THE PROJECTED HYDROLOGIC CYCLE UNDER THE SCENARIO OF 936 PPM CO 2 IN 2100: A SYNTHESIS

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PAPER

Review: The projected hydrologic cycle under the scenario of 936 ppm CO_2 in 2100

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Abstract

A host of environmental consequences will result from global warming, but arguably, the effect on water resources is one of the most consequential. This paper synthesizes results of published modeling studies that examined the groundwater system and hydrologic cycle under the Representative Concentration Pathway (RCP) 8.5 scenario (CO_2 at 936-ppm level at year 2100). Natural replenishment of groundwater occurs predominantly from infiltration of precipitation and surface impoundments. Therefore, the first stage of the study was to review a changed hydrologic cycle under RCP 8.5 in terms of influence from (1) precipitation, evapotranspiration, and soil moisture; (2) surface water and its interaction with groundwater; (3) extreme hydrologic events, and (4) teleconnection patterns. The general pattern of climate impact on groundwater resources follows the precipitation pattern with depletion in tropical and/or subtropical regions and with increase in the high-latitude regions of the Northern and Southern Hemispheres. However, regional variability also corresponds to the heterogenous impact of climate changes on regional distribution of precipitation and evapotranspiration, localized interaction between surface water and groundwater, and distances from the oceans with rising sea level. The decline of the water table in many areas may seriously reduce irrigated crop production and adversely impact groundwater-dependent ecosystems. Relatively fewer studies have been conducted on climate-change impacts on groundwater resources compared to surface-water systems, and the uncertainties on the recharge estimates are large. There appears to be an urgent need for including groundwater systems in climate impact assessment and in climate mitigation strategies.

Keywords Climate change · RCP 8.5 · Hydrologic cycle · Groundwater recharge/water budget · Water resources management

Introduction

Global CO_2 concentration has exceeded 405 ppm since 2016, and the current global mean temperature is 0.83 °C above the pre-industrial level (1850–1900 period; NOAA 2017). In order to project future carbon-climate scenarios, Representative Concentration Pathways (RCPs)—a set of greenhouse gas (GHG) concentration and emissions pathways (Moss et al. 2010; van Vuuren et al. 2011)—are used to support climate change research on potential impacts and to guide policy responses to global warming (Moss et al. 2010; van Vuuren et al. 2011). Specifically, the RCP 8.5 scenario—similar to Special Report on Emissions Scenarios (SRES) A1FI, a scenario with extreme global warming and CO_2 emission proposed in IPCC 2001—corresponds to the upper bound of the RCPs, known as the "baseline scenario", which states that GHG emissions and concentrations considerably increase over time, leading to a radiative forcing of 8.5 W/m^2 by the end of the twenty-first century (Riahi et al. 2011). Under this scenario, CO_2 levels will rise to 936 ppm by 2100 (Wittmann and Pörtner 2013), resulting in a global temperature increase of 4–6 °C above the pre-industrial level (IPCC 2013; Parry et al. 2007; Van Vuuren et al. 2011; Wittmann and Pörtner 2013; Fig. 1).

Climate change is projected to change global hydrologic behavior (Hansen et al. 2016; Held and Soden 2006; Huntington 2006; Trenberth 2011). Increased precipitation, high-intensity evapotranspiration, and enhanced glacier melting will alter the global water resource availability and distribution (Betts et al. 2007; Collins et al. 2013; Radić and Hock

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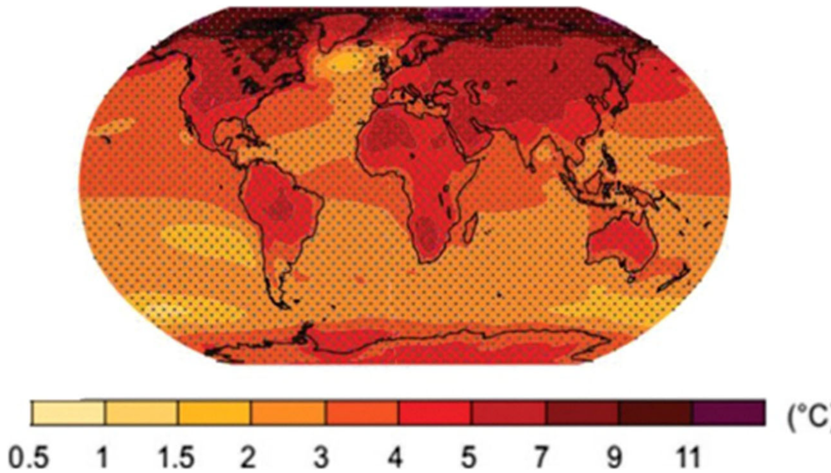

Fig. 1 Projected change in average annual temperature over the period 2081–2100 (compared to the period 1986–2005) under the scenario RCP 8.5 (IPCC 2013)

2011). Extreme hydrologic events such as flooding and drought, will increase in frequency in certain regions, threaten inhabited locations, and affect land use (Hirabayashi et al. 2013). Additionally, global temperature and GHG level increases will have a significant effect on seawater pH (Allen and Ingram 2002; Bala et al. 2008; Barnett et al. 2005; Collins et al. 2010; Fu et al. 2008; Hall-Spencer et al. 2008), increase the exceedance frequency of ecosystem tolerance thresholds, and potentially lead to chronic degradation of water quality (Murdoch et al. 2000). Obviously, impacts of climate change on the hydrological cycle cover a wide range of topics. Specifically, this review emphasizes the impacts of climate change on groundwater under RCP 8.5.

In this paper, projected hydrologic changes under the RCP 8.5 scenario are presented in seven sections: (1) precipitation, evapotranspiration, soil moisture, and glaciers; (2) surface water; (3) oceans; (4) groundwater; (5) soil erosion and sediment load; (6) extreme hydrologic events and (7) teleconnection patterns influence. The projected impacts, vulnerabilities, and risks of hydrologic changes under RCP 8.5 are also presented in order to demonstrate hydrologic cycle changes in the most extreme climate conditions by the end of twenty-first century. Based on these changes, impacts, vulnerabilities, and risks, proposed water resources management strategies, responding to such extreme climate conditions and hydrologic changes, are discussed.

Projected hydrologic changes

Precipitation, evapotranspiration, soil moisture, and glaciers

Precipitation

Overall, precipitation is expected to increase under high GHG emissions. An increase of 4.5 mm/month of global average precipitation by the end of the twenty-first century is based on results of simulation of Coupled Model Intercomparison Project Phase 3 (CMIP3) from 15 general circulation models (GCMs; Collins et al. 2013). Precipitation associated with monsoons is projected to increase by 16%, affecting East Asia, South Asia, and Australia. These predictions used monthly mean data from 29 Coupled Model Intercomparison Project Phase 5 (CMIP5) models and daily precipitation data from 21 CMIP5 models (Christensen et al. 2013; Hsu et al. 2013; Kitoh et al. 2013). A GHG emission increase will potentially affect hurricane intensity, frequency, and storm size (Knutson and Tuleya 1999). This might already be occurring in an increasing number of intense storms in the Arabian Sea, including severe cyclones that have killed more than 3,500 people and caused over \$6.5 billion in damage since 1998—in 2011 US\$, Evan et al. (2011).

However, the change in precipitation is uneven across the globe due to internal variability in atmospheric circulation (Fig. 2). Compared to the pre-industrial global precipitation level, the global precipitation under RCP 8.5 has changed significantly. The dry areas have become even drier at mid-latitudes and subtropical dry regions of the Southern Hemisphere and the Northern Hemisphere, while the wet areas have become even wetter at high latitudes of the Northern and Southern Hemispheres as well as at some mid- and low latitude wet regions (Chou and Neelin 2004; Christensen et al. 2013; Giorgetta et al. 2013; Held and Soden 2006; Mitchell et al. 1987).

Evapotranspiration and soil moisture

Potential evapotranspiration—defined as the amount of water that would evaporate given unlimited available water (Freeze and Cherry 1979)—is expected to increase with global warming (Kingston et al. 2009). Specifically, global mean evapotranspiration is projected to increase approximately 5%/year due to CO_2 enrichment (Betts et al. 2007). The same

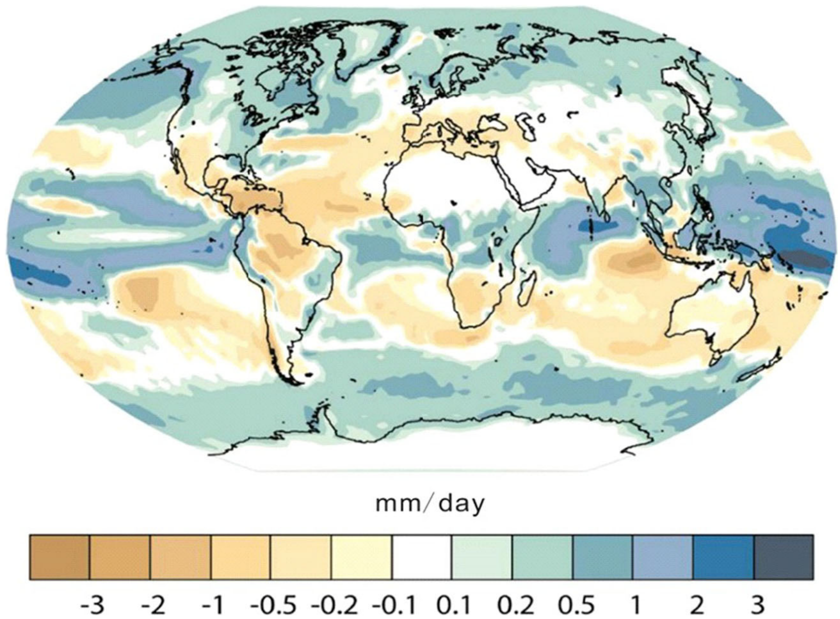

Fig. 2 Projected change in precipitation by twenty-first century (2081–2100) under RCP 8.5 (Giorgetta et al. 2013)

conclusions were reached through six distinct methodologies, with pronounced increases projected especially in Southern Europe, Central America, Southern Africa, and Siberia (Seneviratne et al. 2010).

Increased evapotranspiration will likely have a serious impact on soil moisture and may induce soil drought conditions. Strong influence of regional soil-moisture dryness is also estimated by the Global Land-Atmosphere Climate Experiment–Coupled Model Intercomparison Project phase 5 (GLACE-CMIP5; Seneviratne et al. 2013). Based on the simulation results of GLACE-CMIP5 for example, in the Mediterranean region soil moisture will decrease about 25% under RCP 8.5 scenario by 2100 (Seneviratne et al. 2013). Droughts that last 4–6 months will double in both extent and frequency under RCP 8.5, and droughts longer than 12 months will be three times more common between the mid-twentieth century and the end of the twenty-first century (Sheffield and Wood 2008).

Glaciers

Glaciers will be subjected to higher melting rates due to increased temperatures. Global average volume losses range from 12 to 30%, according to ten GCM simulations (Radić and Hock 2011). In Greenland, a projected glaciers' volume reduction of 41–63.8% from 2000 to 2100 has been established by a regional climate model (RCM) and glacier model (Nick et al. 2013). Over roughly the same period (2006–2100) a 68% reduction in the Himalayas is projected by CMIP5 projections from 14 GCMs (Radić and Hock 2014). The approximately 40,800 km^2 of glaciers in the Karakoram and Himalaya (Himalaya: 22,800 km^2; Karakoram: 18,000 km^2) contribute irrigation water used to grow food for 800 million people in Asia, a crucial resource especially in the dry months (Immerzeel et al. 2010; Bolch et al. 2012). Under RCP 8.5, these glaciers would lose about 35 Gt/year from 2070 to 2099, compared to a glacial mass balance in 2000 based on simulation results of 21 CMIP5 models, which is equivalent to 38.8 km^3/year water resources loss. Moreover, about 27% of the glaciers may face "eventual disappearance" by 2100, straining the water resources available to 800 million people (Chaturvedi et al. 2014).

Surface water

The current hydrologic cycle consists of continental precipitation of 110,000 km^3/year, evapotranspiration of 65,000 km^3/year, and runoff of 40,000–45,000 km^3/year worldwide (FAO 2005; Oki and Kanae 2006; Oelkers et al. 2011). Under RCP 8.5 at 2100, continental precipitation is projected to increase to 118,158 km^3/year, global mean evapotranspiration to 68,208 km^3/year, and runoff to 49,950 km^3/year (Betts et al. 2007).

However, these changes are not projected to be uniform. A decrease in average annual runoff is predicted for low latitude, inland areas, while an increase is predicted at high latitudes (Arnell and Gosling 2013). By the late twenty-first century (2071–2100), mean streamflow increases are projected in 68.9% of streams worldwide that were included in the model simulation (excluding Greenland and Antarctica) but projected decreases in 31.1% of streams. Increased streamflows were projected in Asia, Africa, Australia, parts of eastern South America, and high latitudes of North America and Eurasia (Koirala et al. 2014). On the other hand, decreased stream-flows were primarily in Europe, the Middle East, Central Asia, northern and southern Africa, the southwestern

United States, and most of Central and South America (Koirala et al. 2014). These results were from simulations using 11 recent atmospheric–oceanic general circulation models (AOGCMs), which, despite differences in details and by independent modeling institutes participating in CMIP5 (Taylor et al. 2012), projected similar trends (Koirala et al. 2014). The magnitude of change varies regionally. In 5.5% of the world, the increase in 2071–2100 is 50% over the 1971–2000 values; 0.2% displays a decrease of the same magnitude (Koirala et al. 2014).

Groundwater

Groundwater accounts for 98% of accessible freshwater. It is the vital component of the hydrological cycle in the critical zone between the surface and subsurface (Green et al. 2011). There is a marked increase in research that focuses on the direct and indirect effects of climate change and variable projections on groundwater, especially under high GHG emission and extreme global warming scenarios (Holman et al. 2012; Taylor et al. 2013a, b; Meixner et al. 2016). In this article, groundwater resource variability under global warming, as well as feedback between climate and groundwater, are overviewed.

Groundwater quantity variation

As climate impacts on surface-water quantity and quality are geographically uneven under RCP 8.5, impacts on groundwater resource variability also vary from region to region. Increased precipitation contributes to increased groundwater recharge and replenishes aquifer storage; however, increased evapotranspiration or decreased precipitation can also lead to groundwater depletion (Taylor et al. 2013b). For example, mean annual water tables in Jylland and Sjaelland, Denmark, are projected to increase 0.2 and 0.5 m, respectively, by 2100, assuming a temperature increase of 3.2 °C compared to 1990–2004 (van Roosmalen et al. 2007). The renewable groundwater resources, defined as those which can be recharged or replenished to overcome resource depletion caused by natural processes and anthropogenic activities (Postel et al. 1996), are expected to decrease by 38% under RCP 8.5, especially in arid and semi-arid regions (Portmann et al. 2013). From the regional climate model (RCM) simulations, the total decline of the groundwater level is projected to a range of 6.6–83.5 m in four major South Korean river basins (Han River, Nakdong River, Geum River, and Yeongsan-Sumjin River basins) at 2100 under RCP 8.5 (Jang et al. 2015). Thus, the regional characteristics of precipitation and evapotranspiration directly impact groundwater resource in specific regions. Generally, the groundwater resource variability corresponds to precipitation distribution patterns: (1) groundwater resource depletion increases in tropical and/or subtropical regions; and (2) groundwater resource quantity increases in the high-latitude regions of the Northern and Southern Hemispheres.

Increased evapotranspiration may lead to a dramatic decline of streams, lakes, and other surface-water resources. The traditional source of urban, industrial, and agricultural water will shift from surface water to groundwater, thus increasing groundwater pumping and accelerating its depletion (e.g. Southwestern America, Southern Europe, India; Falloon and Betts 2010; Aeschbach-Hertig and Gleeson 2012; Taylor et al. 2013b).

Impacts on groundwater quality

In particular, intensified global hydrologic cycle (e.g., increase or decrease in frequency and intensity of precipitation event, increased evapotranspiration intensity, sea-level rise) will directly influence groundwater quality via pollutant infiltration, interaction between groundwater and other water systems, and socio-economic development for meeting increasing population requirements (Cotterman et al. 2018; Dunn et al. 2012; Ferguson and Gleeson 2012; Van Vuuren and Carter 2014). This paper specifically discusses the groundwater quality variation in two categories of regions: (1) agricultural areas and (2) coastal areas.

Groundwater quality in agricultural areas The increased demand of future agricultural development will aggravate groundwater depletion and degradation as a result of high-intensity fertilization and land-use changes (Green et al. 2011). Agricultural intensification usually corresponds to the heavy use of fertilization, especially nitrogen (N; Gordon et al. 2008; Johansson et al. 2009), which will accelerate the cycling of N, contributing globally to observed increases in N-loads in surface runoff and subsurface-water systems (Seitzinger et al. 2010). For example, Basso et al. (2016) evaluated impacts of different N fertilizer treatments on NO_3^- leaching with the SALUS model in Italy, and the simulation results indicated that urea fertilization treatment might lead to the highest biomass production and NO_3^- leaching under RCP 8.5 in 2070. Savard (2016) simulated groundwater flow impact of climate change and agricultural adaptation under RCP 4.5 and 8.5 by year 2050 on Prince Edward Island (PEI, Canada), predicting that it would lead to a 25–32% increase in NO_3-N concentration over the Island aquifer system. Arheimer et al. (2005) modelled N leaching in the Rönneå River in southern Sweden using different climate change scenarios (SRES A2 and B2, scenarios with less GHG emission than in RCP 8.5) and found an average increase in N concentrations of 50% in the root zone on arable land. Similarly, Kaste et al. (2006) used modelling of N-fluxes in a Norwegian catchment to reveal significant growth in nitrate-N fluxes (40–50%) when regional temperature increased approximately 3 °C. Based on the projection of hydrological N and phosphorus (P) in coastal subsurface-water system of agricultural areas in Sweden, the N and P loads from the subsurface-water system to the sea were projected to increase from 12.9 and 50% in long-term climate changes (2005–2100), respectively, due to the increased non-point source pollution from cropland (Destouni and Darracq 2009).

Furthermore, higher nitrate loads in agricultural regions may lead to higher nitrous oxide (N_2O) emission because of increased denitrification in the groundwater system (Groffman et al. 2000). Increased subsurface temperature and NO_3^- concentration in groundwater can result in motivating denitrification; meanwhile, it can also contribute to the feedback of GHG emission (Jeppesen et al. 2011; Stocker et al. 2013; van Vuuren et al. 2011). Besides, global warming can also influence the danger and transformation of pesticides and therefore affect groundwater quality (Bloomfield et al. 2006; Howarth et al. 2006). In addition, higher temperatures can result in increased toxicity of pesticides (Noyes et al. 2009; Noyes and Lema 2015). Compared to surface water, groundwater receptors are usually minor pesticide receptors due to a combination of major pesticide loss in the soil by sorption, degradation and volatilization, and dilution and dispersion in the saturated zone (Bloomfield et al. 2006). However, future agricultural development will not only increase the demand for fertilization but also enhance the application of pesticides. Moreover, high intense precipitation and flooding will induce pesticide percolation and leaching from adsorbed colloids and sediments in soil into surface-water and groundwater systems. For instance, in the Odense Fjord in Denmark, the integrity of water ecosystems, no matter surface water or groundwater, has been damaged due to urbanization and use of fertilizers and pesticides derived from the industrialization of the agricultural sector, extensive channelization of rivers, summer droughts and groundwater abstraction (Molina-Navarro et al. 2018). Characteristic features of pesticide concentrations in groundwater system are temporal-spatial disparities (Gooddy et al. 2005). Overall, the impact of climate change on pesticide exposure in groundwater systems is important in future warming. However, projected methodology, field investigation, and data acquisition for pesticide contamination in groundwater systems for various climate change scenarios needs to be further developed.

Groundwater quality in coastal areas Coastal aquifers in the interface between the oceanic and terrestrial hydrologic systems supply water resources for more than one billion people living in coastal areas (Small and Nicholls 2003). Likewise, water quality in coastal aquifers is likely to be affected by seawater intrusion or saltwater inundation (Taylor et al. 2013b). Sea level rise will increase the water-table difference between seawater and surface water or groundwater in coastal zones, causing seawater intrusion in coastal areas (Ferguson and Gleeson 2012). World population along the coasts was estimated by using the digital World Vector Shoreline, and results indicated that approximately 37% (2.07 billion) of the 1994 population (5.62 billion) lived within 100 km of a coastline, and approximately 44% (2.45 billion) lived within 150 km of a coastline (Small and Nicholls 2003). Assuming a similar current population distribution, for 2017 these figures would be 2.8 and 3.3 billion (total 7.69 billion), respectively. Seawater intrusion caused by sea-level rise will inevitably impact fresh groundwater in coastal aquifers (Werner and Simmons 2009). Vandenbohede et al. (2008) simulated a probable 15% increase in recharge of a Belgian coastal aquifer at 2100. Due to a 0.4 m sea-level rise, the interaction between sea water in low-lying inland areas and groundwater in adjacent aquifers will become more frequent, which will result in brackish and saltwater intrusion, thus increasing salinity of groundwater and causing water degradation. Under RCP 8.5, sea-level projections indicate a possible rise of 1.4 m in the Caribbean, which will result in inevitable impact on coastal aquifers and polluted freshwater in aquifers by saline intrusion, even in the absence of human activity such as pumping (Cashman and Nagdee 2017). Along the southwest coast of the Netherlands, due to rising sea levels, salt loads will double by the year 2100. In the deeper inland, increasing salt loads will lead to saline groundwater, and salt loads will also result in shallow groundwater salinization (Oude Essink et al. 2010).

In summary, sea-level rise driven by climate change and intense groundwater withdrawal driven by anthropogenic activity will exacerbate seawater intrusion in coastland regions. Shallow aquifer salinization will increase groundwater salinity and lead to water quality degradation. Moreover, it will bring more challenges to aquifer management in the coastal areas in the future.

Impacts on groundwater recharge

Due to regional variability of precipitation and evapotranspiration, groundwater recharge also varies from region to region. Compared to groundwater recharge levels during 1971–2000, groundwater recharge in the 2080s is projected to range from –70% to +100%. According to results of five CMIP5 GCMs provided by the ISI-MIP effort to the global hydrological model WaterGAP, more than a 10% decrease of groundwater recharge is projected for large parts of eastern China, southern Australia, the Mediterranean region, the Middle East, Central and South America, and southwestern South Africa. In contrast, a significant increase is projected in the high latitudes of the Northern Hemisphere due to increased precipitation, sea level, or other groundwater recharge sources (Portmann et al. 2013). Moreover, results of GCM hydrological simulations show that groundwater recharge in the San Pedro Basin (Arizona/Sonora, USA) in 2100 would decrease from 17 to 30% with a 3 °C temperature increase compared to

2000 (Serrat-Capdevila et al. 2007). Groundwater recharge in the Dill catchment, which is situated in the southeast of the Rhenish Massif in Germany, is projected to have a significant summertime reduction (more than 50%) by the 2080s. Simulation results of the Soil and Water Assessment Tool (SWAT) indicate that enhanced potential evapotranspiration and decreased precipitation are the main contributors to groundwater recharge decrease under the 4.65 °C annual mean temperature increase scenario (Eckhardt and Ulbrich 2003).

Surface-water/groundwater interaction

Surface water-groundwater interaction will be further complicated when the individual and combined impacts of climate change and human activities are considered. The projected changes in Denmark are related to increased groundwater–river interaction brought on by an increase of up to 30% in annual net precipitation under SRES A2 for the 2080s (van Roosmalen et al. 2007). According to a simulation with GSFLOW in the Luanhe River Basin (China), Feng et al. (2018) found that when temperature increased by 4 °C (RCP 8.5), precipitation would simultaneously increase 15%, river outflow would increase approximately 2%, and groundwater would decline approximately 4%; therefore, groundwater resources were more sensitive to climate change than surface water in the study area. Through coupling variable infiltration capacity (VIC) and MODFLOW models (VIC-MF), surface-water levels will increase 0.12–0.96 m in most study areas, and water tables will increase 2.6 m under RCP 8.5 due to intense rainfall and frequent surface-water/groundwater interaction by the year 2042. (Sridhar et al. 2017).

However, studies that quantify integrated surface-water/groundwater systems in global warming are rarer. As already mentioned, most studies focused separately on global warming impacts on either surface water or groundwater, but a few studies attempted to quantify the interaction process in surface-water/groundwater systems. Although there is some research that explores an integrated hydrologic cycle in a specific region in the current situation (2000–2020) by developing integrated hydrologic model (Essaid and Caldwell 2017; Goderniaux et al. 2009; Huntington and Niswonger 2012; Kløve et al. 2014; Maxwell et al. 2014), there are few studies attempting to project surface-water/groundwater interaction under various future climate change impacts (2080–2100; Li et al. 2015; Pulido-Velazquez et al. 2015). For extreme future climate change scenarios, the relevant research studies are even more rare due to the imperfection of integrated hydrological model development, the discrepancy of temporal-spatial scale in climate model, hydrological model and groundwater model, and the difficulty in accurately generalizing and describing the complicated hyporheic zone. Thus, extreme climate change impact on surface water-groundwater interaction needs further study.

Oceans

Although there is a consensus that the global mean sea level will continue increasing under global warming, there is no general agreement on the exact extent. An adopted value of global mean sea level rise for RCP 8.5 by IPCC is 0.63 m in 2100 compared to 1986–2005 (with a range from 0.45 to 0.82 m; Church et al. 2013).

Meanwhile, water chemistry will also change with increased temperature and GHG emissions; however, due to a high level of uncertainty, few projections of the impacts of climate change on water quality are available (Jiménez-Cisneros et al. 2014). Water quality projections depend strongly on (1) local conditions; (2) climatic and environmental assumptions; and (3) the current or reference pollution state (Bonte and Zwolsman 2010; Sahoo et al. 2011; Whitehead et al. 2009a, 2009b). For instance, surface ocean pH is projected to decrease by 0.3–0.5 (Ciais et al. 2014) and dissolved oxygen (DO) is projected to decline significantly (Cocco et al. 2013). Projections of DO decrease range by 6–12 μmol/kg by 2100 (the current level is approximately 175 μmol/kg; Bopp et al. 2002; Matear et al. 2000; Matear and Hirst 2003; Oschlies et al. 2008; Plattner et al. 2002; Sarmiento et al. 1998; Schmittner et al. 2008; Shaffer et al. 2009). Increased temperatures will also result in expanded ranges of harmful warm-water algal species and algal bloom seasons (Hallegraeff 2010). Blooms of *A. catenella* increase when water temperatures are greater than 13 °C (Nishitani and Chew 1984); the algae already cause shellfish toxicity in Puget Sound (Washington, USA), primarily in the late summer and early fall when water temperatures reach their maxima (Moore et al. 2009). Harmful algal blooms of toxin-producing *Microcystis aeruginosa* were found from 2010 to 2011 in Monterey Bay (California, USA), a time period that was associated with warm water temperatures (Gibble and Kudela 2014). Cyanobacteria blooms usually occur in water temperatures higher than 16–17 °C and extensive accumulate in the Baltic Sea, reaching an area of ~200,000 km^2 (Kahru and Elmgren 2014). Furthermore, global warming and increasing CO_2 concentration may benefit the growth of *Synechococcus* (Fu et al. 2007), a cosmopolitan cyanobacterium, and it also leads to harmful blooms in various ecosystems including Florida Bay, USA (Boyer et al. 2006).

Soil Erosion and sediment load

Predicted changes in precipitation volume and intensity, runoff conditions, and soil moisture will affect soil erosion and sediment load. On the global scale, the mean value of global soil erosion is projected to increase about 14% by the 2090s compared to the 1980s under RCP 8.5. Of the projected increase in soil erosion, 64% is attributed to climate change and 36% to land use change. As much as 40 to 50% increase of global mean soil erosion is projected in Australia and Africa (Yang et al. 2003). Assuming a typical soil bulk density of 1.3 Mg/m, the estimated erosion corresponds to removal of a surface layer of 0.7–1.0 mm annually (Ito 2007).

By the end of the twenty-first century, the impact of climate change on soil erosion is expected to have twice the impact of land use change (Yang et al. 2003). Increased precipitation in many regions will enhance rainfall erosivity, resulting in intensification of erosion phenomena and stream sediment loads (Jiménez-Cisneros et al. 2014). For instance, a 10% increase in winter rainfall accompanying a projected increase of 4.5 °C would increase annual erosion of arable land by up to 180% in the UK (Favis-Mortlock and Boardman 1995). While erosion rates are likely to rise in locations that are projected to receive more rainfall, rates may abate where precipitation decreases—for example, more than 14% of the projected decline in rainfall in Australia is during erosion-sensitive months for 2070–2099, thus reducing soil erosion over 24% according to results of a revised Morgan Morgan Finney (MMF) model (Scholz et al. 2008). On the other hand, in the tropics, the intensity of cyclones is projected to increase by 2–11% by 2100, which might increase soil erosion and landslides (Knutson et al. 2010).

Extreme hydrologic events

Floods

Overall, annual global flooding is projected to dramatically increase under RCP 8.5 in many densely inhabited locations. With Shared Socio-economic Pathways 2 (SSP2, "middle-of-the-road") and RCP 8.5 by 2050, the climate change will increase water resource stress and river flood risk for approximately 920–3,400 million people and 100 and 580 million people, respectively (Arnell and Lloyd-Hughes 2014). The number of people exposed to 100-year flood events in 2100 is projected to be more than twice the population affected in 2040 (Fig. 3).

High intensity and frequent precipitation is the dominant factor for flood occurrence. Under conditions of global warming, precipitation is more likely to form heavy rainfalls accompanied by an increase of flood risk in different regions (Goswami et al. 2006; Min et al. 2011)—for example, in RCP 8.5, global flood exposure will increase by about 14 ± 10 times from the time-period 1971–2000 to 2071–2100 in the areas of increasing annual precipitation and heavy precipitation, including South Asia, Southeast Asia, Northeast Eurasia, eastern and low-latitude Africa (Hirabayashi et al. 2013).

Likewise, sea-level rise can also impact flood risk, especially in coastal areas. Flood events' probabilities can be estimated via probabilistic projections of future local sea-level rise (Hinkel et al. 2014; Nicholls and Cazenave 2010). For example, when considering local sea-level rise impact, it will likely result in more extreme flood events, i.e., New York is projected nine 100-year-floods over 2001–2100 under RCP 8.5, the same as 11-year events without sea-level rise (Kopp et al. 2014).

Droughts

A comparison of the proportion of land exhibiting significant projected changes in hydrological drought frequency (reduction in the availability of surface and subsurface water) to the proportion exhibiting significant changes in meteorological drought (reduction in precipitation relative to the mean for a particular location) and agricultural drought frequency (results from an insufficient supply of water for plant growth and includes soil moisture deficit) was made under SRES A1fi. Excluding cold areas, 18–30% of the land surface was projected to experience a significant increase in the frequency of 3-month droughts, while about 15–45% will see a decrease from the baseline period 1961–1990 to the 2080s (Taylor et al. 2013a).

Duration of drought, as the length of a drought event in months (Touma et al. 2015), is one of the predominant characteristics of a drought (Giorgi and Bi 2005). It has a significant variability in spatial scales due to the heterogeneous distribution of precipitation and/or evapotranspiration in climate change (Samaniego et al. 2017). For example, according to 15 global climate models available in the CMIP5, there are longer drought duration events in low-latitude regions (subtropical and tropical regions); in contrast, higher latitudes regions (e.g. South Africa in the southern hemisphere, and Northeastern Europe in the northern hemisphere) tend to show little change under RCP 8.5 for the period 2050–2099 (Touma et al. 2015). Meanwhile, longer droughts may result in urban, industrial, and agricultural water shifting from surface water to predominantly groundwater, thus accelerating the depletion of groundwater (e.g. Southwestern America, Taylor et al. 2013a). Furthermore, increased groundwater depletion may also trigger secondary disaster such as land subsidence and seawater intrusion (Taylor et al. 2013a).

Several drought indicators have been applied to evaluate meteorological drought severity, such as the Palmer drought severity index (PDSI, Palmer 1965), the Standardized Precipitation Index (SPI, McKee et al. 1993), the Streamflow Drought Index (SDI, Nalbantis and Tsakiris 2009), the Standardized Precipitation Evaporation Index (SPEI, Vicente-Serrano et al. 2010), the Standardized Groundwater Level Index (SGI, Bloomfield and Marchant 2013), the Groundwater Resource Index (GRI, Mendicino et al. 2008), and the Groundwater Drought Index (GDI, Thomas et al. 2015). Among these indices, PDSI is the most widely available for drought evaluation under different climate change scenarios (Dai 2011, 2013; Trenberth et al. 2014; Zhao and Running 2010). It is a locally normalized index of

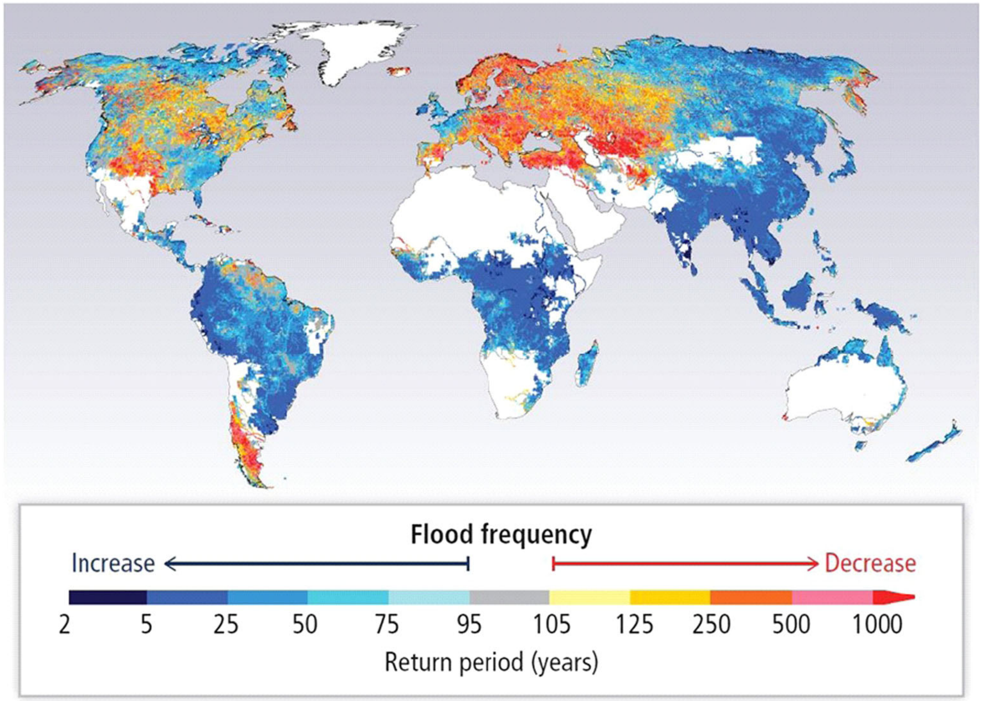

Fig. 3 Multi-model median return period (years) in the 2080s for the twentieth century 100-year flood (Hirabayashi et al. 2013), based on one hydrological model driven by 11 Coupled Model Inter-comparison Project Phase 5 (CMIP5) general circulation models (GCMs) under RCP 8.5. At each location, the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. Regions with mean runoff less than 0.01 mm/day, Antarctica, Greenland, and small islands are excluded from the analysis and indicated in white (Jiménez-Cisneros et al. 2014)

soil moisture availability calculated from the balance of moisture supply (precipitation) and demand (evapotranspiration; Cook et al. 2015). Relative to a defined baseline, negative PDSI values (PDSI<0) represent drier than average conditions (droughts), and positive PDSI values (PDSI>0) represent wetter conditions (pluvials; Cook et al. 2015). Moreover, the severity of groundwater drought can also be estimated by PDSI (Dai 2011; von Freyberg et al. 2015)—for example, von Freyberg et al. (2015) applied PDSI into drought characteristics analysis in monthly time-scale of precipitation and groundwater recharge in northeastern Switzerland.

In addition to PDSI, the SGI builds on SPI and can efficiently reveal and quantify characteristics (intensity, severity etc.) of groundwater drought under precipitation variation in the future due to the high correlation between SPI and SGI indices (Table 1; Bloomfield and Marchant 2013). The SPI has been successfully applied into groundwater drought assessment in the eastern Netherlands, southern Germany, southern Sweden, the UK, and Iran (Bloomfield et al. 2015; Jönson 2017; Motlagh et al. 2017; Van Loon et al. 2017).

Moreover, based on the literature, the trend of drought under global warming tendency in the twenty-first century demonstrates a significant variability over spatial and temporal scales due to reduced precipitation and/or increased evapotranspiration (Cook et al. 2015; Park et al. 2015; Seneviratne et al. 2012). A decreasing trend of drought has been detected in East Asia (Dai 2013) and in most parts of China (Chen et al. 2013). In contrast, an increasing trend of the frequency and intensity of drought was identified in the United Kingdom and France (Vidal et al. 2012; Vidal and Wade 2009), East Asia (Manabe et al. 2004; Wang 2005), Southwestern United States (Cook et al. 2015), Europe (Beniston et al. 2007) and globally (Dai 2013).

Teleconnection patterns influence

Teleconnection patterns such as the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and the El Niño-Southern Oscillation (ENSO), are closely

Table 1 The interval value of SPI and SGI (Bloomfield and Marchant 2013)

SPI values	SGI values	Drought degree
$SPI < -2$	$SGI < 0$	Extreme drought
$-2 < SPI < -1.5$	$SGI < 0$	Severe drought
$-1.5 < SPI < -1$	$SGI < 0$	Moderate drought
$-1 < SPI < 0$	$SGI < 0$	Minor drought
$0 < SPI$	$SGI > 0$	No drought

associated with changes in the amount and temporal-spatial distribution of precipitation, air temperature, and evapotranspiration (De Vita et al. 2012; Ropelewski and Halpert 1986; Shang et al. 2011). These teleconnection patterns therefore are also essential to recharge rates and changes in groundwater storage (Fleming and Quilty 2006; Gurdak et al. 2007; Kuss and Gurdak 2014). Holman et al. (2011) applied wavelet analysis to indicate that large-scale climate patterns such as the North Atlantic Oscillation (NAO), may affect groundwater recharge rates and mechanisms in aquifers across the UK. Kuss and Gurdak (2014) quantified the effects of ENSO, PDO, AMO, and NAO on precipitation and groundwater levels of North Atlantic Coastal Plain principal aquifers (PAs) in the US by singular spectrum analysis (SSA), wavelet coherence analysis, and lag correlation. The results demonstrated that ENSO and PDO had greater control than NAO and AMO on variability in groundwater levels across the US, particularly in the western and central PAs. Velasco et al. (2017) used SSA and found that PDO, ENSO, and Pacific/North American Oscillation (PNA) significantly impacted on precipitation and groundwater fluctuations across a north–south gradient of the West Coast in the US, and low frequency signals (PDO) seemed to be better preserved in groundwater fluctuations than high frequency signals (ENSO and PNA).

With increasing GHG emission in the future, the characteristics (duration, frequency, amplitude) of teleconnection patterns will be affected, resulting in the variability of precipitation, temperature, and evapotranspiration (Sabziparvar et al. 2011; Tremblay et al. 2011). Therefore, groundwater storage, groundwater recharge, and groundwater level fluctuation will have more complexity by 2100 (Kuss and Gurdak 2014).

Uncertainty analysis of the groundwater recharge

Synthesizing hydrologic changes with multiple GCMs allows uncertainty analysis (Crosbie et al. 2013; Deser et al. 2012; Kurylyk and MacQuarrie 2013; Meixner et al. 2016; Rogelj et al. 2012; Smerdon 2017; Taylor et al. 2013a, b). Three sources drive the uncertainty of the hydrologic cycle under climate change: (1) type of GCM; (2) type of catchment scale; and (3) GHG emission scenario (Friedlingstein et al. 2014; Hawkins and Sutton 2009; Tebaldi and Knutti 2007). Groundwater recharge is an essential driver of many hydrologic processes as well as an important variable in the water cycle (Bakker et al. 2013). Arguably, the predicted impacts of climate change on groundwater system are quite uncertain, especially for groundwater recharge, due to the two dominant sources of uncertainty in climate change predictions: GCM types and downscaling (Green et al. 2011; Taylor et al. 2013b; Smerdon 2017).

The process of predicting recharge under climate change in the future by various GCMs involves high uncertainty (Holman et al. 2012; Jyrkama and Sykes 2007; Meixner et al. 2016). Crosbie et al. (2010) fitted recharge projections derived from 15 GCMs with low, medium, and high global warming scenarios to a weighted Pearson Type III distribution, and there was an 80% of the variability range between the wet (10%) and dry (90%) future recharge at 2030. Jackson et al. (2011) simulated groundwater recharge and flow variation at an ensemble of catchment scale by applying 13 GCMs under A2 emission scenario (second highest emission scenario in IPCC 2001), and there was −26% to +31% range in potential groundwater recharge. When only applying a single GCM and emission scenario (A2) and adopting an average decrease recharge of 5% by 2100, Hanson et al. (2012) found that the variability range was still large: −60 to +20%. The potential impact of climate change on groundwater recharge across the western US was analyzed by synthesizing existing studies, and the uncertainty range in these areas demonstrated regional discrepancy from southern (−100 to +30%) to northern regions (little change; Meixner et al. 2016).

Direct application of GCMs may lead to biased hydrological simulations due to the uncertainty of predicted precipitation and runoff in global scale (Prudhomme and Davies 2009). Thus, downscaling the results of global climate models are appropriate for climate change impact assessments and overcome the limitations previously discussed (Beniston et al. 2007; Moeck et al. 2016). Van Vuuren et al. (2011) suggested that using more-emission scenarios would increase uncertainty of global climate models and that combining some downscaling methods could lower it; however, the uncertainty related to the global-regional climate model was inevitable. Crosbie et al. (2011) indicated that the largest uncertainty of global climate models is higher than the uncertainty of the downscaling method. Dynamical downscaling and statistical downscaling are two major downscaling methods for global-scale or large-scale models (Fowler et al. 2007, Prudhomme et al. 2002; Crosbie et al. 2011).

However, downscaling the projection from a global climate model to the scale of a hydrologic or hydrogeologic model can also introduce additional error and uncertainty into the analysis (Jyrkama and Sykes 2007). Mileham et al. (2009) indicated that multiple downscaling methods could result in 50% increase or decrease in recharge using the same GCM and hydrological model. Allen et al. (2010) applied state-of-the-art downscaling method to four global climate models and showed the variability of groundwater recharge was −10.5 to +23.2% in coastal British Columbia, Canada, and Washington State, USA. Kurylyk and MacQuarrie (2013) found out that the variability of average annual groundwater recharge is −6 to +58% with combinations of global climate models, emission scenarios, and downscaling approaches in eastern Canada. In addition to GCM types and downscaling, hydrological model (Crosbie et al. 2011), limited data (Ordens et al. 2014), emission scenarios (Holman et al. 2012), land types (Shanafield and Cook 2014), heavy precipitation (Seiller et al. 2012), and heatwave (Merz et al. 2011) can also affect the uncertainty of groundwater recharge projection. Comparing the estimated uncertainty at different scales (local and global), there is no significant correlation among these studies (Table 2). The number of global climate models, emission scenarios, and downscaling methods are different in each case and may result in the lack of correlation between scales and uncertainty of groundwater recharge estimation.

Feedback between water-table dynamics, land-surface energy fluxes, and atmospheric response have been investigated in recent studies, which impart a new perspective to understanding the groundwater recharge process in diverse climate change scenarios (Ferguson and Maxwell 2010; Gilbert et al. 2017; Maxwell and Kollet 2008). The strong positive correlation between groundwater depth and land-surface response is usually investigated in a "critical zone", which is 2–5 m below the surface (Leung et al. 2011; Maxwell and Kollet 2008). With the case studies in the southern Great Plains (USA), the San Joaquin River watershed in central California (USA), North Rhine in Westphalia region (Germany), Ballona Creek Watershed (Los Angeles, USA), various researchers found that groundwater depth dynamics in a "critical zone"—which is driven by lateral water flow—might not only determine the relative sensitivity of regions to temperature and precipitation change but also in turn affect atmospheric response, especially on moisture transportation and precipitation (Ferguson and Maxwell 2010; Gilbert et al. 2017; Jiang et al. 2009; Maxwell and Condon 2016; Maxwell and Kollet 2008; Reyes et al. 2016; Sulis et al. 2017). Moreover, lateral groundwater flow processes may be vital to characterizing evapotranspiration and plant transpiration at large scales (Maxwell and Condon 2016) and could result in variation of water table, soil moisture, and atmospheric moisture. Meanwhile, land-energy fluxes will be affected by water-table changes due to the positive correlation relationship between land-energy fluxes and water table, and finally, it would have important implications to atmospheric simulation (Maxwell and Condon 2016). However, comparing to the groundwater recharge process, there is a lack of uncertainty estimation in atmospheric response caused by groundwater depth dynamics and lateral water flow fluxes. Thus, additional work is needed to estimate uncertainties in groundwater feedbacks between water table dynamics and land-surface energy fluxes and atmospheric response at different scales.

Projected impacts, vulnerabilities, and risks

Under climate change, reliable surface-water supply is expected to decrease due to increased variability of river flow, increased precipitation variability, and decreased snow and ice storage (Barnett et al. 2005; De Wit and Stankiewicz 2006; Vörösmarty et al. 2000). Meanwhile, renewable groundwater resources also decrease remarkably under high GHG emission levels. The percentage of the global population living in river

Table 2 An overview of uncertainty evaluation in several studies about the impact of projected climate change on groundwater recharge

Scale	Number of GCMs	Number of ES	Selection of DM	Uncertainty	References
Global	2	2	NA	−30% ~ +100%	Döll 2009
7,617,930 km^2	16	3	Delta change method[a]	+45 ~ +283%	Crosbie et al. 2013
451,000 km^2	19	4	Delta change method[a]	−37% ~ +27%	Meixner et al. 2016
106,000 km^2	15	3	Daily downscaling approach[a]	+10% ~ +90%	Crosbie et al. 2010
52,000 km^2	3	8	Bias corrected statistical downscaling[a]	+20% ~ +60%	Meixner et al. 2016
20,000 km^2	15	3	Daily downscaling approach[a]	−33% ~ +28%	Ali et al. 2012
7,560 km^2	17	4	Delta change method and CMIP3 GCM[a]	−100% ~ +35%	Serrat-Capdevila et al. 2007
2,600 km^2	13	1	Change factor method[b]	−26% ~ +31%	Jackson et al. 2011
2,098 km^2	1	1	Providing regional climates for impact studies[b]	−50% or + 50%	Mileham et al. 2009
1,600 km^2	1	2	Stochastic weather generator[a] and change factor method[b]	−14% ~ −37%	Holman et al. 2009
581 km^2	5	2	Change factor method[b]	−20% ~ +7%	Dams et al. 2012
161 km^2	4	1	state-of-the-art downscaling method[a]	−10.5% ~ +23.2%	Allen et al. 2010
9.5 km^2	4	4	Daily translation method[a]	−6% ~ +58%	Kurylyk and MacQuarrie 2013

GCMs global climate models; *ES* emission scenarios; *DM* downscaling methods; *NA* not applicable

[a] Statistical downscaling method

[b] Dynamic downscaling method

basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2 °C to 13% at 5 °C (Gerten et al. 2013).

Water resources

Water scarcity is the lack of sufficient available water resources to meet water needs within a region, and it is referred to, in increasing order of severity, as "water shortage," "water stress or deficits," and "water crisis" (Gleick 1998; Rijsberman 2006). Water scarcity is an important index for evaluating regional water-resource crises. Models have shown that mean global warming of 5 °C would expose an additional 13% of the world population to new or aggravated water scarcity (Gerten et al. 2013).

Projected water scarcity varies by region (Bernstein et al. 2008). Northern China and North Africa are expected to suffer less water stress while Southern Europe and most of the Middle East are expected to experience more intense water stress based on simulation with agro-land use model and water supply–demand model (Hayashi et al. 2013).

According to statistical data, there were 1.2 billion people living in areas of water scarcity in 2003 (Rijsberman 2006). By 2050, under RCP 8.5, an additional 0.5–3.1 billion people are projected to be exposed to water scarcity (Gosling and Arnell 2016). That means the population affected by water scarcity will increase by 42 to 258%.

In a study specifically about groundwater, 27–50% of the projected global population (SSP2 population scenario) is projected to suffer from a decrease of renewable groundwater resources of more than 10% by the 2080s (as compared to 1980s levels) under RCP 8.5 (Portmann et al. 2013). The land area affected by the decrease in groundwater resources is projected to increase linearly with global mean temperature rise between 0 and 3 °C; for each degree of global mean temperature increase, an additional 4% of the global land area is projected to suffer a decrease in groundwater resources of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann et al. 2013).

Agricultural irrigation

Under RCP 8.5, global irrigation water demand (IWD) is projected to increase by 6.7 to 10% (Hanasaki et al. 2013). Future IWD is projected to increase by more than 20% by 2100 during the summer in the Northern Hemisphere (Döll 2002; Konzmann et al. 2013; Wada et al. 2013). Due to the increased water demands of intensified agriculture in 2100 (Schewe et al. 2014), more than 17% of the global population will suffer from a severe reduction (more than 20%) in water resources.

The present peak IWD is projected to shift 1 month or more in ≥80% of current global irrigated areas, currently home to 4 billion people—for example, peak IWD is projected to occur approximately a month later in Eastern Asia (June–July), the Arabian Peninsula (May–July), and Northern Africa (May–June). However, these peaks may occur about 1 month earlier over Central America (April–March) and Central Asia (July–June; Wada et al. 2013).

Energy production

Climate change affects hydropower generation through changes in mean annual streamflow, shifts of seasonal flows, increases of streamflow variability (including floods and droughts), increases in evaporation from reservoirs, and changes in sediment flux (Bergström et al. 2001; Hamududu and Killingtveit 2012; van Vliet et al. 2016). Global hydropower potential is expected to increase 6.3% (RCP 8.5) by the 2080s compared to 1971–2000, according to GCM-global hydrological models (GCM-GHMs; van Vliet et al. 2016). The strongest increases in hydropower potential are expected for Central Africa, India, Central Asia and the northern high-latitudes, with 18–33% of the world population living in these areas by the 2080s (van Vliet et al. 2016). Hydropower projections correspond with a pattern of precipitation under RCP 8.5; high latitudes of the Northern Hemisphere have more precipitation.

In addition to the effects of precipitation, changes in temperature, evapotranspiration, and snowmelt, as well as warmer ambient temperatures will also affect the hydrologic regime and hydropower production (Schaefli et al. 2007; van Vliet et al. 2016). By the 2050s, global warming effects will be felt in US states in the lower Colorado River Basin where hydropower generation will decline by as much as 40% due to decreasing reservoir levels and flows (Barnett et al. 2004). By the 2080s, warmer ambient temperatures leading to warmer cooling water are projected to lower thermal power plant efficiency and thus decrease electricity production by 1.5–3% in European countries under emissions scenario SRES A1fi (Golombek et al. 2012).

Municipal services

Rising surface-water temperatures will not only affect hydropower efficiency. They will also affect basic parameters such as pH, DO, and dissolved organic carbon (DOC; Evans et al. 2005) as well as increase pollutant concentrations in drier places (Van Vliet and Zwolsman 2008). For instance, results of the PAYSER model have identified an increased risk of water-treatment-plant "failure" that would result in high nitrate pollution levels in the 2050s through 2090s under A1fi at Grafham (located in the east of England). Additionally, DYRESM-CAEDYM modeling has been applied to project deterioration of water quality by the increased frequency of stratification and increased phytoplankton and DOC levels caused by decreasing precipitation in the reservoir (Thorne and Fenner 2011).

On the other hand, increased precipitation may cause its own problems in the form of increased pathogen loads. Five simulated rainfall events illustrated that under these events, runoff release of staphylococci, enterococci, and *Clostridium perfringens* (*C. perfringens*) was ~3–6 log units greater in the litter because of aggravated leaching pollution (Brooks et al. 2009). This would increase water treatment costs in farming areas; nevertheless, on the positive side, biological water and wastewater treatment are more efficient when the water is warmer (Tchobanoglous et al. 2003).

Freshwater ecosystems

Increased air temperature will affect the temperature of surface water and groundwater and result in variation in lentic systems, especially the quality of fish and amphibian habitat (Ficke et al. 2007). In the northeastern United States, there would be a nearly 50% decrease of fish habitat in cold and cool water under a hypothetical scenario of a projected air temperature increase of 4.5 °C (Eaton and Scheller 1996). Similarly, warming of just 3.8 °C is projected to drastically reduce the range of brook trout in the southeastern United States (Flebbe 1993) and in southern Canada (Meisner 1990).

Moreover, the vulnerabilities of groundwater-dependent ecosystems (GDEs, including groundwater-dependent springs, lakes, rivers, wetlands, peatland, wet forest and species) will also be more prominent under such extreme CO_2 concentration (Kløve et al. 2014). CO_2 not only impacts most important climate forcing factors for RCP 8.5 but also affects the productivity of many terrestrial plants and aquatic organisms (Van Vuuren and Carter 2014)—for example, through 26 GCMs simulation based on RCP 8.5, the number of ecoregions that are impacted by habitat loss and fragmentation–climate change (HLF–CC) will increase to 170 in 2090 (Segan et al. 2016). Due to the high density of CO_2, the acidification of the superficial zone in GDEs may be dominant in the regions of rainfall increase (Bertrand et al. 2008). Meanwhile, it will also alter the sulfur dynamic, organic acid production, and soil acid-buffering ability in GDEs (Kløve et al. 2014).

Increased soil erosion caused by additional precipitation will also impact water quality, especially in agricultural countries such as China, India, and much of Latin America (Lal 1998). Non-point source pollution of nitrogen, phosphorus, and pesticides may affect river water quality along with surface runoff inflow into rivers, thus leading to eutrophication. In eutrophic freshwater systems, 700 ppm of atmospheric CO_2 may result in an increase in phytoplankton productivity of more than 50%; therefore, nuisance phytoplankton blooms may be further aggravated by elevated atmospheric CO_2 concentrations (Schippers et al. 2004).

Climate change also has a connection with eutrophication in lakes (Straile and Adrian 2000). Higher temperatures can reduce water viscosity, enhance nutrient diffusion, and induce vertical gradient variation of pH and DO (Peperzak 2003). Meanwhile, the decreased viscosity caused by increased temperature will promote the sinking of larger, non-motile phytoplankton that have weak buoyancy regulation mechanisms (e.g. diatoms, Paerl and Huisman 2009). Higher temperatures also foster cyanobacteria blooms, increasing the potential of eutrophication in lakes (Paul 2008).

Links to other sectors and services

Adaptation in other sectors such as agriculture, forestry, and industry can have impacts on the freshwater system and should therefore be considered as part of adaptation planning in the water sector (Jiang et al. 2005). Climate change parameters include higher temperatures, changes in precipitation, and higher atmospheric CO_2 concentrations. Although rising temperature has both positive and negative effects on crop yields, in general it has been found to reduce yields and quality of many crops, most importantly cereal and feed grains (Adams et al. 1988, 1998). An atmosphere with higher CO_2 concentrations would result in higher net photosynthetic rates (Allen et al. 1987; Cure and Acock 1986). It may also reduce transpiration as plants reduce their stomatal apertures, the small openings in the leaves through which CO_2 and water vapor are exchanged with the atmosphere (Adams et al. 1998)—for example, in Amazonia, stomatal closure caused by increasing CO_2 concentration and temperature contributes approximately 20% to the precipitation decrease, suppressing local evaporative water recycling (Betts et al. 2004).

Under RCP 8.5, the increased surface-water temperature will encourage algal blooms not only in the marine system but also in interior lakes (van Vliet et al. 2016). For example, there was a cyanobacterial bloom outbreak event at Taihu (the third largest freshwater lake in China) because of an unusually warm and dry spring in 2007, which induced a drinking water crisis that affected approximately 2 million people for at least 1 week (Zhu and Schwartz 2011). According to five projected model results, cyanobacterial blooms will likely occur with more frequency in the coming decades (Qin et al. 2010).

Perspective of water resources management

In general, available water resources will decline by 2100 under RCP 8.5 due to increased urban, agricultural, industrial water consumption; increased evapotranspiration in low latitudes; and additional water consumption by vegetation expansion in areas where human pressure will decrease and cultivation will disappear (García-Ruiz et al. 2011). Climate and land use changes indicate an increase in water stress and a shortage of water availability, especially in the mid-latitude and subtropical dry regions. However, due to an increase in precipitation, streamflow and groundwater are projected to increase significantly and flood frequency is also estimated to rise in the high latitudes of both the Northern and Southern Hemispheres (Christensen et al. 2013; Hirabayashi et al. 2013; Portmann et al. 2013). Thus, water resource management needs to be improved to respond to future challenges.

Comprehensive management approaches to water resources may greatly reduce human vulnerability to extreme GHG emissions and climate change and thereby promote global water and food security (Taylor et al. 2013b). However, current strategies and policies cannot cope with such dramatic increase of global water crisis and extreme GHG emission scenarios. Thus, water resource management needs to be adapted to respond to future challenges.

To deal with projected hydrologic cycle changes and potential risks, several strategies for water resource management under scenario RCP 8.5 are feasible:

1. *Increase development of hydraulic infrastructures*. Developing hydraulic infrastructure in the high latitudes, mid-latitudes, and wet tropical basin, while also developing some indispensable hydraulic infrastructure in the mid- and low latitudes of the Northern and Southern Hemispheres would help precipitation to dramatically increase in these regions in both the Northern and Southern Hemispheres and enhance suitable conditions for hydropower generation. The development of reservoirs and hydropower dams would not only adjust streamflow and achieve flood control (Schwanenberg et al. 2015) but also would meet increasing future electricity demands (Hamududu and Killingtveit 2012). Decreased precipitation will challenge the affected countries where water supply already depends mainly on irregular stream flows, thwarting increasing crop production with its increasing irrigation demand. Indispensable reservoir development for rainfall and surface runoff storage can help adjust water resource distribution for regions with a lack of sufficient available water resources to meet demand (García-Ruiz et al. 2011). Moreover, adjustment of water resources and reservoir management cannot be ignored but must rather adapt to changing river regimes and water resource availability.
2. *Optimize conjunctive use of surface water and groundwater*. An effective option to reduce groundwater depletion under RCP 8.5 scenario is conjunctive usage of surface water and groundwater. Although there are several methods for conjunctive use, the optimization of alternative water-resource-development modes still needs further study (Giordano 2009; Iglesias et al. 2007; Scanlon et al. 2012). Identification of inherent uncertainty in water resource projections and the residence time of freshwater in both surface-water and groundwater systems is essential to set sustainability goals of conjunctive use (Aeschbach-Hertig and Gleeson 2012). Further development of conjunctive usage of surface water and groundwater such as riverbank filtration technology, is also vital to mitigate future water crises (Hiscock and Grischek 2002; Hoppe-Jones et al. 2010; Hu et al. 2016).
3. *Enhance groundwater recharge from supply-side management via technical development*. Aquifer recharge management is essential to mitigate groundwater depletion issue when domestic, agricultural, and industrial water habits alter or occur during droughts (Aeschbach-Hertig and Gleeson 2012). Artificial recharge of groundwater with excess surface water, desalinated water, and treated wastewater is an effective method for aquifer recovery and has been applied in the North China Plain, Western United States, and India (Foster et al. 2004; Shah 2009; Scanlon et al. 2012). However, the efficiency of artificial recharge is unsatisfactory, and technologies of seawater desalination and wastewater treatment are immature (Elimelech and Phillip 2011). Thus, development of seawater desalination and sewage purification with emerging technologies will be beneficial to artificial recharge of groundwater and in the face of droughts.
3. *Improve water treatment technologies*. Technological improvements in sewage treatment, seawater desalination, and so forth are essential to sustainable water resource development in water stressed regions. Increasing freshwater resources by seawater desalination and sewage purification with emerging technologies will help global-water-crisis mitigation. Limited efficiency and capital operation costs are common problems for both sewage treatment and recycling and seawater desalination with current technological level (Missimer et al. 2013; Muga and Mihelcic 2008; Peñate and García-Rodríguez 2012; Van der Bruggen et al. 2003). Moreover, for seawater desalination, the high specific energy consumption, membranes selection, harmful effects of scaling and fouling on membranes may further limit desalination efficiency (Peñate and García-Rodríguez 2012). Although rainwater harvesting (RWH) is an integral part of the sustainable rainwater management for coping with future climate change, especially in the areas where precipitation will significantly increase (Kahinda et al. 2010; Pandey et al. 2003), the capital costs, materials for manufacturing systems, as well as the costs and resource requirements related to system installation and maintenance are also neglected (Ward et al. 2012). Thus, to promote essential water treatment technologies, further research is required in materialogy, microbiology, environmental science, toxicology, and relevant other subjects.
4. *Improve integrated hydrologic modeling*. The purpose for establishing an integrated hydrologic model is to better

understand and predict the hydrologic cycle with climate changes at both the global and regional scale and to develop measures to cope with the projected hydrologic change (Green et al. 2011; Maxwell et al. 2014). However, as already discussed (see section "Surface-water/groundwater interaction" and section "Uncertainty analysis of the groundwater recharge"), the limitation of current integrated hydrologic modeling is highlighted such as the discrepancy of temporal-spatial scale in sub-models (e.g. climate model, hydrological model and groundwater model) and hyporheic zone generalization. In the temporal-scale, most of existing integrated hydrologic models prefer to focus on the current situation rather than make a projection for the future with different climate change impacts (Kløve et al. 2014; Pulido-Velazquez et al. 2015). Furthermore, inherent uncertainties in models also affect the reliability of the projection by integrated models (Crosbie et al. 2013; Smerdon 2017). Thus, integrated hydrologic models need to be further developed, not only in computing methods but also in fundamental theories, especially for description and generalization of hyporheic zones. Meanwhile, models also need to shift the simulation target from the current (2000–2020) to the future (2080–2100) under multiple climate change and GHG emission scenarios. Moreover, lowering the uncertainties in integrated hydrologic models is essential to develop possible adaptation strategies for policymakers.

5. *Establish new legal and policy frameworks for water resource management*. It is critical to propose regionally adapted strategies from this range of options and generally strengthen regulation, policy and management for water, energy and agriculture (Giordano 2009; Sophocleous 2010; Theesfeld 2010). There is no uniform solution for water resource management due to climatic, hydrologic, political, social-economic conditions that vary significantly between different regions (Aeschbach-Hertig and Gleeson 2012). Future research needs to identify appropriate, adaptable, and sustainable long-term strategies for each region no matter whether it is arid, semi-arid, or wet, and this research must try to transfer knowledge and measures between regions; only then can change be promoted to meet the challenges of water resource management at a global scale under extreme GHG emission and global warming scenario.

Moreover, mitigation of CO_2 emissions is vital to slowing global warming and mitigating future water crises. Strong institutional frameworks will need to be established socially, economically, and environmentally in order to achieve CO_2 limit goals and relieve water crises caused by global warming. Carbon capture and storage (CCS) and development of renewable clean energy are feasible to mitigate CO_2 emissions and achieve the target. Recently, bioenergy carbon capture and storage (BECCS) have been promoted as an effective mitigation option for GHG negative emissions (Fuss et al. 2014) due to their ability to achieve negative CO_2 emissions (Obersteiner et al. 2001). However, water consumption of BECCS may itself jeopardize the sustainability of global water resources. Therefore, the water balance of the widespread application of BECCS needs to be assessed.

Conclusions

This paper synthesizes model predictions of the changed groundwater system and hydrologic cycle in the literature under the global warming scenario of CO_2 at 936 ppm in 2100 (RCP 8.5). These model predictions describe a global hydrologic cycle that is dramatically different from that of today. The impacts of climate change on groundwater resources vary regionally due to the regional distribution of precipitation and evapotranspiration, localized interaction between surface water and groundwater, distances from the oceans and impacts from sea-level rise, and teleconnection pattern effects. Generally, the groundwater resource variability corresponds to precipitation distribution patterns in RCP 8.5 scenario: (1) groundwater resource depletion will increase in tropical and/or subtropical regions, and (2) groundwater resource quantity will increase in the high-latitude regions of the Northern and Southern Hemispheres. Meanwhile, increased evapotranspiration may lead to a dramatic decline of streams, lakes, and other surface-water resources and result in a shift from traditional source for urban, industrial, and agricultural water use from surface water to groundwater, thereby accelerating its depletion (e.g. Southwestern America, Southern Europe, India). An increase in demand of agricultural development and sea-level rise will lead to water degradation in agricultural and coastal areas by nonpoint pollution and seawater intrusion, respectively.

However, predicted groundwater recharge variations as a result of global warming carry large uncertainties. GCMs types and downscaling methods are two dominating factors affecting the reliability of groundwater recharge prediction. Studies of feedbacks among water-table dynamics, land-surface energy fluxes, and atmospheric provide a new perspective to understanding the groundwater recharge processes in diverse climate change scenarios, but there is a lack of uncertainty estimation in atmospheric response caused by groundwater depth dynamics and lateral water flow fluxes.

Besides, for global hydrologic cycle under RCP 8.5, a 4–6 °C increase in global mean temperature will increase the global mean precipitation 54.75 mm/year, evapotranspiration by 5%, and available fresh water by 68.9%, while decreasing groundwater resources by 38% by the end of the twenty-first century compared to the pre-industrial period. However, these global average values mask a startling reality: water scarcity will be exacerbated in areas already experiencing water stress. Under RCP 8.5, the global mean sea level will rise 0.63 m by 2100 and soil erosion will increase 9% by the 2090s, while the frequency of extreme hydrologic events, i.e., floods and droughts, will increase for 18–30% of the land area. These changes in the hydrologic cycle will seriously threaten water resource security. Thirteen percent of the world's population will suffer new or aggravated water scarcity, whereas due to increased demand of intensified agriculture, more than 17% of the global population may suffer from a severe reduction (more than 20%) in water resources, further complicating water resource distribution. An increase in surface-water temperature will contribute to ecosystem degradation, a reduction of hydropower efficiency and overall generation (affecting more than 46% of the world population), and increased water treatment costs.

Moreover, water security is one important impetus among many for human societies to slow down global warming. In addition to hydraulic infrastructure construction and institutional framework establishment, conjunctive usage of surface water and groundwater, water-treatment-technology improvement, integrated hydrologic modeling improvement, groundwater recharge enhancement by human intervention, and mitigation of CO_2 emission is essential to water resource management. Such an extremely complicated problem will require interdisciplinary cooperation to respond to climate change, river regimes, reservoir management, and CO_2 emission mitigation, necessitating the participation of engineers, climatologists, hydrologists, human and physical geographers, general environmentalists and stakeholders.

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References

Adams RM, McCarl BA, Dudek DJ, Glyer JD (1988) Implications of global climate change for western agriculture. Western J Agr Econ 13(2):348–356

Adams RM, Hurd BH, Lenhart S, Leary N (1998) Effects of global climate change on agriculture: an interpretative review. Clim Res 11:19–30

Aeschbach-Hertig W, Gleeson T (2012) Regional strategies for the accelerating global problem of groundwater depletion. Nat Geosci 5(12): 853–861. https://doi.org/10.1038/ngeo1617

Allen D, Cannon A, Toews M, Scibek J (2010) Variability in simulated recharge using different GCMs. Water Resour Res 46(10). https://doi.org/10.1029/2009WR008932

Allen L, Boote K, Jones J, Jones P, Valle R, Acock B, Rogers H, Dahlman R (1987) Response of vegetation to rising carbon dioxide: photosynthesis, biomass, and seed yield of soybean. Global Biogeochem Cy 1(1):1–14. https://doi.org/10.1029/GB001i001p00001

Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. Nature 419(6903):224–232. https://doi.org/10.1038/nature01092

Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I, Hodgson G (2012) Potential climate change impacts on the water balance of regional unconfined aquifer systems in South-Western Australia. Hydrol Earth Syst Sci 16:4581–4601. https://doi.org/10.5194/hess-16-4581-2012

Arheimer B, Andréasson J, Fogelberg S, Johnsson H, Pers CB, Persson K (2005) Climate change impact on water quality: model results from southern Sweden. Ambio 34(7):559–566. https://doi.org/10.1579/0044-7447-34.7.559

Arnell NW, Gosling SN (2013) The impacts of climate change on river flow regimes at the global scale. J Hydrol 486:351–364. https://doi.org/10.1016/j.jhydrol.2013.02.010

Arnell NW, Lloyd-Hughes B (2014) The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. Clim Chang 122(1–2):127–140. https://doi.org/10.1007/s10584-013-0948-4

Bakker M, Bartholomeus R, Ferre T (2013) Groundwater recharge: processes and quantification. Hydrol Earth Syst Sci 17(7):2653–2655. https://doi.org/10.5194/hess-17-2653-2013

Bala G, Duffy P, Taylor K (2008) Impact of geoengineering schemes on the global hydrological cycle. PNAS 105(22):7664–7669. https://doi.org/10.1073/pnas.0711648105

Barnett T, Malone R, Pennell W, Stammer D, Semtner B, Washington W (2004) The effects of climate change on water resources in the west: introduction and overview. Clim Chang 62:1–11. https://doi.org/10.1023/B:CLIM.0000013695.21726.b8

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309. https://doi.org/10.1038/nature04141

Basso B, Giola P, Dumont B, Migliorati MDA, Cammarano D, Pruneddu G, Giunta F (2016) Tradeoffs between maize silage yield and nitrate leaching in a Mediterranean nitrate-vulnerable zone under current and projected climate scenarios. PLoS One 11(1):e0146360. https://doi.org/10.1371/journal.pone.0146360

Beniston M, Stephenson DB, Christensen OB, Ferro CA, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Chang 81:71–95. https://doi.org/10.1007/s10584-006-9226-z

Bergström S, Carlsson B, Gardelin M, Lindström G, Pettersson A, Rummukainen M (2001) Climate change impacts on runoff in Sweden: assessments by global climate models, dynamical downscaling and hydrological modelling. Clim Res 16(2):101–112. https://doi.org/10.3354/cr016101

Bernstein L, Bosch P, Canziani O, Chen Z, Christ R, Riahi K (2008) IPCC, 2007: climate change 2007—synthesis report IPCC. IPCC, Geneva

Bertrand G, Celle-Jeanton H, Laj P, Rangognio J, Chazot G (2008) Rainfall chemistry: long range transport versus below cloud scavenging—a two-year study at an inland station (Opme, France). J Atmos Chem 60(3):253–271. https://doi.org/10.1007/s10874-009-9120-y

Betts R, Cox P, Collins M, Harris P, Huntingford C, Jones C (2004) The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. Theor Appl Climatol 78:157–175. https://doi.org/10.1007/s00704-004-0050-y

Betts RA, Boucher O, Collins M, Cox PM, Falloon PD, Gedney N, Hemming DL, Huntingford C, Jones CD, Sexton DM (2007) Projected increase in continental runoff due to plant responses to increasing carbon dioxide. Nature 448:1037–1041. https://doi.org/10.1038/nature06045

Bloomfield J, Marchant B (2013) Analysis of groundwater drought building on the standardised precipitation index approach. Hydrol Earth Syst Sci 17(12):4769–4787. https://doi.org/10.5194/hess-17-4769-2013

Bloomfield J, Williams R, Gooddy D, Cape J, Guha P (2006) Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater: a UK perspective. Sci Total Environ 369(1–3):163–177. https://doi.org/10.1016/j.scitotenv.2006.05.019

Bloomfield JP, Marchant BP, Bricker SH, Morgan RB (2015) Regional analysis of groundwater droughts using hydrograph classification. Hydrol Earth Syst Sci 19(10):4327–4344. https://doi.org/10.5194/hess-19-4327-2015

Bolch T, Kulkarni A, Kääb A, Huggel C, Paul F, Cogley J, Frey H, Kargel JS, Fujita K, Scheel M (2012) The state and fate of Himalayan glaciers. Science 336(6079):310–314. https://doi.org/10.1126/science.1215828

Bonte M, Zwolsman JJ (2010) Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. Water Res 44:4411–4424. https://doi.org/10.1016/j.watres.2010.06.004

Bopp L, Le Quéré C, Heimann M, Manning AC, Monfray P (2002) Climate-induced oceanic oxygen fluxes: implications for the contemporary carbon budget. Global Biogeochem Cy 16(2). https://doi.org/10.1029/2001GB001445

Boyer JN, Dailey SK, Gibson PJ, Rogers MT, Mir-Gonzalez D (2006) The role of dissolved organic matter bioavailability in promoting phytoplankton blooms in Florida Bay. Hydrobiologia 569(1):71–85. https://doi.org/10.1007/s10750-006-0123-2

Brooks JP, Adeli A, Read JJ, McLaughlin MR (2009) Rainfall simulation in greenhouse microcosms to assess bacterial-associated runoff from land-applied poultry litter. J Environ Qual 38(1):218–229. https://doi.org/10.2134/jeq2008.0029

Cashman A, Nagdee MR (2017) Impacts of climate change on settlements and infrastructure in the coastal and marine environments of Caribbean small island developing states (SIDS). Sci Rev 2017: 155–173

Chaturvedi RK, Kulkarni A, Karyakarte Y, Joshi J, Bala G (2014) Glacial mass balance changes in the Karakoram and Himalaya based on CMIP5 multi-model climate projections. Clim Chang 123(2):315–328. https://doi.org/10.1007/s10584-013-1052-5

Chen F, Yuan YJ, Chen FH, Wei WS, Yu SL, Chen XJ, Fan ZA, Zhang RB, Zhang TW, Shang HM, Qin L (2013) A 426-year drought history for Western Tian Shan, Central Asia, inferred from tree rings and linkages to the North Atlantic and Indo–West Pacific Oceans. The Holocene. 23(8):1095–1104. https://doi.org/10.1177/0959683613483614

Chou C, Neelin JD (2004) Mechanisms of global warming impacts on regional tropical precipitation. J Clim 17:2688–2701. https://doi.org/10.1175/1520-0442(2004)017<2688:MOGWIO>2.0.CO;2

Christensen JH, Kanikicharla KK, Marshall G, Turner J (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1217–1308

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1137–1216

Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, ChHabra A, Defries R, Galloway J, Heimann M (2014) Carbon and other biogeochemical cycles. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 465–570

Cocco V, Joos F, Steinacher M, Frölicher T, Bopp L, Dunne J, Gehlen M, Heinze C, Orr J, Oschlies A (2013) Oxygen and indicators of stress for marine life in multi-model global warming projections. Biogeosciences 10(3):1849–1868. https://doi.org/10.5194/bg-10-1849-2013

Collins M, An S-I, Cai W, Ganachaud A, Guilyardi E, Jin F-F, Jochum M, Lengaigne M, Power S, Timmermann A (2010) The impact of global warming on the tropical Pacific Ocean and El Niño. Nat Geosci 3: 391–397. https://doi.org/10.1038/ngeo868

Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ, Wehner M (2013) Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Cook BI, Ault TR, Smerdon JE (2015) Unprecedented 21st century drought risk in the American southwest and central plains. Sci Adv 1(1):e1400082. https://doi.org/10.1126/sciadv.1400082

Cotterman KA, Kendall AD, Basso B, Hyndman DW (2018) Groundwater depletion and climate change: future prospects of crop production in the central High Plains aquifer. Clim Chang 146(1–2): 187–200. https://doi.org/10.1007/s10584-017-1947-7

Crosbie RS, Dawes WR, Charles SP, Mpelasoka FS, Aryal S, Barron O, Summerell GK (2011) Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. Geophys Res Lett 38(11). https://doi.org/10.1029/2011GL047657

Crosbie RS, McCallum JL, Walker GR, Chiew FH (2010) Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. Hydrogeol J 18(7):1639–1656. https://doi.org/10.1007/s10040-010-0625-x

Crosbie RS, Pickett T, Mpelasoka FS, Hodgson G, Charles SP, Barron OV (2013) An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. Clim Chang 117(1–2):41–53. https://doi.org/10.1007/s10584-012-0558-6

Cure JD, Acock B (1986) Crop responses to carbon dioxide doubling: a literature survey. Agric For Meteorol 38:127–145. https://doi.org/10.1016/0168-1923(86)90054-7

Dai A (2011) Drought under global warming: a review. WIREs Clim Chang 2(1):45–65. https://doi.org/10.1002/wcc.81

Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Chang 3:52–58. https://doi.org/10.1038/nclimate1633

Dams J, Salvadore E, Van Daele T, Ntegeka V, Willems P, Batelaan O (2012) Spatio-temporal impact of climate change on the groundwater system, Hydrol Earth Syst Sc. 16: 1517-1531. https://doi.org/10.5194/hess-16-1517-2012

De Vita P, Allocca V, Manna F, Fabbrocino S (2012) Coupled decadal variability of the North Atlantic oscillation, regional rainfall and karst spring discharges in the Campania region (southern Italy). Hydrol Earth Syst Sci 16(5):1389–1399

De Wit M, Stankiewicz J (2006) Changes in surface water supply across Africa with predicted climate change. Science 311(5679):1917–1921. https://doi.org/10.1126/science.1119929

Deser C, Phillips A, Bourdette V, Teng H (2012) Uncertainty in climate change projections: the role of internal variability. Clim Dyn 38(3–4):527–546. https://doi.org/10.1007/s00382-010-0977-x

Destouni G, Darracq A (2009) Nutrient cycling and N_2O emissions in a changing climate: the subsurface water system role. Environ Res Lett 4(3):035008. https://doi.org/10.1088/1748-9326/4/3/035008

Döll P (2002) Impact of climate change and variability on irrigation requirements: a global perspective. Clim Chang 54(3):269–293. https://doi.org/10.1023/A:1016124032231

Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ Res Lett 4:035006. https://doi.org/10.1088/1748-9326/4/3/035006

Dunn S, Brown I, Sample J, Post H (2012) Relationships between climate, water resources, land use and diffuse pollution and the significance of uncertainty in climate change. J Hydrol 434:19–35. https://doi.org/10.1016/j.jhydrol.2012.02.039

Eaton JG, Scheller RM (1996) Effects of climate warming on fish thermal habitat in streams of the United States. Limnol Oceanogr 41(5): 1109–1115. https://doi.org/10.4319/lo.1996.41.5.1109

Eckhardt K, Ulbrich U (2003) Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. J Hydro 284(1–4):244–252. https://doi.org/10.1016/j.jhydrol.2003.08.005

Elimelech M, Phillip WA (2011) The future of seawater desalination: energy, technology, and the environment. Science 333(6043):712–717. https://doi.org/10.1126/science.1200488

Essaid HI, Caldwell RR (2017) Evaluating the impact of irrigation on surface water–groundwater interaction and stream temperature in an agricultural watershed. Sci Total Environ 599:581–596. https://doi.org/10.1016/j.scitotenv.2017.04.205

Evan AT, Kossin JP, Ramanathan V (2011) Arabian Sea tropical cyclones intensified by emissions of black carbon and other aerosols. Nature 479:94–97. https://doi.org/10.1038/nature10552

Evans C, Monteith D, Cooper D (2005) Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. Environ Pollut 137(1):55–71. https://doi.org/10.1016/j.envpol.2004.12.031

Falloon P, Betts R (2010) Climate impacts on European agriculture and water management in the context of adaptation and mitigation: the importance of an integrated approach. Sci Total Environ 408(23): 5667–5687. https://doi.org/10.1016/j.scitotenv.2009.05.002

FAO (2005) AQUASTAT Information System on Water and Agriculture: Online database. In: Food and Agriculture Organization of the United Nations (FAO). Land and Water Development Division, Rome www.fao.org/nr/water/aquastat/maps/index.stm

Favis-Mortlock D, Boardman J (1995) Nonlinear responses of soil erosion to climate change: a modelling study on the UK South Downs. Catena 25(1–4):365–387. https://doi.org/10.1016/0341-8162(95)00018-N

Feng D, Zheng Y, Mao Y, Zhang A, Wu B, Li J, Tian Y, Wu X (2018) An integrated hydrological modeling approach for detection and attribution of climatic and human impacts on coastal water resources. J Hydrol 557:305–320. https://doi.org/10.1016/j.jhydrol.2017.12.041

Ferguson G, Gleeson T (2012) Vulnerability of coastal aquifers to groundwater use and climate change. Nat Clim Chang 2:342–345. https://doi.org/10.1038/nclimate1413

Ferguson IM, Maxwell RM (2010) Role of groundwater in watershed response and land surface feedbacks under climate change. Water Resour Res 46(10). https://doi.org/10.1029/2009WR008616

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fisher 17(4):581–613. https://doi.org/10.1007/s11160-007-9059-5

Flebbe PA (1993) Comment on Meisner (1990): Effect of climatic warming on the southern margins of the native range of brook trout, Salvelinus fontinalis. Can J Fish Aquat Sci 50(4):883–884. https://doi.org/10.1139/f90-122

Fleming SW, Quilty EJ (2006) Aquifer responses to El Niño–Southern Oscillation, Southwest British Columbia. Groundwater 44(4):595–599. https://doi.org/10.1111/j.1745-6584.2006.00187.x

Foster S, Garduno H, Evans R, Olson D, Tian Y, Zhang W, Han Z (2004) Quaternary aquifer of the North China plain: assessing and achieving groundwater resource sustainability. Hydrogeol J 12(1):81–93. https://doi.org/10.1007/s10040-003-0300-6

Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int J Climatol 27(12):1547–1578. https://doi.org/10.1002/joc.1556

Friedlingstein P, Meinshausen M, Arora VK, Jones CD, Anav A, Liddicoat SK, Knutti R (2014) Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. J Clim 27(2):511–526. https://doi.org/10.1175/JCLI-D-12-00579.1

Fu C, Jiang Z, Guan Z, He J, Xu Zf (2008) Regional climate studies of China. Springer, Heidelberg, Germany

Fu FX, Warner ME, Zhang Y, Feng Y, Hutchins DA (2007) Effects of increased temperature and CO_2 on photosynthesis, growth, and elemental ratios in marine Synechococcus and Prochlorococcus (cyanobacteria). J Phycol 43(2):485–496. https://doi.org/10.1111/j.1529-8817.2007.00355.x

Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N (2014) Betting on negative emissions. Nat Clim Chang 4:850–853. https://doi.org/10.1038/nclimate2392

García-Ruiz JM, López-Moreno JI, Vicente-Serrano SM, Lasanta–Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario, Earth-Sci Rev 105(3–4):121–139. https://doi.org/10.1016/j.earscirev.2011.01.006

Gerten D, Lucht W, Ostberg S, Heinke J, Kowarsch M, Kreft H, Kundzewicz ZW, Rastgooy J, Warren R, Schellnhuber HJ (2013) Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. Environ Res Lett 8(3):034032. https://doi.org/10.1088/1748-9326/8/3/034032

Gibble CM, Kudela RM (2014) Detection of persistent microcystin toxins at the land–sea interface in Monterey Bay, California. Harmful Algae 39:146–153. https://doi.org/10.1016/j.hal.2014.07.004

Gilbert JM, Maxwell RM, Gochis DJ (2017) Effects of water-table configuration on the planetary boundary layer over the San Joaquin River watershed, California. J Hydrometeorol 18(5):1471–1488. https://doi.org/10.1175/JHM-D-16-0134.1

Giordano M (2009) Global groundwater? Issues and solutions. Annu Rev Environ Resour 34:153–178. https://doi.org/10.1146/annurev.environ.030308.100251

Giorgetta MA, Jungclaus J, Reick CH, Legutke S, Bader J, Böttinger M, Brovkin V, Crueger T, Esch M, Fieg K (2013) Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the coupled model Intercomparison project phase 5. J Adv Model Earth Sy 5:572–597. https://doi.org/10.1002/jame.20038

Giorgi F, Bi X (2005) Updated regional precipitation and temperature changes for the 21st century from ensembles of recent AOGCM simulations. Geophys Res Lett 32(21). https://doi.org/10.1029/2005GL024288

Gleick PH (1998) Water in crisis: paths to sustainable water use. Ecol Appl 8:571–579. https://doi.org/10.1890/1051-0761(1998)008[0571:WICPTS]2.0.CO;2

Goderniaux P, Brouyère S, Fowler HJ, Blenkinsop S, Therrien R, Orban P, Dassargues A (2009) Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. J Hydrol 373(1–2):122–138. https://doi.org/10.1016/j.jhydrol.2009.04.017

Golombek R, Kittelsen SA, Haddeland I (2012) Climate change: impacts on electricity markets in Western Europe. Clim Chang 113(2):357–370. https://doi.org/10.1007/s10584-011-0348-6

Gordon LJ, Peterson GD, Bennett EM (2008) Agricultural modifications of hydrological flows create ecological surprises. Trends Ecol Evol 23(4):211–219. https://doi.org/10.1016/j.tree.2007.11.011

Gosling SN, Arnell NW (2016) A global assessment of the impact of climate change on water scarcity. Clim Chang 134(3):371–385. https://doi.org/10.1007/s10584-013-0853-x

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan M, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314(5804):1442–1445. https://doi.org/10.1126/science.1132027

Gooddy DC, Stuart ME, Lapworth DJ, Chilton PJ, Bishop S, Cachandt G, Knapp M, Pearson T (2005) Pesticide pollution of the Triassic Sandstone aquifer of South Yorkshire. Q J Eng Geol Hydrogeol 38(1):53–63. https://doi.org/10.1144/1470-9236/04-012

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: impacts of climate change on groundwater. J Hydrol 405(3–4):532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Groffman PM, Gold AJ, Addy K (2000) Nitrous oxide production in riparian zones and its importance to national emission inventories. Chemosphere-Global Chang Sci 2(3–4):291–299. https://doi.org/10.1016/S1465-9972(00)00018-0

Gurdak JJ, Hanson RT, McMahon PB, Bruce BW, McCray JE, Thyne GD, Reedy RC (2007) Climate variability controls on unsaturated water and chemical movement, High Plains Aquifer, USA. Vadose Zone J 6(3):533–547. https://doi.org/10.2136/vzj2006.0087

Hallegraeff GM (2010) Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. J Phycol 46(2):220–235. https://doi.org/10.1111/j.1529-8817.2010.00815.x

Hall-Spencer JM, Rodolfo-Metalpa R, Martin S, Ransome E, Fine M, Turner SM, Rowley SJ, Tedesco D, Buia M-C (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454:96–99. https://doi.org/10.1038/nature07051

Hamududu B, Killingtveit A (2012) Assessing climate change impacts on global hydropower. Energies 5(2):305–322. https://doi.org/10.3390/en5020305

Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, Hijioka Y, Kainuma M, Kanamori Y, Masui T, Takahashi K (2013) A global water scarcity assessment under shared socio-economic pathways. Hydrol Earth Syst Sci 17(7):2393–2413. https://doi.org/10.5194/hess-17-2393-2013

Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, Masson-Delmotte V, Russell G, Tselioudis G, Cao J, Rignot E (2016) Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. Atmos Chem Phys 16:3761–3812. https://doi.org/10.5194/acp-16-3761-2016

Hanson RT, Flint LE, Flint AL, Dettinger MD, Faunt CC, Cayan D, Schmid W (2012) A method for physically based model analysis of conjunctive use in response to potential climate changes. Water Resour Res 48(6). https://doi.org/10.1029/2011WR010774

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bull Am Meteorol Soc 90(8):1095–1107. https://doi.org/10.1175/2009BAMS2607.1

Hayashi A, Akimoto K, Tomoda T, Kii M (2013) Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population. Mitig Adapt Strat Glob Change 18(5):591–618. https://doi.org/10.1007/s11027-012-9377-3

Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. J Clim 19:5686–5699. https://doi.org/10.1175/JCLI3990.1

Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RS, Marzeion B, Fettweis X, Ionescu C, Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. PNAS 111(9):3292–3297. https://doi.org/10.1073/pnas.1222469111

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S (2013) Global flood risk under climate change. Nat Clim Chang 3:816–821. https://doi.org/10.1038/nclimate1911

Hiscock K, Grischek T (2002) Attenuation of groundwater pollution by bank filtration. J Hydrol 266(3–4):139–144. https://doi.org/10.1016/S0022-1694(02)00158-0

Holman I, Tascone D, Hess T (2009) A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management. Hydrogeol J 17:1629–1641. https://doi.org/10.1007/s10040-009-0457-8

Holman IP, Rivas-Casado M, Bloomfield JP, Gurdak JJ (2011) Identifying non-stationary groundwater level response to North Atlantic Ocean-atmosphere teleconnection patterns using wavelet coherence. Hydrogeol J 19:1269–1278. https://doi.org/10.1007/s10040-011-0755-9

Holman IP, Allen D, Cuthbert M, Goderniaux P (2012) Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeol J 20(1):1–4. https://doi.org/10.1007/s10040-011-0805-3

Hoppe-Jones C, Oldham G, Drewes JE (2010) Attenuation of total organic carbon and unregulated trace organic chemicals in US riverbank filtration systems. Water Res 44(15):4643–4659. https://doi.org/10.1016/j.watres.2010.06.022

Howarth R, Swaney D, Boyer E, Marino R, Jaworski N, Goodale C (2006) The influence of climate on average nitrogen export from large watersheds in the northeastern United States. In: Martinelli LA, Howarth RW (eds) Nitrogen cycling in the Americas: natural and anthropogenic influences and controls. Springer, Dordrecht, The Netherlands, pp 163–186

Hsu PC, Li T, Murakami H, Kitoh A (2013) Future change of the global monsoon revealed from 19 CMIP5 models. J Geophys Res-Atmos 118(3):1247–1260. https://doi.org/10.1002/jgrd.50145

Hu B, Teng Y, Zhai Y, Zuo R, Li J, Chen H (2016) Riverbank filtration in China: a review and perspective. J Hydrol 541:914–927. https://doi.org/10.1016/j.jhydrol.2016.08.004

Huntington JL, Niswonger RG (2012) Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: an integrated modeling approach. Water Resour Res 48(11). https://doi.org/10.1029/2012WR012319

Huntington TG (2006) Evidence for intensification of the global water cycle: review and synthesis. J Hydrol 319(1–4):83–95. https://doi.org/10.1016/j.jhydrol.2005.07.003

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manag 21(5):775–788. https://doi.org/10.1007/s11269-006-9111-6

Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers. Science 328(5984):1382–1385. https://doi.org/10.1126/science.1183188

IPCC (2013) Summary for policymakers Climate Change 2013: The Physical Science Basis. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York

Ito A (2007) Simulated impacts of climate and land-cover change on soil erosion and implication for the carbon cycle, 1901 to 2100. Geophys Res Lett 34(9):L09403. https://doi.org/10.1029/2007GL029342

Jackson CR, Meister R, Prudhomme C (2011) Modelling the effects of climate change and its uncertainty on UK chalk groundwater resources from an ensemble of global climate model projections. J

Hydrol 399(1–2):12–28. https://doi.org/10.1016/j.jhydrol.2010.12.028

Jang S, Hamm S-Y, Yoon H, Kim G-B, Park J-H, Kim M (2015) Predicting long-term change of groundwater level with regional climate model in South Korea. Geosci J 19(3):503–513. https://doi.org/10.1007/s12303-015-0002-9

Jeppesen E, Kronvang B, Olesen JE, Audet J, Søndergaard M, Hoffmann CC, Andersen HE, Lauridsen TL, Liboriussen L, Larsen SE (2011) Climate change effects on nitrogen loading from cultivated catchments in Europe: implications for nitrogen retention, ecological state of lakes and adaptation. Hydrobiologia 663(1):1–21. https://doi.org/10.1007/s10750-010-0547-6

Jiang FQ, Zhu C, Mu GJ, Hu RJ, Meng QX (2005) Magnification of flood disasters and its relation to regional precipitation and local human activities since the 1980s in Xinjiang, northwestern China. Nat Hazards 36(3):307–330. https://doi.org/10.1007/s11069-005-0977-z

Jiang X, Niu GY, Yang ZL (2009) Impacts of vegetation and groundwater dynamics on warm season precipitation over the central United States. J Geophys Res Atmos 114(D6). https://doi.org/10.1029/2008JD010756

Jiménez-Cisneros B, Oki T, Arnell N, Benito G, Cogley J, Döll P, Jiang T, Mwakalila S (2014) Freshwater resources. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, et al. (eds) Climate change 2014: impacts, adaptation, and vulnerability, part a: global and sectoral aspects. Contribution of Working Group II to the fifth assessment of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp 229–269

Johansson O, Aimbetov I, Jarsjö J (2009) Variation of groundwater salinity in the partially irrigated Amudarya River delta, Uzbekistan. J Marine Syst 76:287–295. https://doi.org/10.1016/j.jmarsys.2008.03.017

Jönson R (2017) Groundwater drought explained by climate, hydrogeological and environmental controls in southern Sweden. MSC Thesis,, Univ. of Gothenburg, Sweden

Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). J Hydrol 338(3–4):237–250. https://doi.org/10.1016/j.jhydrol.2007.02.036

Kahinda JM, Taigbenu A, Boroto R (2010) Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. Phys Chem Earth A/B/C 35(13–14):742–751. https://doi.org/10.1016/j.pce.2010.07.004

Kahru M, Elmgren R (2014) Multidecadal time series of satellite-detected accumulations of cyanobacteria in the Baltic Sea. Biogeosciences 11(13):3619–3633. https://doi.org/10.5194/bg-11-3619-2014

Kaste Ø, Wright R, Barkved L, Bjerkeng B, Engen-Skaugen T, Magnusson J, Sælthun N (2006) Linked models to assess the impacts of climate change on nitrogen in a Norwegian river basin and fjord system. Sci Total Environ 365(1–3):200–222. https://doi.org/10.1016/j.scitotenv.2006.02.035

Kingston DG, Todd MC, Taylor RG, Thompson JR, Arnell NW (2009) Uncertainty in the estimation of potential evapotranspiration under climate change. Geophys Res Lett 36(20):L20403. https://doi.org/10.1029/2009GL040267f

Kitoh A, Endo H, Krishna Kumar K, Cavalcanti IF, Goswami P, Zhou T (2013) Monsoons in a changing world: a regional perspective in a global context. J Geophys Res Atmos 118(8):3053–3065. https://doi.org/10.1002/jgrd.50258

Kløve B, Ala-Aho P, Bertrand G, Gurdak JJ, Kupfersberger H, Kværner J, Muotka T, Mykrä H, Preda E, Rossi P (2014) Climate change impacts on groundwater and dependent ecosystems. J Hydrol 518:250–266. https://doi.org/10.1016/j.jhydrol.2013.06.037

Knutson T, Tuleya R (1999) Increased hurricane intensities with CO_2-induced warming as simulated using the GFDL hurricane prediction system. Clim Dynam 15(7):503–519. https://doi.org/10.1007/s003820050296

Knutson TR, McBride JL, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin JP, Srivastava A, Sugi M (2010) Tropical cyclones and climate change. Nat Geosci 3:157–163. https://doi.org/10.1038/ngeo779

Koirala S, Hirabayashi Y, Mahendran R, Kanae S (2014) Global assessment of agreement among streamflow projections using CMIP5 model outputs. Environ Res Lett 9:064017. https://doi.org/10.1088/1748-9326/9/6/064017

Konzmann M, Gerten D, Heinke J (2013) Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. Hydrol Sci J 58(1):88–105. https://doi.org/10.1080/02626667.2013.746495

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen D, Strauss BH, Tebaldi C (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future 2(8):383–406. https://doi.org/10.1002/2014EF000239

Kurylyk BL, MacQuarrie KT (2013) The uncertainty associated with estimating future groundwater recharge: a summary of recent research and an example from a small unconfined aquifer in a northern humid-continental climate. J Hydrol 492(7):244–253. https://doi.org/10.1016/j.jhydrol.2013.03.043

Kuss AJM, Gurdak JJ (2014) Groundwater level response in US principal aquifers to ENSO, NAO, PDO, and AMO. J Hydrol 519:1939–1952. https://doi.org/10.1016/j.jhydrol.2014.09.069

Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. Crit Rev Plant Sci 17(4):319–464. https://doi.org/10.1080/07352689891304249

Leung LR, Huang M, Qian Y, Liang X (2011) Climate–soil–vegetation control on groundwater table dynamics and its feedbacks in a climate model. Clim Dynam 36(1–2):57–81. https://doi.org/10.1007/s00382-010-0746-x

Li Q, Li P, Li H, Yu M (2015) Drought assessment using a multivariate drought index in the Luanhe River basin of northern China. Stoch Env Res Risk A 29(6):1509–1520. https://doi.org/10.1007/s00477-014-0982-4

Manabe S, Wetherald RT, Milly P, Delworth TL, Stouffer RJ (2004) Century-scale change in water availability: CO_2-quadrupling experiment. Clim Chang 64(1–2):59–76. https://doi.org/10.1023/B:CLIM.0000024674.37725.ca

Matear R, Hirst A, McNeil B (2000) Changes in dissolved oxygen in the Southern Ocean with climate change. Geochem Geophy Geosy 1(11):2000GC000086. https://doi.org/10.1029/2000GC000086

Matear RJ, Hirst AC (2003) Long-term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming. Glob Biogeochem Cycles 17(4). https://doi.org/10.1029/2002GB001997

Maxwell RM, Condon LE (2016) Connections between groundwater flow and transpiration partitioning. Science 353(6297):377–380. https://doi.org/10.1126/science.aaf7891

Maxwell RM, Kollet SJ (2008) Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nat Geosci 1(10):665–669. https://doi.org/10.1038/ngeo315

Maxwell RM, Putti M, Meyerhoff S, Delfs JO, Ferguson IM, Ivanov V, Kim J, Kolditz O, Kollet SJ, Kumar M (2014) Surface-subsurface model intercomparison: a first set of benchmark results to diagnose integrated hydrology and feedbacks. Water Resour Res 50(2):1531–1549. https://doi.org/10.1002/2013WR013725

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, American Meteorological Society, Boston, pp 179–183

Meisner JD (1990) Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. Can J Fish Aquat Sci 47(6):1065–1070. https://doi.org/10.1139/f90-122

Meixner T, Manning AH, Stonestrom DA, Allen DM, Ajami H, Blasch KW, Brookfield AE, Castro CL, Clark JF, Gochis DJ (2016) Implications of projected climate change for groundwater recharge in the western United States. J Hydrol 534:124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

Mendicino G, Senatore A, Versace P (2008) A groundwater resource index (GRI) for drought monitoring and forecasting in a Mediterranean climate. J Hydrol 357(3–4):282–302. https://doi.org/10.1016/j.jhydrol.2008.05.005

Merz R, Parajka J, Blöschl G (2011) Time stability of catchment model parameters: implications for climate impact analyses. Water Resour Res 47(2). doi https://doi.org/10.1029/2010WR009505

Mileham L, Taylor RG, Todd M, Tindimugaya C, Thompson J (2009) The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment: sensitivity of projections to rainfall intensity. Hydrol Sci J 54(4):727–738. https://doi.org/10.1623/hysj.54.4.727

Min S-K, Zhang X, Zwiers FW, Hegerl GC (2011) Human contribution to more-intense precipitation extremes. Nature 470:378–381. https://doi.org/10.1038/nature09763

Missimer TM, Ghaffour N, Dehwah AH, Rachman R, Maliva RG, Amy G (2013) Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics. Desalination 322:37–51. https://doi.org/10.1016/j.desal.2013.04.021

Mitchell JF, Wilson C, Cunnington W (1987) On CO_2 climate sensitivity and model dependence of results. Q J Roy Meteor Soc 113(475):293–322. https://doi.org/10.1002/qj.49711347517

Moeck C, Brunner P, Hunkeler D (2016) The influence of model structure on groundwater recharge rates in climate-change impact. Hydrogeol J 24(5):1171–1184. https://doi.org/10.1007/s10040-016-1367-1

Molina-Navarro E, Andersen HE, Nielsen A, Thodsen H, Trolle D (2018) Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: a modelling approach in the Odense Fjord catchment (Denmark). Sci Total Environ 621:253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251

Moore SK, Mantua NJ, Hickey BM, Trainer VL (2009) Recent trends in paralytic shellfish toxins in Puget Sound: relationships to climate, and capacity for prediction of toxic events. Harmful Algae 8(3):463–477. https://doi.org/10.1016/j.hal.2008.10.003

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. https://doi.org/10.1038/nature08823

Motlagh MS, Ghasemieh H, Talebi A, Abdollahi K (2017) Identification and analysis of drought propagation of groundwater during past and future periods. Water Resour Manag 31(1):109–125. https://doi.org/10.1007/s11269-016-1513-5

Muga HE, Mihelcic JR (2008) Sustainability of wastewater treatment technologies. J Environ Manag 88(3):437–447. https://doi.org/10.1016/j.jenvman.2007.03.008

Murdoch PS, Baron JS, Miller TL (2000) Potential effects of climate change on surface-water quality in north america. J Am Water Resour As 36:347–366. https://doi.org/10.1111/j.1752-1688.2000.tb04273.x

Nalbantis I, Tsakiris G (2009) Assessment of hydrological drought revisited. Water Resour Manag 23(5):881–897. https://doi.org/10.1007/s11269-008-9305-1

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520. https://doi.org/10.1126/science.1185782

Nick FM, Vieli A, Andersen ML, Joughin I, Payne A, Edwards TL, Pattyn F, van de Wal RS (2013) Future sea-level rise from Greenland's main outlet glaciers in a warming climate. Nature 497:235–238. https://doi.org/10.1038/nature12068

Nishitani L, Chew KK (1984) Recent developments in paralytic shellfish poisoning research. Aquaculture 39(1–4):317–329. https://doi.org/10.1016/0044-8486(84)90274-6

NOAA (National Centers for Environmental Information) (2017) State of the climate: global climate report for May 2017. https://www.ncdc.noaa.gov/sotc/global/201705; www.esrl.noaa.gov. Accessed September 26, 2017

Noyes PD, Lema SC (2015) Forecasting the impacts of chemical pollution and climate change interactions on the health of wildlife. Curr Zool 61(4):669–89. https://doi.org/10.1093/czoolo/61.4.669

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN, Levin ED (2009) The toxicology of climate change: environmental contaminants in a warming world. Environ Int 35(6):971–986. https://doi.org/10.1016/j.envint.2009.02.006

Obersteiner M, Azar C, Kossmeier S, Mechler R, Moellersten K, Nilsson S, Read P, Yamagata Y, Yan J (2001) Managing climate risk. Science 294(5543):786–787

Oelkers EH, Hering JG, Zhu C (2011) Water: is there a global crisis? Elements 7(3):157–162. https://doi.org/10.2113/gselements.7.3.157

Oki T, Kanae S (2006) Global hydrological cycles and world water resources. Science 313(5790):1068–1072. https://doi.org/10.1126/science.1128845

Ordens CM, Post VE, Werner AD, Hutson JL (2014) Influence of model conceptualisation on one-dimensional recharge quantification: Uley South, South Australia. Hydrogeol J 22(4):795–805. https://doi.org/10.1007/s10040-014-1100-x

Oschlies A, Schulz KG, Riebesell U, Schmittner A (2008) Simulated 21st century's increase in oceanic suboxia by CO_2-enhanced biotic carbon export. Global Biogeochem Cy 22(4):GB4008. https://doi.org/10.1029/2007GB003147

Oude Essink GHP, Van Baaren ES, De Louw PG (2010) Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. Water Resour Res 46(10). https://doi.org/10.1029/2009WR008719

Paerl HW, Huisman J (2009) Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. Env Microbiol Rep 1(1):27–37. https://doi.org/10.1111/j.1758-2229.2008.00004.x

Palmer W (1965) Meteorological drought. Weather Bureau Research Paper no. 45, US Department of Commerce, Washington, DC

Pandey DN, Gupta AK, Anderson DM (2003) Rainwater harvesting as an adaptation to climate change. Curr Sci India 85(1):46–59

Park C-K, Byun H-R, Deo R, Lee B-R (2015) Drought prediction till 2100 under RCP 8.5 climate change scenarios for Korea. J Hydrol 526:221–230. https://doi.org/10.1016/j.jhydrol.2014.10.043

Parry M, Canziani O, Palutikof J, van der Linden PJ, Hanson CE (2007) Climate change 2007: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge

Paul VJ (2008) Global warming and cyanobacterial harmful algal blooms. In: Hudnell HK (ed) Cyanobacterial harmful algal blooms: state of the science and research needs. Advances in Experimental Medicine and Biology, vol 619. Springer, New York, pp 239–258

Peñate B, García-Rodríguez L (2012) Current trends and future prospects in the design of seawater reverse osmosis desalination technology. Desalination 284:1–8. https://doi.org/10.1016/j.desal.2011.09.010

Peperzak L (2003) Climate change and harmful algal blooms in the North Sea. Acta Oecol 24:S139–S144. https://doi.org/10.1016/S1146-609X(03)00009-2

Plattner GK, Joos F, Stocker TF (2002) Revision of the global carbon budget due to changing air-sea oxygen fluxes. Global Biogeochem CY 16(4):43-1–43-12. https://doi.org/10.1029/2001GB001746

Portmann FT, Döll P, Eisner S, Flörke M (2013) Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. Environ Res Lett 8(2):024023. https://doi.org/10.1088/1748-9326/8/2/024023

Postel SL, Daily GC, Ehrlich PR (1996) Human appropriation of renewable fresh water. Science 271:785–788. https://doi.org/10.1126/science.271.5250.785

Prudhomme C, Davies H (2009) Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK, part 1: baseline climate. Clim Chang 93(1–2):177–195. https://doi.org/10.1007/s10584-008-9464-3

Prudhomme C, Reynard N, Crooks S (2002) Downscaling of global climate models for flood frequency analysis: where are we now? Hydrol Process 16(6):1137–1150. https://doi.org/10.1002/hyp.1054

Pulido-Velazquez M, Peña-Haro S, García-Prats A, Mocholi-Almudever A, Henriquez-Dole L, Macian-Sorribes H, Lopez-Nicolas A (2015) Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the Mancha oriental system (Spain). Hydrol Earth Syst Sci 19(4):1677–1693. https://doi.org/10.5194/hess-19-1677-2015

Qin B, Zhu G, Gao G, Zhang Y, Li W, Paerl HW, Carmichael WW (2010) A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management. Environ Manag 45(1):105–112. https://doi.org/10.1007/s00267-009-9393-60

Radić V, Hock R (2011) Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. Nat Geosci 4:91–94. https://doi.org/10.1038/ngeo1052

Radić V, Hock R (2014) Glaciers in the Earth's hydrological cycle: assessments of glacier mass and runoff changes on global and regional scales. Surv Geophys 35(3):813–837. https://doi.org/10.1007/s10712-013-9262-y

Reyes B, Maxwell RM, Hogue TS (2016) Impact of lateral flow and spatial scaling on the simulation of semi-arid urban land surfaces in an integrated hydrologic and land surface model. Hydrol Process 30(8):1192–1207. https://doi.org/10.1002/hyp.10683

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P (2011) RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Clim Chang 109(1-2):33–57. https://doi.org/10.1007/s10584-011-0149-y

Rijsberman FR (2006) Water scarcity: fact or fiction? Agr Water Manage 80(1–3):5–22. https://doi.org/10.1016/j.agwat.2005.07.001

Rogelj J, Meinshausen M, Knutti R (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nat Clim Chang 2:248–253. https://doi.org/10.1038/nclimate1385

Ropelewski CF, Halpert MS (1986) North American precipitation and temperature patterns associated with the El Niño/southern Oscillation (ENSO). Mon Weather Rev 114:2352–2362. https://doi.org/10.1175/1520-0493(1986)114<2352:NAPATP>2.0.CO;2

Sabziparvar A, Mirmasoudi S, Tabari H, Nazemosadat M, Maryanaji Z (2011) ENSO teleconnection impacts on reference evapotranspiration variability in some warm climates of Iran. Int J Climatol 31(11):1710–1723. https://doi.org/10.1002/joc.2187

Sahoo G, Schladow S, Reuter J, Coats R (2011) Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. Stoch Env Res Risk A 25(4):445–456. https://doi.org/10.1007/s00477-010-0414-z

Samaniego L, Kumar R, Breuer L, Chamorro A, Flörke M, Pechlivanidis IG, Schäfer D, Shah H, Vetter T, Wortmann M (2017) Propagation of forcing and model uncertainties on to hydrological drought characteristics in a multi-model century-long experiment in large river basins. Clim Chang 141(3):435–449. https://doi.org/10.1007/s10584-016-1778-y

Sarmiento JL, Hughes TM, Stouffer RJ, Manabe S (1998) Simulated response of the ocean carbon cycle to anthropogenic climate warming. Nature 393:245–249. https://doi.org/10.1038/30455

Savard MM (2016) Groundwater nitrate concentration evolution under climate change and agricultural adaptation scenarios: Prince Edward Island, Canada. Earth Syst Dynam 7(1):183–202. https://doi.org/10.5194/esd-7-183-2016

Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB (2012) Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. PNAS 109(24):9320–9325. https://doi.org/10.1073/pnas.1200311109

Schaefli B, Hingray B, Musy A (2007) Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. Hydrol Earth Syst Sci 11(3):1191–1205. https://doi.org/10.5194/hess-11-1191-2007

Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB, Dankers R, Eisner S, Fekete BM, Colón-González FJ (2014) Multimodel assessment of water scarcity under climate change. PNAS 111(9):3245–3250. https://doi.org/10.1073/pnas.1222460110

Schippers P, Lürling M, Scheffer M (2004) Increase of atmospheric CO_2 promotes phytoplankton productivity. Ecol Lett 7(6):446–451. https://doi.org/10.1111/j.1461-0248.2004.00597.x

Schmittner A, Oschlies A, Matthews HD, Galbraith ED (2008) Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO_2 emission scenario until year 4000 AD. Global Biogeochem Cy 22(1):GB1013. https://doi.org/10.1029/2007GB002953

Scholz G, Quinton JN, Strauss P (2008) Soil erosion from sugar beet in Central Europe in response to climate change induced seasonal precipitation variations. Catena 72(1):91–105. https://doi.org/10.1016/j.catena.2007.04.005

Schwanenberg D, Fan FM, Naumann S, Kuwajima JI, Montero RA, Dos Reis AA (2015) Short-term reservoir optimization for flood mitigation under meteorological and hydrological forecast uncertainty. Water Resour Manag 29(5):1635–1651. https://doi.org/10.1007/s11269-014-0899-1

Segan DB, Murray KA, Watson JE (2016) A global assessment of current and future biodiversity vulnerability to habitat loss–climate change interactions. Global Ecol Conserv 5:12–21. https://doi.org/10.1016/j.gecco.2015.11.002

Seiller G, Anctil F, Perrin C (2012) Multimodel evaluation of twenty lumped hydrological models under contrasted climate conditions. Hydrol Earth Syst Sci 16(4):1171–1189. https://doi.org/10.5194/hess-1116-1171-2012

Seitzinger S, Mayorga E, Bouwman A, Kroeze C, Beusen A, Billen G, Van Drecht G, Dumont E, Fekete B, Garnier J (2010) Global river nutrient export: a scenario analysis of past and future trends. Global Biogeochem Cy 24(4). https://doi.org/10.1029/2009GB003587

Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, Lehner I, Orlowsky B, Teuling AJ (2010) Investigating soil moisture–climate interactions in a changing climate: a review. Earth-Sci Rev 99(3–4):125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M (2012) Changes in climate extremes and their impacts on the natural physical environment: an overview of the IPCC SREX report. EGU General Assembly 2012, Vienna, 22–27 April, 2012

Seneviratne SI, Wilhelm M, Stanelle T, Hurk B, Hagemann S, Berg A, Cheruy F, Higgins ME, Meier A, Brovkin V (2013) Impact of soil moisture-climate feedbacks on CMIP5 projections: first results from the GLACE-CMIP5 experiment. Geophys Res Lett 40(19):5212–5217. https://doi.org/10.1002/grl.50956

Serrat-Capdevila A, Valdés JB, Pérez JG, Baird K, Mata LJ, Maddock T III (2007) Modeling climate change impacts–and uncertainty–on the hydrology of a riparian system: the San Pedro Basin (Arizona/Sonora). J Hydrol 347(1–2):48–66. https://doi.org/10.1016/j.jhydrol.2007.08.028

Shaffer G, Olsen SM, Pedersen JOP (2009) Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels. Nat Geosci 2:105–109. https://doi.org/10.1038/ngeo420

Shah T (2009) Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ Res Lett 4:035005. https://doi.org/10.1088/1748-9326/4/3/035005

Shanafield M, Cook PG (2014) Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: a review of applied methods. J Hydrol 511:518–529. https://doi.org/10.1016/j.jhydrol.2014.01.068

Shang H, Yan J, Zhang X (2011) El Niño–southern oscillation influence on winter maximum daily precipitation in California in a spatial model. Water Resour Res 47(11). https://doi.org/10.1029/2011WR010415

Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim Dyn 31(1):79–105. https://doi.org/10.1007/s00382-007-0340-z

Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coastal Res 19(3):584–599. https://doi.org/10.2307/4299200

Smerdon BD (2017) A synopsis of climate change effects on groundwater recharge. J Hydrol https://doi.org/10.1016/j.jhydrol.2017.09.047

Sophocleous M (2010) Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA: lessons and recommended actions. Hydrogeol J 18(3):559–575. https://doi.org/10.1007/s10040-009-0540-1

Sridhar V, Billah MM, Hildreth JW (2017) Coupled surface and groundwater hydrological modeling in a changing climate. Groundwater. https://doi.org/10.1111/gwat.12610

Stocker BD, Roth R, Joos F, Spahni R, Steinacher M, Zaehle S, Bouwman L, Prentice IC (2013) Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios. Nat Clim Chang 3:666–672. https://doi.org/10.1038/nclimate1864

Straile D, Adrian R (2000) The North Atlantic Oscillation and plankton dynamics in two European lakes: two variations on a general theme. Glob Chang Biol 6(6):663–670. https://doi.org/10.1046/j.1365-2486.2000.00350.x

Sulis M, Williams JL, Shrestha P, Diederich M, Simmer C, Kollet SJ, Maxwell RM (2017) Coupling groundwater, vegetation, and atmospheric processes: a comparison of two integrated models. J Hydrometeorol 118(5):1489–1511. https://doi.org/10.1175/JHM-D-16-0159.1

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. B Am Meteorol Soc 93(4):485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Taylor I, Burke E, McColl L, Falloon P, Harris G, McNeall D (2013a) The impact of climate mitigation on projections of future drought. Hydrol Earth Syst Sci 17(6):2339–2358. https://doi.org/10.5194/hess-17-2339-2013

Taylor RG, Scanlon B, Döll P, Rodell M, Van Beek R, Wada Y, Longuevergne L, Leblanc M, Famiglietti JS, Edmunds M (2013b) Ground water and climate change. Nat Clim Chang 3:322–329. https://doi.org/10.1038/nclimate1744

Tebaldi C, Knutti R (2007) The use of the multi-model ensemble in probabilistic climate projections. Philo Trans Royal Soc London A 365:2053–2075. https://doi.org/10.1098/rsta.2007.2076

Tchobanoglous G, Burton FL, Stensel HD (2003) Wastewater engineering treatment and reuse Boston. McGraw-Hill Higher Education, US

Theesfeld I (2010) Institutional challenges for national groundwater governance: policies and issues. Groundwater. 48(1):131–142. https://doi.org/10.1111/j.1745-6584.2009.00624.x

Thomas T, Jaiswal R, Nayak P, Ghosh N (2015) Comprehensive evaluation of the changing drought characteristics in Bundelkhand region of Central India. Meteorog Atmos Phys 127(2):163–182. https://doi.org/10.1007/s00703-014-0361-1

Thorne O, Fenner R (2011) The impact of climate change on reservoir water quality and water treatment plant operations: a UK case study. Water Environ J 25(1):74–87. https://doi.org/10.1111/j.1747-6593.2009.00194.x

Touma D, Ashfaq M, Nayak MA, Kao S-C, Diffenbaugh NS (2015) A multi-model and multi-index evaluation of drought characteristics in the 21st century. J Hydrol 526:196–207. https://doi.org/10.1016/j.jhydrol.2014.12.011

Tremblay L, Larocque M, Anctil F, Rivard C (2011) Teleconnections and interannual variability in Canadian groundwater levels. J Hydrol 410(3–4):178–188. https://doi.org/10.1016/j.jhydrol.2011.09.013

Trenberth KE (2011) Changes in precipitation with climate change. Clim Res 47(1/2):123–138. https://doi.org/10.3354/cr00953

Trenberth KE, Dai A, Van Der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global warming and changes in drought. Nat Clim Chang 4:17–22. https://doi.org/10.1038/nclimate2067

Van der Bruggen B, Vandecasteele C, Van Gestel T, Doyen W, Leysen R (2003) A review of pressure-driven membrane processes in wastewater treatment and drinking water production. Environ Prog Sustain 22(1):46–56. https://doi.org/10.1002/ep.670220116

Van Loon AF, Kumar R, Mishra V (2017) Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time. Hydrol Earth Syst Sc. 21(4):1947–1971. https://doi.org/10.5194/hess-21-1947-2017

van Roosmalen L, Christensen BS, Sonnenborg TO (2007) Regional differences in climate change impacts on groundwater and stream discharge in Denmark. Vadose Zone J 6(3):554–571. https://doi.org/10.2136/vzj2006.0093

van Vliet MTH, van Beek LPH, Eisner S, Flörke M, Wada Y, Bierkens MFP (2016) Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob Environ Chang 40: 156–170. https://doi.org/10.1016/j.gloenvcha.2016.07.007

Van Vliet M, Zwolsman J (2008) Impact of summer droughts on the water quality of the Meuse River. J Hydrol 353(1–2):1–17. https://doi.org/10.1016/j.jhydrol.2008.01.001

Van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. Clim Chang 122(3):415–429. https://doi.org/10.1007/s10584-013-0974-2

Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F (2011) The representative concentration pathways: an overview. Clim Chang 109(1–2):5–31. https://doi.org/10.1007/s10584-011-0148-z

Vandenbohede A, Luyten K, Lebbe L (2008) Effects of global change on heterogeneous coastal aquifers: a case study in Belgium. J Coastal Res 24(2A):160–170. https://doi.org/10.2112/05-0447.1

Velasco EM, Gurdak JJ, Dickinson JE, Ferré T, Corona CR (2017) Interannual to multidecadal climate forcings on groundwater resources of the US west coast. J Hydrol 11:250–265. https://doi.org/10.1016/j.ejrh.2015.11.018

Vicente-Serrano SM, Beguería S, López-Moreno JI, Angulo M, El Kenawy A (2010) A new global 0.5 gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the palmer drought severity index. J Hydrometeorol 11:1033–1043. https://doi.org/10.1175/2010JHM1224.1

Vidal J-P, Martin E, Kitova N, Najac J, Soubeyroux J-M (2012) Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios. Hydrol Earth Syst Sci 16(8):2935–2955. https://doi.org/10.5194/hess-16-2935-2012

Vidal JP, Wade S (2009) A multimodel assessment of future climatological droughts in the United Kingdom. Int J Climatol 29(14):2056–2071. https://doi.org/10.1002/joc.1843 von Freyberg J, Moeck C, Schirmer M (2015) Estimation of groundwater recharge and drought severity with varying model complexity. J Hydrol 527:844–857. https://doi.org/10.1016/j.jhydrol.2015.05.025

Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science 289(5477):284–288. https://doi.org/10.1126/science.289.5477.284

Wada Y, Wisser D, Eisner S, Flörke M, Gerten D, Haddeland I, Hanasaki N, Masaki Y, Portmann FT, Stacke T (2013) Multimodel projections and uncertainties of irrigation water demand under climate change. Geophys Res Lett 40(17):4626–4632. https://doi.org/10.1002/grl.50686o

Wang G (2005) Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment. Clim Dynam. 25(7–8):739–753. https://doi.org/10.1007/s00382-005-0057-9

Ward S, Memon F, Butler D (2012) Performance of a large building rainwater harvesting system. Water Res 46(16):5127–5134. https://doi.org/10.1016/j.watres.2012.06.043

Werner AD, Simmons CT (2009) Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater 47(2):197–204. https://doi.org/10.1111/j.1745-6584.2008.00535.x

Whitehead P, Wade AJ, Butterfield D (2009a) Potential impacts of climate change on water quality and ecology in six UK rivers. Hydrol Res 40(2–3):113–122. https://doi.org/10.2166/nh.2009.078

Whitehead P, Wilby R, Battarbee R, Kernan M, Wade AJ (2009b) A review of the potential impacts of climate change on surface water quality. Hydrol Sci J. 54(1):101–123. https://doi.org/10.1623/hysj.54.1.101

Wittmann AC, Pörtner H-O (2013) Sensitivities of extant animal taxa to ocean acidification. Nat Clim Chang 3:995–1001. https://doi.org/10.1038/nclimate1982

Yang D, Kanae S, Oki T, Koike T, Musiake K (2003) Global potential soil erosion with reference to land use and climate changes. Hydrol Process 17:2913–2928. https://doi.org/10.1002/hyp.1441

Zhao M, Running SW (2010) Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329(5994):940–943. https://doi.org/10.1126/science.1192666

Zhu C, Schwartz FW (2011) Hydrogeochemical processes and controls on water quality and water management. Elements 7(3):169–174. https://doi.org/10.2113/gselements.7.3.169