area, and reservoirs. The spatial patterns of both climate and direct human impacts are discussed.

3.1. Data

[24] The international Model Parameter Estimation Experiment (MOPEX) data set is used in this study. The data set is described by Duan et al. [2006] and can be downloaded from <ftp://hydrology.nws.noaa.gov/>. This data set includes mean areal precipitation, potential evaporation, daily streamflow, and daily maximum and minimum air temperature for 432 watersheds with an adequate number of precipitation gauges. The daily precipitation, potential evaporation, and discharge are aggregated to the annual values (1948–2003) for the analysis in this study. Because of the missing data for some watersheds, 413 watersheds are selected for the quantification of climate and direct human impacts on mean annual streamflow change. The precipitation data are from the National Climate Data Center and the Natural Resources Conservation Service SNOTEL network. Most of the streamflow data are included in the Hydroclimatic Data Network (HCDN) [Slack et al., 1993], which includes only gauges believed to be unaffected by upstream regulations. That is not the case as follows from this study. The HCDN data set has been used in many studies [e.g., Sankarasubramanian et al., 2001;

[McCabe and Wolock, 2002; Small et al., 2006; Krakauer and Fung, 2008; Luce and Holden, 2009].

[25] Statistical tests, such as Pettitt's test, on streamflow have been used to identify significant change points in time [Zhang et al., 2008; Ma et al., 2008], and then the change of mean annual streamflow from the prechange period to the postchange period is computed. For the purpose of cross comparison among watersheds and their spatial patterns, the data set is split in to two periods at the same change point. Moreover, it has been documented that streamflow exhibits an upward (increasing) step change around 1970 and that the observed streamflow change is in concert with an increase in precipitation in the contiguous United States [McCabe and Wolock, 2002; Small et al., 2006; Krakauer and Fung, 2008]. Thus, changes of mean annual precipitation, evaporation, and streamflow from the preperiod of 1948–1970 to the postperiod of 1971–2003 are calculated for each of the 413 selected watersheds.

[26] To validate the results of the proposed methodology, a set of independent data sets are compiled, including population density at the county scale, percent of urbanization, land coverage, percent of irrigated land, and average reservoir storage, at various spatial resolutions (Table 3). All covering the entire contiguous United States and using the boundaries of all 413 watersheds to intersect with the ArcGIS layers of relevant variables, the average or total value of all grids (or points) located within the boundary of each watershed are computed to estimate population density, percent of urban land, percent of cropland, percent of irrigated land, and average reservoir storage (Figure 3). For example, the population data, available at the county scale, are converted to population density by dividing the total population by the total area in square miles for each county and then by converting all polygons to raster data and finally by averaging the density values of all grids that lie within the boundary of each of the 413 watersheds. Unfortunately, these are reflective of conditions at a particular point in time rather than a relative change between the two tested time periods (Table 3). However, assuming somewhat natural conditions in the early period, current conditions can be considered as a reasonable estimate of the relative change. This information will be used as an independent data set to validate the results, especially with respect to the estimated direct human impact on MAS.

3.2. Results

[27] The first step is to compute the parameter of the Budyko type curve (i.e., w or v in Table 1) for each watershed. Then climate- and direct human-induced MAS change are computed. To compare the results between watersheds,

the climate- and direct human-induced percentage changes relative to the prechange period are computed:

$$\begin{aligned}\Delta Q^c\% &= 100(\Delta Q^c/Q_1), \\ \Delta Q^h\% &= 100(\Delta Q^h/Q_1).\end{aligned}\quad (10)$$

Figure 4 shows a cross comparison of $\Delta Q^h\%$ and $\Delta Q^c\%$ between the Fu and Turc-Pike equations. The estimations by Fu and Turc-Pike match reasonably well, except for some watersheds around $\Delta Q^h\% = 0$. In the following, only the results based on Fu's equation are presented.

[28] Figure 5 shows $\Delta Q^h\%$ versus $\Delta Q^c\%$ for each watershed. The direct human impact has induced a wide range of both increasing and decreasing shifts in MAS. Climate change, however, has mainly attributed to an increase in mean streamflow in most of the selected 413 watersheds. When averaging across all the watersheds (Table 4) and given the direct impact of human activities on annual streamflow is mixed with almost equal numbers of watersheds with opposite (i.e., increasing or decreasing) induced changes (Figure 5), there is no clear trend to whether direct human impact has caused more or less annual streamflow change. But climate has induced an increase in annual streamflow by +18%. When comparing the absolute impact of climate and direct human activities on streamflow ($|\Delta Q^h\%|$ and $|\Delta Q^c\%|$), climate exhibits a stronger impact (Table 4). This finding is expected given that the MOPEX data set used in this study was collected for watersheds with minimal human activities [Duan et al., 2006]. However, $|\Delta Q^h\%|$ (i.e., 16%) is only slightly smaller than $|\Delta Q^c\%|$ (i.e., 18%). This signifies two important messages: (1) although climate change is found to induce greater impact on MAS than direct human interferences, this conclusion is likely to change if a more comprehensive set of watersheds in the contiguous United States (in which human interferences are more significant) has been included or if human contribution to climate change is accounted for as part of the human impact on MAS, and (2) assuming that the selected set of watersheds has negligible human-induced changes is questionable, and this suggests that the impact of human interferences to hydrology is far more reaching and that the assumption of human-free watersheds is less likely in the real world.

[29] For example, most of the selected watersheds exhibited a negligible percentage of urbanization (Figure 3b), an implicit assumption about the MOPEX data set. However, the fact that these watersheds have undergone minimal urbanization does not rule out the direct impact of humans on MAS through other means, i.e., irrigation, cropland

Table 3. List of Variables Used as a Validation of the Results of Direct Human Impacts on Mean Annual Streamflows

Item	Unit	Spatial Resolution	Period Coverage	Source
Population density	persons/mile ²	county scale	1990	U.S. Geological Survey [2010]
Urban land	%	grid scale (~9 km)	2001	U.S. Geological Survey [2001]
Cropland	%	grid scale (~1 km)	1981–1994	NOAA ^a
Irrigated land	%	grid scale (~9 km)	2000	Siebert et al. [2007]
Average reservoir storage	acre-feet	point scale	1815–2002 ^b	National Atlas of the United States [2006]

^aU.S. MOPEX Data Set: Fractional coverage of each vegetation type according to the University of Maryland (UMD) vegetation classification system ([ftp://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/Basin_Characteristics/Vegetation/UMD/](http://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/Basin_Characteristics/Vegetation/UMD/), accessed in March 2011).

^bYear in which the reservoir's construction was completed.

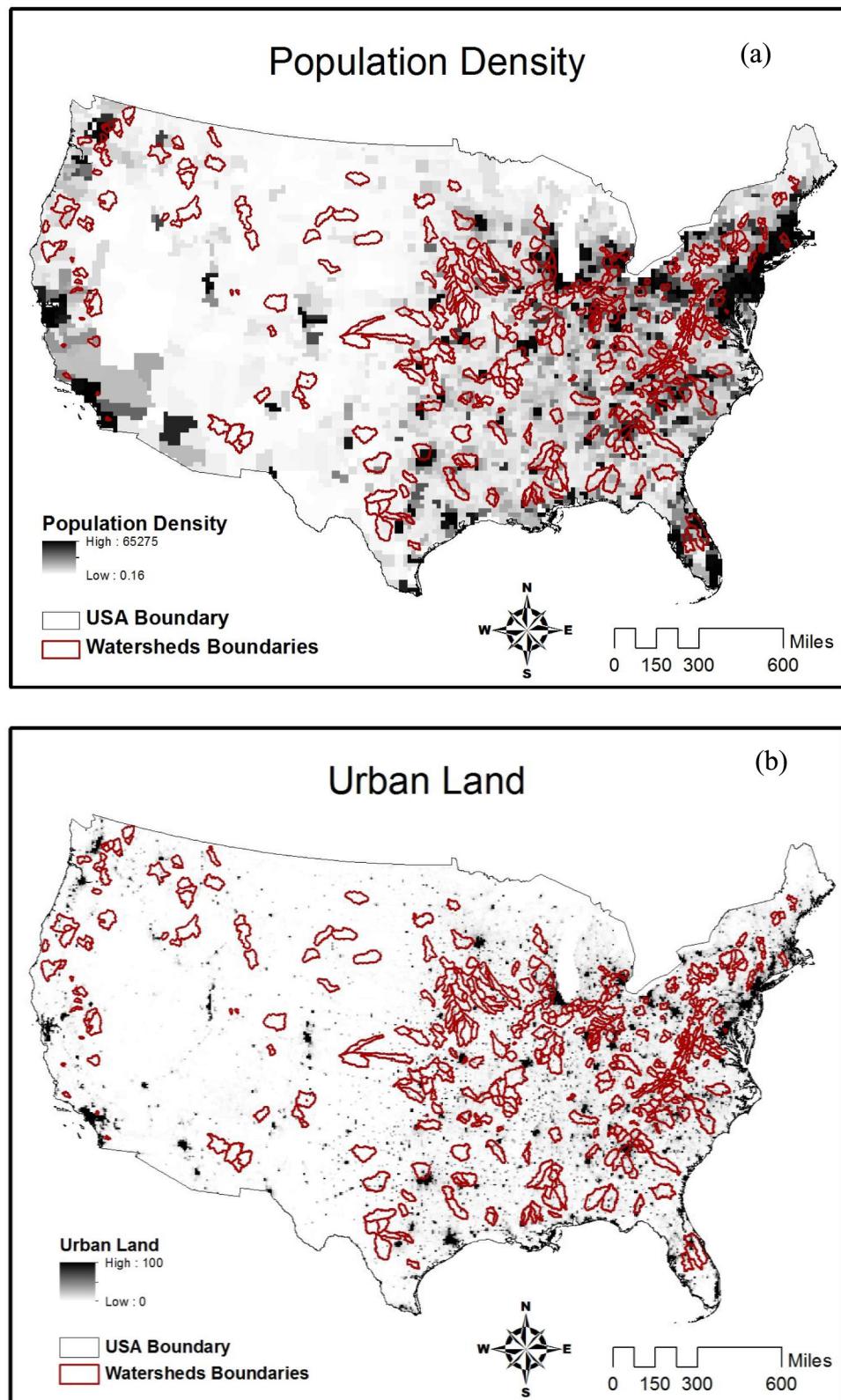


Figure 3. Spatial coverage of exogenous information used as a validation of the direct human impacts on mean annual streamflows.

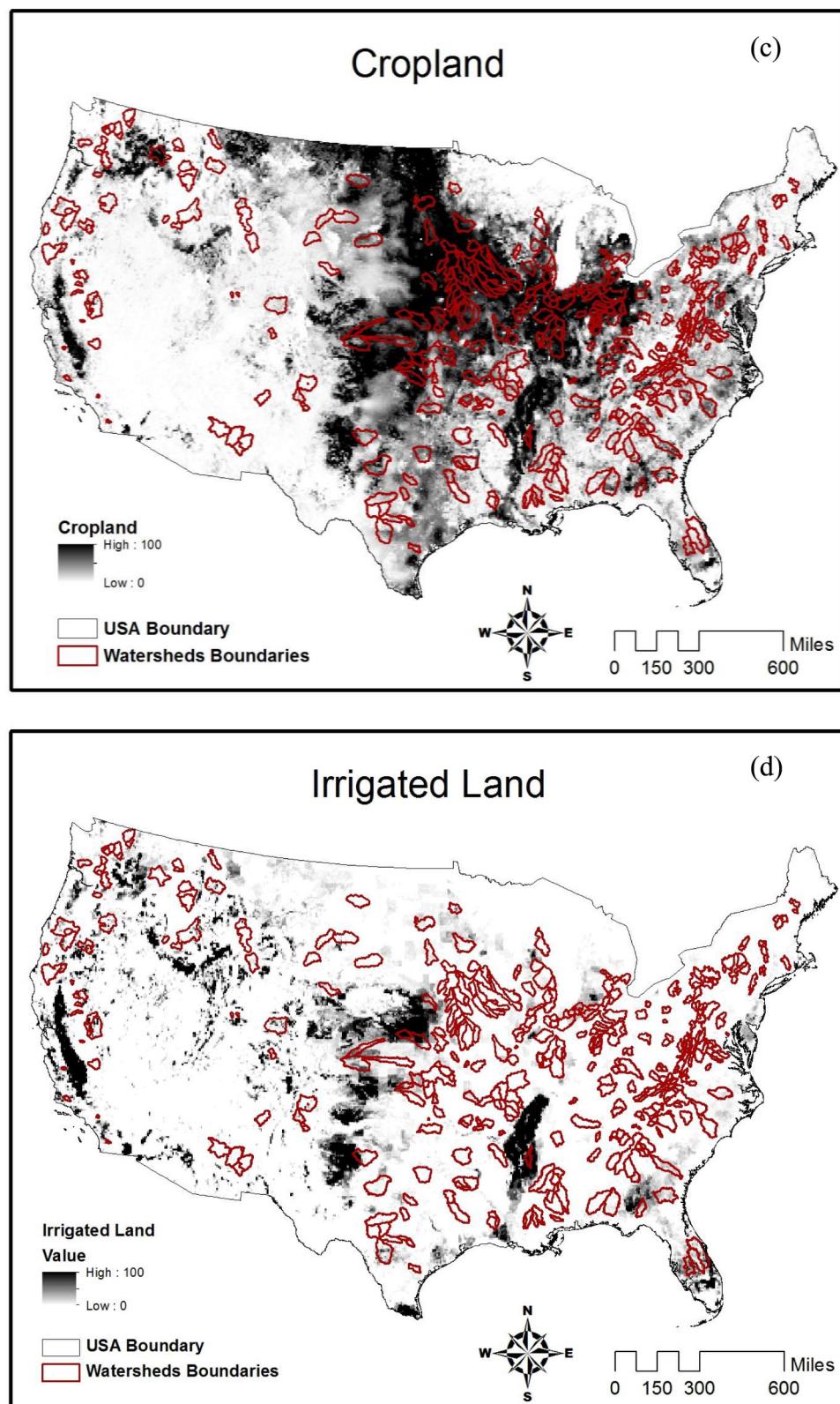


Figure 3. (continued)

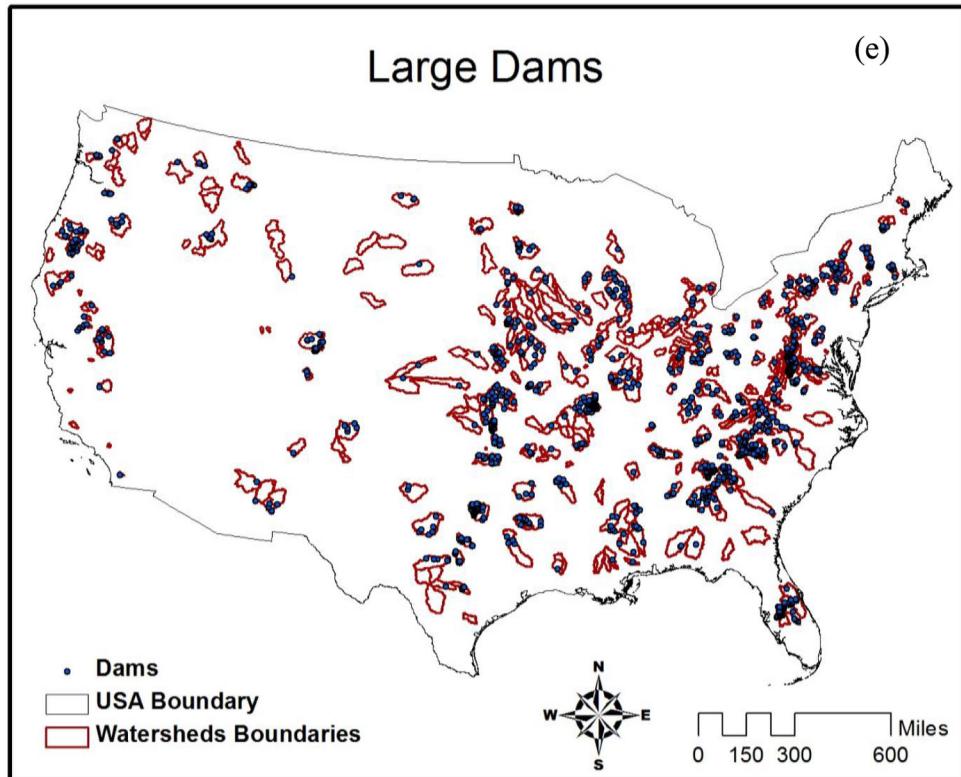


Figure 3. (continued)

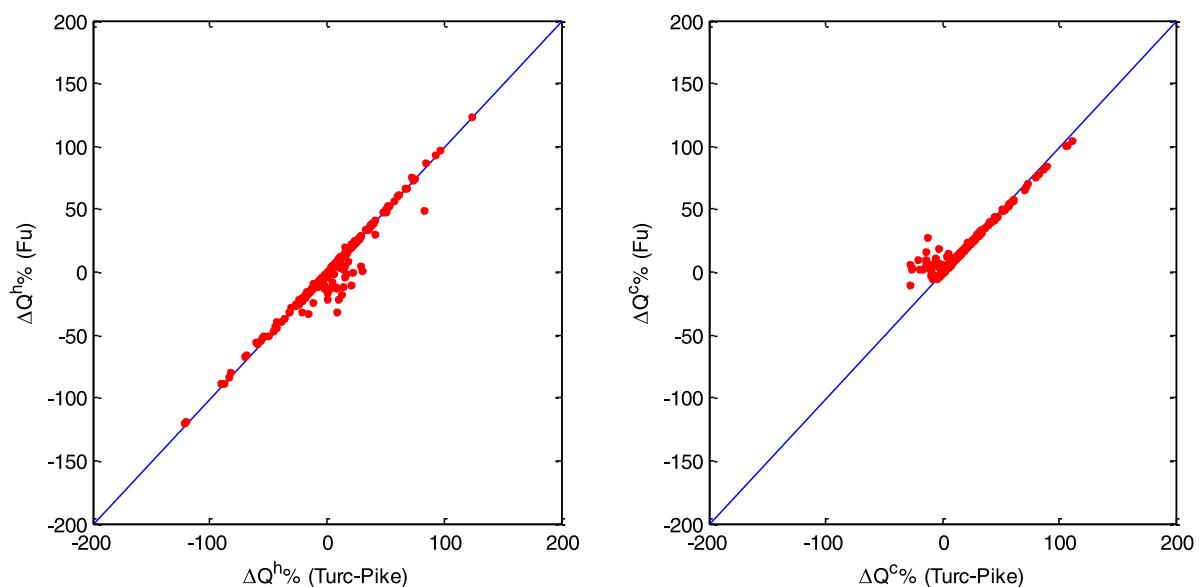


Figure 4. The cross comparison of estimated climate- and direct human-induced streamflow change between Fu and Turc-Pike equations.

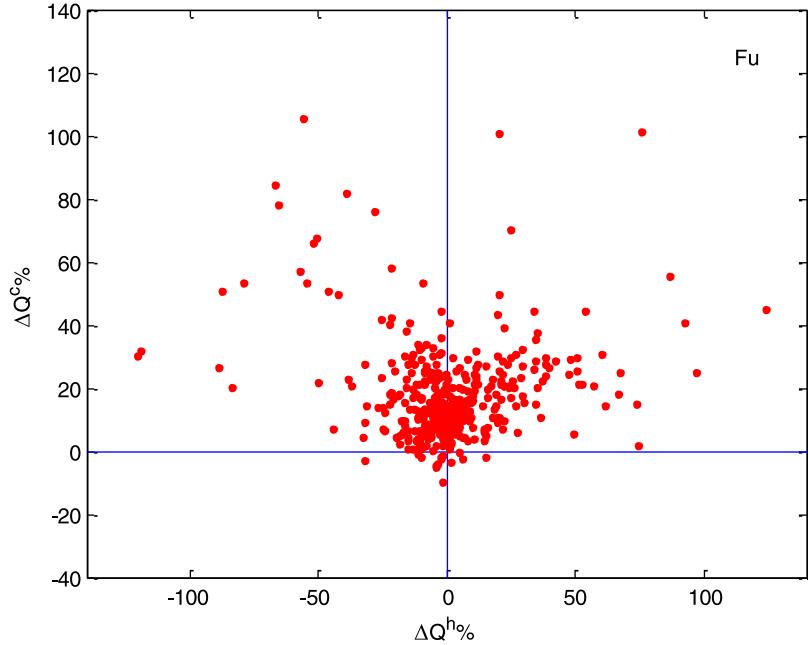


Figure 5. The climate-induced versus direct human-induced streamflow changes by percentage for the 413 watersheds.

expansion, increased municipal water consumption, and increased evaporation due to dam construction and hydro-power generation. To build upon this hypothesis, the watersheds are grouped into seven categories (Table 5) on the basis of the estimated relative change in streamflow due to direct human impacts only. Then, the corresponding population density, urban land percent, cropland percent, irrigated land percent, and average reservoir storage values are computed for each of the categories (Table 5).

[30] As shown in Figure 6, the validation data indicate that on average, the level of estimated direct human impact on streamflow is proportional to population density and percent of urban and cropland areas and inversely proportional to the percent of irrigated land and the average storage of reservoirs in the watersheds. These relations are intuitive and a necessary step to validate the proposed decomposition methodology. For example, watersheds with large population density and urban land percent values are likely to have experienced an increase in mean annual streamflow because of increasing imperviousness (reduced infiltration). Watersheds with a larger fraction of cropland could easily lead to less or more water consumption and thus more or less MAS. For instance, if more irrigation is being applied, then more water is likely to be consumed by crops than if no crops

existed originally (e.g., grass and forest). Assuming rain-fed crops are dominant, whether, annually, crops are bigger or smaller consumers of water than the original land cover dictates the sign of the change. *Zhang and Schilling [2006]* attributed the increasing trend of annual low flows in the Mississippi River to land cover change. In another study, *Schilling et al. [2008]* stated that agricultural development in the Midwest during the last century has converted perennial grasslands to annual row crops. Perennial vegetation transpires throughout the spring, summer, and autumn seasons, while the majority of the transpiration from row crops occurs during the summer. As a result, the annual ET loss has a decreasing trend, which, in turn, increases the base flow and annual flow [*Schilling et al., 2008*]. Thus, increases in cropland areas in the selected watersheds are likely to increase MAS given reduced evapotranspiration during the nongrowing seasons when the land is fallow. Our validation results exhibit a similar trend. Moreover, watersheds with large shares of irrigated land are likely to have enhanced evapotranspiration, thus leading to lower mean annual streamflows (Figure 6d). Last, augmenting rivers by constructing dams increases both the human water consumption (e.g., water supply, hydropower via higher evaporation, and irrigation) and water losses due to enhanced evaporation from the larger surface areas of impounded water bodies. Thus, watersheds with larger reservoir storage are likely to reflect a reduction in MAS. Although a direct validation of the estimated direct human impacts is not possible, the meaningful relations between the estimated human-induced MAS change and the set of external validation data sets show the consistency of the proposed methodology.

[31] The spatial distribution of the estimated climate- and direct human-induced streamflow change are analyzed. Figure 7 shows the spatial distribution of the relative magnitude of climate and direct human factors. The red

Table 4. Minimum, Maximum, Mean, and Coefficient of Variance (CV) of $\Delta Q^h\%$, $\Delta Q^c\%$, $|\Delta Q^h\%|$, and $|\Delta Q^c\%|$ Among the 413 Watersheds

	Minimum, Maximum	Mean	CV
$\Delta Q^h\%$	[-120.2, 124.1]	0.6	44.8
$\Delta Q^c\%$	[-9.5, 105.3]	18.0	0.9
$ \Delta Q^h\% $	[0.02, 124.1]	16.0	1.2
$ \Delta Q^c\% $	[0.2, 105.3]	18.2	0.8

Table 5. Comparison of the Estimated $\Delta Q^{h\%}$ With External Validation Data, Namely, Population Density, Urban Land, Cropland, Irrigated Land, and Average Reservoir Storage

$\Delta Q^{h\%}$ Range	$\Delta Q^{h\%}$ Mean	Count of Watersheds	Population Density (persons/mile ²)	Urban Land (%)	Crop Land (%)	Irrigated Land (%)	Reservoir Storage (acre-feet)
$\Delta Q^{h\%} < -20\%$	-44	42	33	0.7	12	1.9	77,508
$-20\% < \Delta Q^{h\%} < -10\%$	-14	57	127	1.6	9	2.6	74,097
$-10\% < \Delta Q^{h\%} < -1\%$	-5	117	92	1.8	11	0.5	94,182
$-1\% < \Delta Q^{h\%} < 1\%$	0	27	113	2.1	17	0.1	49,121
$1\% < \Delta Q^{h\%} < 10\%$	5	73	108	2.8	28	0.9	36,952
$10\% < \Delta Q^{h\%} < 20\%$	15	33	183	2.9	44	0.8	36,275
$\Delta Q^{h\%} > 20\%$	40	64	112	1.5	50	1.5	31,396

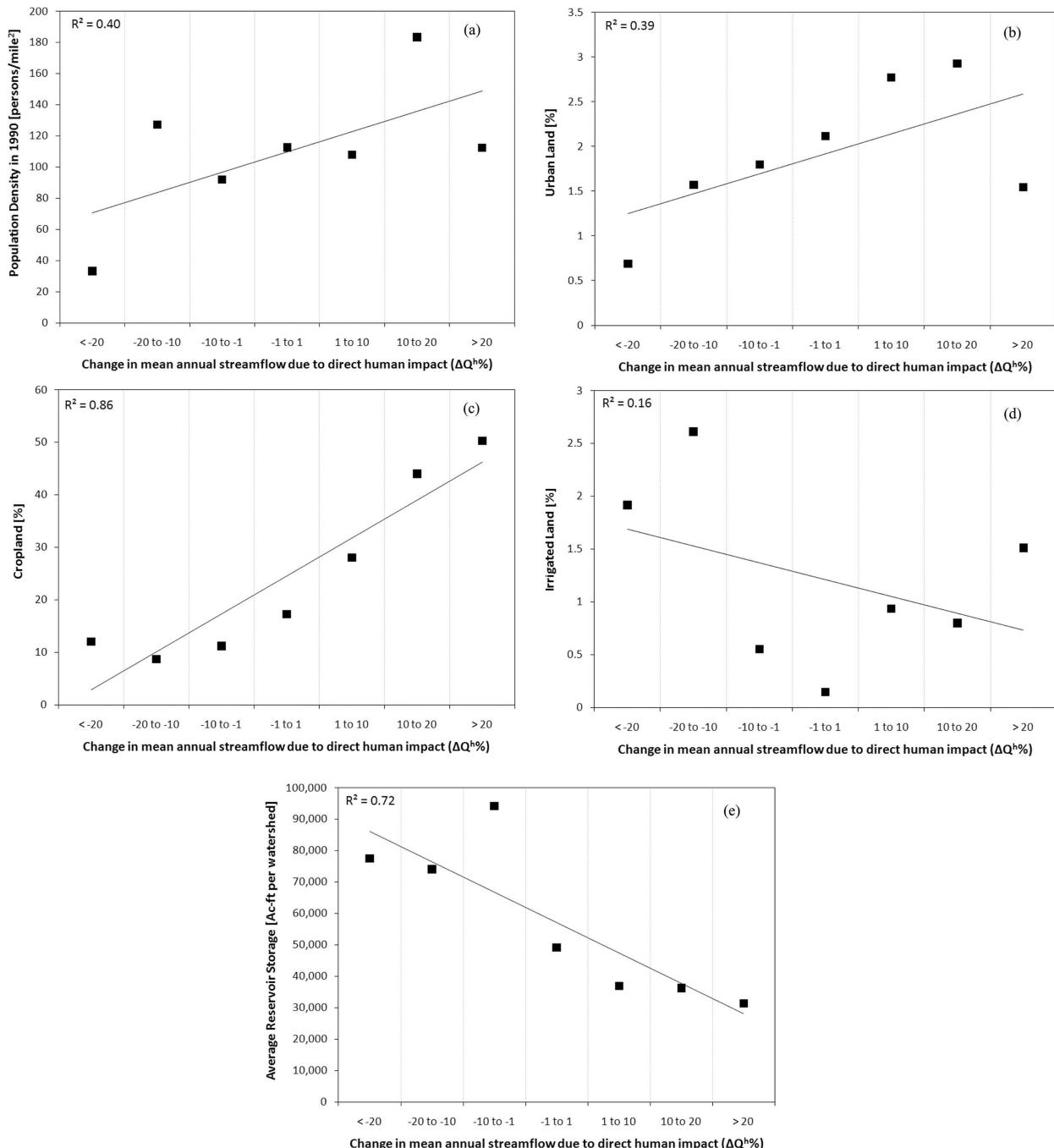


Figure 6. Comparison of the estimated $\Delta Q^{h\%}$ (seven categories) with external validation data, namely, (a) population density, (b) urban land, (c) cropland, (d) irrigated land, and (e) average reservoir storage.

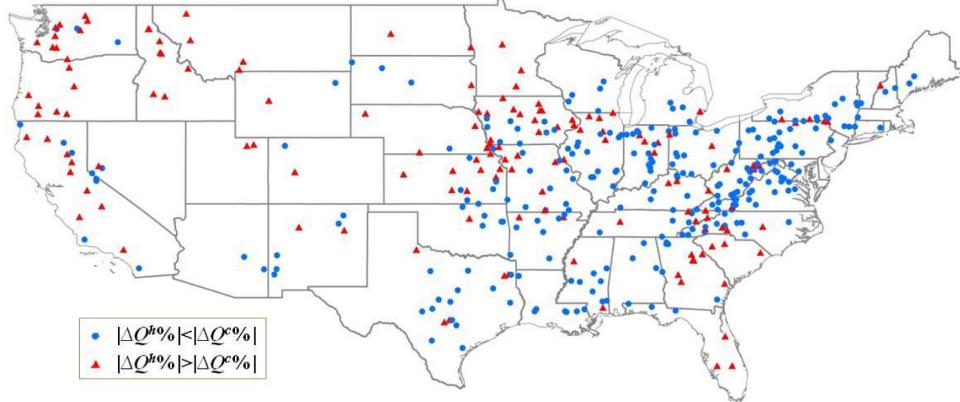


Figure 7. The spatial distribution of the relative role between direct human and climate factors.

triangles represent the gauges where the magnitude of direct human-induced MAS change is larger than that induced by climate change. In the High Plains and western United States, humans play a more important role than climate change. Along the Pacific coast of the United States, a primarily arid region with a large and growing population, Barnett *et al.* [2008] found that 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human induced. Among the 431 watersheds, there are 146 watersheds where $|\Delta Q^h\%|$ is larger than $|\Delta Q^c\%|$.

[32] Figure 8a shows the percentage of net streamflow change ($\Delta Q\%$). Figures 8b and 8c show the spatial distribution of climate-induced ($\Delta Q^c\%$) and direct human-induced ($\Delta Q^h\%$) percentages of MAS change, respectively. The impact of the climate on MAS is homogeneous, with most of the 413 watersheds showing an increasing trend in MAS (Figure 8b). Only a few watersheds in Florida and in the West Coast region showed that climate change reduces the amount of MAS. This is consistent with the findings by previous studies [e.g., Small *et al.*, 2006]. The greatest climate impact is in the southwest regions of the United States where climate change causes 60%–100% increase of MAS (Figure 8b). On the other hand, the impact of human activities is somewhat heterogeneous over the entire contiguous United States (Figure 8c). Nonetheless, spatial patterns are clear at the regional scale; for example, human impact increased MAS in more watersheds in the Midwest. This is consistent with the findings by Schilling *et al.* [2010], who found that the runoff coefficient increased by 32% because of land use change in the Upper Mississippi River Basin. The greatest human impacts in the selected watersheds are in the High Plains, where the direct human-induced streamflow decrease is about 30% and up to 120% (Figure 8c). Human impacts decreased MAS in more watersheds in the southeastern United States.

[33] To further investigate if the estimated climate- and direct human-induced changes can be explained by other factors, the estimated $|\Delta Q^c\%|$ and $|\Delta Q^h\%|$ are plotted against climate dryness index and evaporation ratio, respectively (Figure 9). From Figures 9a and 9b, even though the data points scatter when dryness index is larger than 2, both climate- and direct human-induced MAS changes increase

with the dryness index, and the relationship is close to a linear trend. From Figures 9c and 9d, both climate- and direct human-induced streamflow changes increase with evaporation ratio, and an exponential trend exists, especially for the climate-induced MAS change. Thus, arid regions (i.e., water limited) are more vulnerable to climate change and direct human interferences than wet regions (i.e., energy limited).

4. Summary and Conclusions

[34] In this paper, a decomposition method is proposed to explicitly quantify the relative contributions of climate and direct human impacts on changes in mean annual streamflow and is applied to 413 watersheds in the contiguous United States. The decomposition method is verified with published data in over 20 watersheds, as well as independent data sets on human activities, such as population density, percent of urban, crop, and irrigated lands, and storage of reservoirs. Given the simplicity of the proposed method to separate the climate and direct human impacts on MAS, applying the method to many watersheds becomes feasible as compared to more complex hydrologic simulation models. The method can be easily extended to handle more comprehensive data sets.

[35] The proposed decomposition method hinges on the following assumptions: (1) For a watershed without direct human interferences, if the E_p/P moves to a drier or wetter region because of climate change, E/P will also change to a new region but will still follow the same Budyko-type curve as in the prechange period. (2) Precipitation and potential evaporation are assumed to be stationary during the prechange and postchange periods. The change of precipitation and potential evaporation can be due to natural climate variability at interdecadal or interannual time scales, human-induced climate change, i.e., global warming, and the feedback of human activities (such as urbanization and urban heat island effects, irrigation, and crop evapotranspiration) to climate at regional and local scales. The coupled human, climate, and hydrologic systems are complex, and the separation of total human impact on the streamflow from other factors is complicated by the interactions and feedbacks among the subsystems through physical processes.

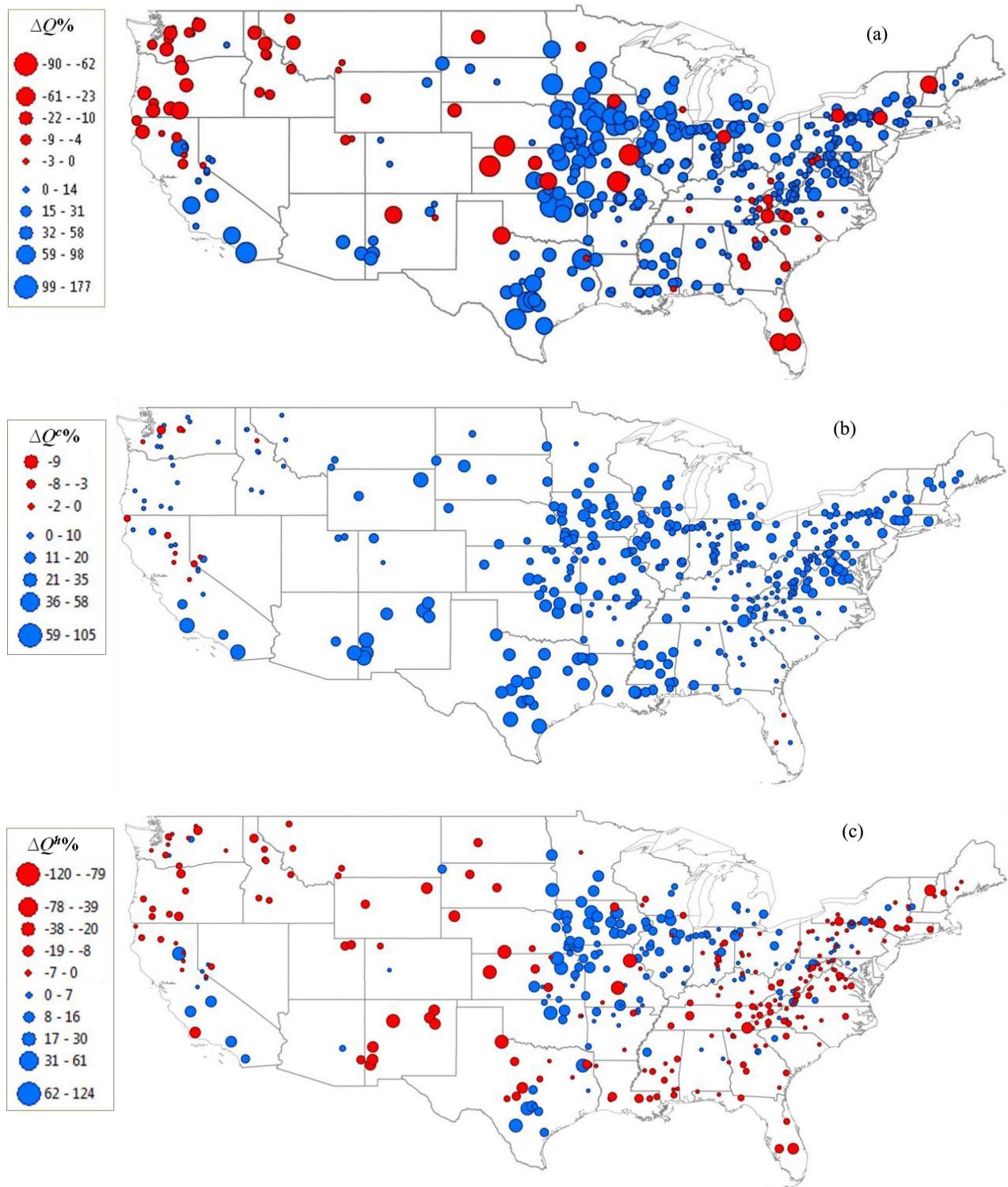


Figure 8. Spatial distribution of the direct human- and climate-induced trend on streamflow by Fu's equation: (a) $\Delta Q\%$, (b) $\Delta Q^c\%$, and (c) $\Delta Q^h\%$.

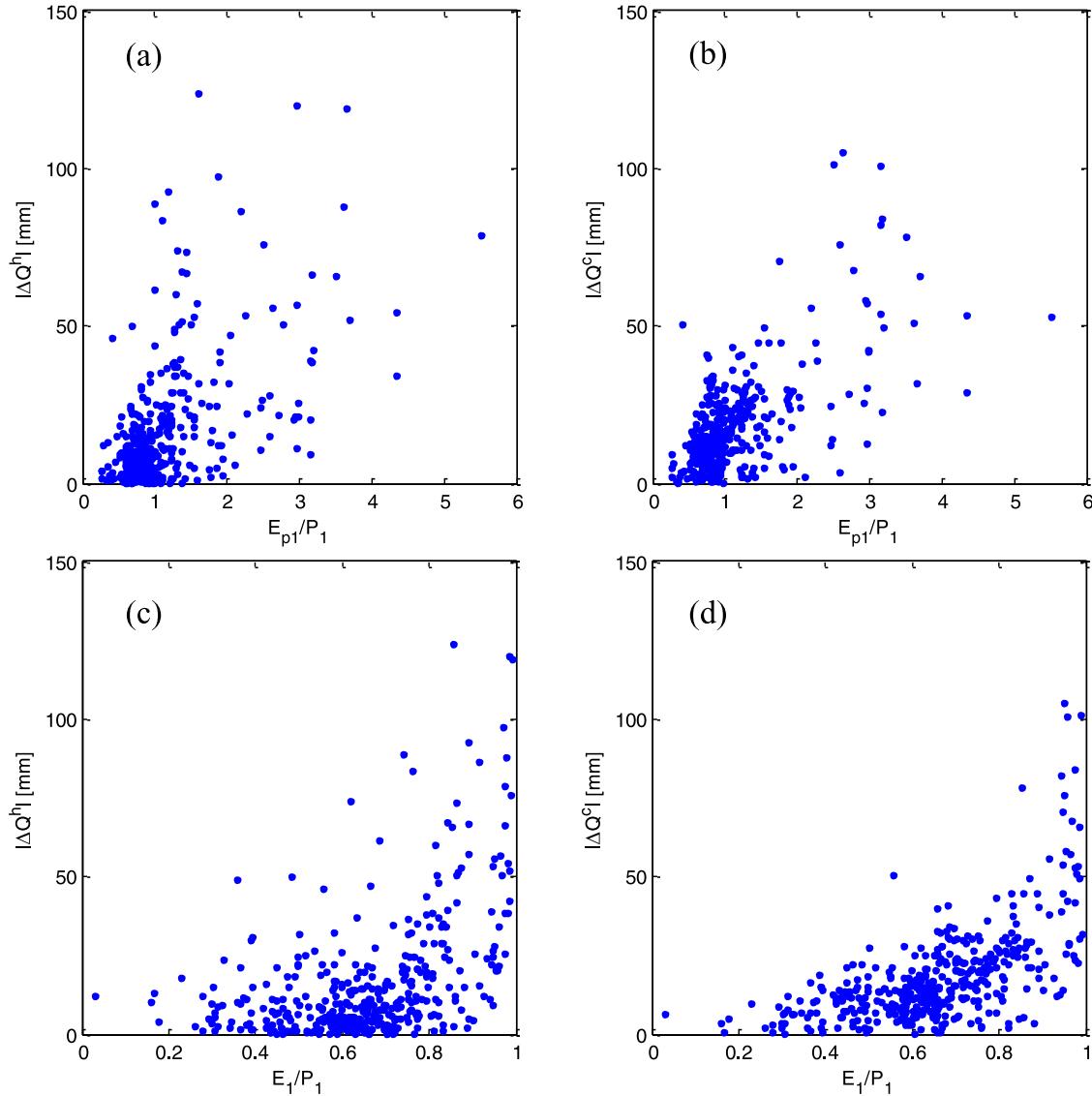


Figure 9. The estimated climate- and direct human-induced streamflow change versus (a, b) climate dryness index and (c, d) evaporation ratio.

Therefore, in this paper the quantified anthropogenic streamflow change is confined to direct human impacts, and the potential indirect feedbacks of human activities to precipitation and potential evaporation change are not included.

[36] The spatial distribution of direct human- and climate-related MAS revealed that unlike climate change, which induces increased MAS in most watersheds, the direct human-induced MAS change is spatially heterogeneous in the contiguous United States, while strong regional patterns exist. For example, direct human impact increased the streamflow in the Midwest, while direct human impact decreased MAS in many watersheds in the High Plains and southeastern United States. The impact of climate change and human interferences on MAS in arid regions is larger than that in wet regions.

[37] When averaging across all 413 watersheds, climate change plays a bigger role than direct human impact. However, the MOPEX data set is constructed to contain

watersheds that have undergone minimal human activities in the United States and has been utilized under the assumption that it includes only gauges believed to be unaffected by upstream regulations. Our study shows that human impact is likely to be more significant in some of the watersheds, such as those with urban areas and extensively irrigated agricultural watersheds. As an extension to this research, one can apply the decomposition method to other watersheds where human activities are significant and map the human interferences to streamflow in the contiguous United States. The specific human activities that affected the streamflow can be identified for each watershed, such as land use change, surface and groundwater water withdrawal, return flow, and water diversion. Moreover, projections of future climate change from general circulation models or regional climate models can be combined with the decomposition method to project the climate change impact on streamflow in the future.

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