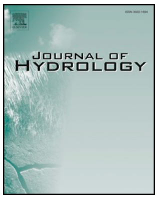
Journal of Hydrology 589 (2020) 125163

Contents lists available at ScienceDirect

Journal of Hydrology

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



Review papers

Groundwater system and climate change: Present status and future considerations

Amobichukwu C. Amanambu[a,e,*], Omon A. Obarein[d], Joann Mossa[a], Lanhai Li[b,c,i,*], Shamusideen S. Ayeni[f], Olalekan Balogun[g], Abiola Oyebamiji[h,k], Friday U. Ochege[b,c,j]

[a] Spatial and Temporal Analysis of Rivers (STAR) Lab, Department of Geography, University of Florida, Gainesville, FL 32611, USA
[b] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi 830011, Xinjiang, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] Department of Geography, Kent State University, 325 S Lincoln St., Kent, OH 44242, USA
[e] Water, Engineering, and Development Center, School of Civil and Building Engineering, Loughborough University, Leicestershire, UK
[f] Department of Geography, University of North Carolina, Greensboro, 1009 Spring Garden Street, Greensboro, NC 27412, USA
[g] Department of Geography, York University, Toronto, ON M3J IP3, Canada
[h] State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China
[i] Yili Station for Watershed Ecosystem Studies, 818 South Beijing Road, Urumqi 830011, Xinjiang, China
[j] Department of Geography & Environmental Management, University of Port Harcourt, Choba, Rivers State, Nigeria
[k] Department of Science Laboratory Technology, Ekiti State University, Ado-Ekiti, Nigeria

ARTICLE INFO

This manuscript was handled by Huaming Guo, Editor-in-Chief, with the assistance of Prosun Bhattacharya, Associate Editor

Keywords:
Climate change
Groundwater
Physical basis
Socioeconomic dimension
Models
Future considerations
Adaptation modeling

ABSTRACT

Climate change will impact every aspect of biophysical systems and society. However, unlike other components of the climate system, the impact of climate change on the groundwater system has only recently received attention. This focus is due to the realization that groundwater is a vital freshwater resource crucial to global food and water security, and is essential in sustaining ecosystems and human adaptation to climate variability and change. This paper synthesizes findings on the direct and indirect impacts of climate change on the entire groundwater system and each component. Also, we appraise the use of coupled groundwater-climate and land surface models in groundwater hydrology as a means of improving existing knowledge of climate change-groundwater interaction, finding that most models anticipate decreases in groundwater recharge, storage and levels, particularly in the arid/semi-arid tropics. Reducing uncertainties in future climate projections and improving our understanding of the physical processes underlying models to improve their simulation of real-world conditions remain a priority for climate and Earth scientists. Despite the enormous progress made, there are still few and inadequate local and regional aquifer studies, especially in less developed regions. The paper proposes two key considerations. First, physical basis: the need for a deeper grasp of complex physical processes and feedback mechanism with the use of more sophisticated models. Second, the need to understand the socio-economic dimensions of climate-groundwater interaction through multidisciplinary synergy, leading to the development of better groundwater-climate change adaptation strategies and modeling.

1. Introduction

Groundwater plays a vital role in sustaining ecosystems and ensuring human adaptation to extreme and unexpected global environmental changes, particularly as surface water systems become increasingly unsustainable in the face of rapid population growth and climate change. Groundwater is an important component of the climate system (Liesch and Wunsch, 2019), but many potential impacts of climate change remain largely unknown, because the climate system is intricate, characterized by a web of complex interactions and feedbacks (Munday et al., 2017). In general, most studies envisage an intensification of the hydrological cycle (Creed et al., 2015; Gloor et al., 2013; Hegerl et al., 2019; Stagl et al., 2014; Trenberth, 2014; Wu et al., 2015): higher temperatures are expected to drive increases in evaporation and evapotranspiration (E_T) (Hegerl et al., 2012; LaFontaine et al., 2015; Mundo-Molina, 2015; Zhang et al., 2016), but a

---

[*] Corresponding authors at: University of Chinese Academy of Sciences, Beijing 100049, China (A.C. Amanambu) and Department of Geography, University of Florida, Gainesville, FL 32611, USA. (L. Li).

E-mail addresses: a.amanambu@ufl.edu (A.C. Amanambu), lilh@ms.xjb.ac.cn (L. Li), uchenna.ochege@uniport.edu.ng (F.U. Ochege).

https://doi.org/10.1016/j.jhydrol.2020.125163
Received 30 December 2019; Received in revised form 23 May 2020; Accepted 5 June 2020
Available online 12 June 2020

simultaneous increase in humidity and CO_2 could counteract the effect of temperature, and leave E_T unchanged in a warming climate (Guo et al., 2017; Mo et al., 2017; Snyder, 2017). Precipitation is projected to increase in amount and intensity in many places while other places are projected to experience drought (Burke and Stott, 2017; Nissen and Ulbrich, 2017). Also, the portion of precipitation falling as snow is likely to decrease (Fassnacht et al., 2016; IPCC, 2013; Kormos et al., 2016). This lesser amount of snow will melt more quickly, leading to higher average annual surface runoff (Wang et al., 2015; Zhou et al., 2017), especially in temperate climates. Fig. 1 depicts the complex interaction between groundwater and the components of the climate system.

Most prior studies on the potential impact of the changing climate on the hydrological cycle have focused on the surface and visible portion of the cycle—precipitation, atmospheric water vapor, E_T, streamflow, snow cover and so on. This bias is mainly due to their visibility and accessibility (Abiy and Melesse, 2017; Pitz, 2016; Scanlon et al., 2012)— qualities which make for relative ease of observation, measurement, and investigation of its component characteristics and interaction. Until recently, there have been fewer studies on climate change-groundwater relationships (Garner et al., 2017; Haldorsen et al., 2016; Hu et al., 2019; Taylor et al., 2013). The difficulties involved in probing the nature and characteristics of water below the Earth surface, in part, account for this deficiency in understanding groundwater response to climate change forcing. Also, groundwater is relatively insensitive to seasonal and even decadal climate variability (Gurdak, 2017; Wada, 2016). Providing a complete picture of groundwater response to the changing climate is even more challenging given that the impacts of climate change are often modified by human and indirect agents such as land-use change and over-exploitation of groundwater.

However, given that groundwater accounts for almost 96% of the Earth’s unfrozen freshwater (Taylor et al., 2013; Wada, 2016) and 33% of total water withdrawals worldwide (Famiglietti, 2014; Siebert et al., 2010), there is growing concern, focus, and research on the impact of climate change on groundwater resources (Green et al., 2011; Kundzewicz and Doell, 2009; Taylor et al., 2013). The dearth in groundwater-climate change studies was summed up by the IPCC’s Fourth Assessment Report which proclaimed that there has been “very little research on the impact of climate change on groundwater, as well as the question of how climate change will affect the relationship between surface waters and aquifers that are hydraulically connected” (Parry et al., 2007). This declaration, according to some scholars (e.g. Smerdon, 2017), was instrumental in driving the massive wave of publications that followed in its wake, and thus provided ample material for a more robust report on climate change impact on groundwater by the Fifth Assessment Report. This review paper is organized into five sections: (1) a review of the global climate change; (2) an assessment of the present state of climate change impact on groundwater components; (3) a review of groundwater models and climate change induced future groundwater changes; (4) groundwater feedbacks to the climate system; and (5) key considerations for groundwater climate change research, Much of the justification for the recent interest in the response of groundwater to climate change is the need for sustainable water use for various human activities, particularly in drought-prone areas and arid regions, and to mitigate against or adapt to any adverse impacts of climate change (Guermazi et al., 2019; Kumar, 2012; Kumar and Singh, 2011). Insufficient information on most of the problems mentioned above, nonetheless, constitute those evolving grey areas facing the successful implementation of sustainable groundwater governance across different regions of the world. This review paper probes the frontiers of groundwater-climate change interaction in both the physical processes and its socio-economic dimension in order to advance the knowledge of groundwater-climate change interaction. Potential future groundwater component changes were presented, together with effective directional consideration for developing groundwater-climate change adaptation strategies. We present a broad understanding to support global groundwater policy and management by providing clarifications on the recent salient issues surrounding the impact of climate change on the global groundwater system.

1.1. Methodology

We reviewed approximately 1000 papers that dealt with the subject of groundwater and climate change together or separately. Google Scholar, the Web of Science, and Scopus were the main repositories searched for relevant materials. In line with the aims of this project, papers that were older than five years were mostly excluded from the list, and an emphasis was placed on those linking potential changes in groundwater components to climate change. This further narrowed the list to just over 300 peer-review papers.

In addition, we sampled some review papers over the last decade (2008 – 2019). Table 1 summarizes their spatial scale, thematic focus, gaps identified, and proposed solutions.

1.2. Global climate change

Climate change is no longer a hypothesis (IPCC, 2013). There is a global consensus among climatologists and other Earth scientists that the global climate is changing. Since the instrumentation period began, the Earth's climate has undergone unprecedented changes, and these changes have been projected to continue well into this century. For instance, the last four years are the warmest years on record and the ten warmest years are all in the 21st century (Cheng and Zhu, 2018; Jackson et al., 2017; Sorokin and Mondello, 2018). The global average temperature has risen almost 1 °C since records began, and atmospheric CO_2 is currently at an all-time high of 416 ppm as of April 2020[1]. Today, climate change has remained on the front burner of world-leading studies in environmental science and climatology, and it remains topical at national and international levels because of its influence on policy and decision making in socioeconomic domains. It is seen as a multidisciplinary subject matter and has attained a universal presence in the academic arena because its impact pervades all of Earth's systems. There is less agreement, however, about how much warming will occur in future and what effect it would have on various life forms.

Earth’s climate is subject to internal variability within the climate system itself and to external factors which may be natural or anthropogenic. However, contemporary changes and warming trends have been attributed solely to anthropogenic influences, particularly the increased emissions of greenhouse gases (GHGs), some of which are now said to be unavoidable (IPCC, 2013). The amount of GHGs has soared considerably since the industrial era, warming the atmosphere and Earth surface, and leading to global warming. $CO_{2,}$ in particular, is a significant GHG, and its increasing concentration in the atmosphere has been classically correlated with the steady rise in average global temperatures in the last 150 years (WMO, 2017). Nevertheless, there are still uncertainties in how global climate change manifests at local and regional scales, and how decadal-to-seasonal temperature variations and extremes affect the lives of people (McGregor, 2018).

Increasing temperatures have led to the melting and receding of glaciers and ice-sheets—reinforced by the Arctic amplification and the cryospheric positive feedback mechanism (Duan et al., 2019; Francis, 2017; Haine and Martin, 2017). This melting of ice, combined with thermal expansion of the oceans cause average sea level to rise. Other parts of the climate system (such as the hydrological cycle) respond to climate change forcing through numerous—often intractable—feedbacks (Jayakumar and Lee, 2017; Smyth et al., 2017).

In all, scientific knowledge of climate processes has improved.

---

[1] Atmospheric CO_2 https://www.co2.earth/, Accessed May 2019

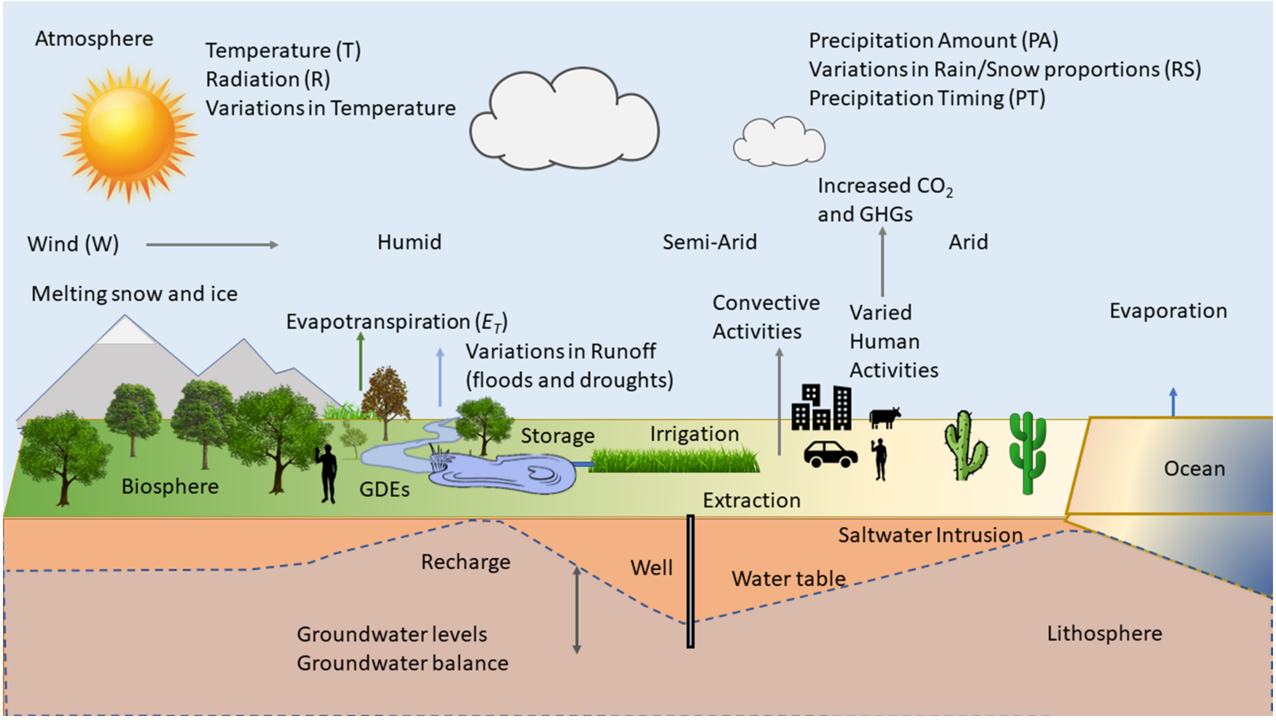


Fig. 1. Groundwater systems interaction with Earth's components in the face of climate change. Directly, changes in precipitation (amount, timing and form), evaporation, transpiration and, indirectly, extraction, affects the groundwater system. All these may separately or together impact the numerous processes and mechanism of the groundwater system. GDEs—Groundwater Dependent Ecosystems.

Climate models now produce realistic simulations of past and future climate change. However, many uncertainties still exist in our knowledge about specific microphysical processes and complex interactions that govern the climate system. Future projections of climate change and alterations to groundwater due to climate change will require sophisticated theoretical models to be more reliable.

1.3. Climate change and world groundwater

An estimated 1.386 billion cubic kilometers of water is present on Earth. Of this total, approximately 97% is salt water found in the oceans, and only 3% is freshwater. Most of this freshwater—about 69%— occur as permanent ice and snow, mainly in Greenland and Antarctica, while the remaining 30% is groundwater (Gleick ,1993). Water in surface water systems such as rivers, lakes, streams and swamps hold less than 1% of fresh water. If we take the water locked up in the cryosphere out of the equation, it would mean that only 1% is usable, and 99% of this is groundwater (Du Plessis, 2017; Liu et al., 2011). Thus, groundwater is a vital source of fresh water, not only for diverse human uses but also for sustaining plant and animal ecosystems.

In terms of human use of groundwater, 1.5–3 billion people rely on groundwater as their primary source of drinking water (López-Morales and Mesa-Jurado, 2017; Misra, 2014; Velis et al., 2017). Irrigation consumes about 60–70% of groundwater withdrawals globally (Bhanja et al., 2017; Zingaro et al., 2017; Siebert et al., 2010), but locally this percentage varies with climate. Desert countries, such as Saudi Arabia, Libya, and Burkina Faso, expend as much as 90% of groundwater on irrigation. In contrast, countries with plentiful rainfall use most of their groundwater for household needs since little is needed for irrigation. The rapid increase in agricultural groundwater use in the last few decades, due to technological advances in pumping techniques, has created better livelihoods for farmers and food security for the world's population (Giordano, 2009). Industrial groundwater use is also growing in industrialized countries as it accounts for about 40% of water demand in France and Japan (Margat and Van der Gun, 2013). Overall, groundwater accounts for a quarter of total water withdrawals and 50% of the world's current potable water (Margat and Van der Gun, 2013). Groundwater is, therefore, crucial for the sustenance of many human and natural systems.

However, there are legitimate concerns and reports of over-exploitation of groundwater, driven by increasing water demand from rapid urban and industrial development, and expansion of irrigated lands (Gleeson and Wada, 2013; Jia et al., 2019; Taylor, 2014; Turner et al., 2019; Wada and Bierkens, 2014). The US, India, and Pakistan together accounted for nearly 55% of total world groundwater withdrawals (Grogan et al., 2017; Pokhrel et al., 2013). In many areas of the world, groundwater exploitation is carried out in an unsustainable way (Omole, 2013; Srinivasan and Lele, 2017), with rates of withdrawal exceeding replenishment by recharge. These include the major agricultural regions in the western US, the Middle East, India, and China, shown in Fig. 2 (Döll et al., 2012; Grogan et al., 2017; Wada et al., 2012a). Left unabated, this current trend of increasing societal dependence on non-renewable groundwater will undermine the resilience of human systems to water shortages and threaten ecological systems that depend on them.

Most naturally dry regions with very little precipitation have seasonally or year-round surface and groundwater depletion (Fig. 2); however, even more rainy regions, such as the Indian sub-continent and the Great Plains of the US, show significant depletion. These latter areas indicate places of intense industrial and agricultural water use. Fig. 2 also maps the ratio of mean annual precipitation to groundwater generated (RPGw) (both in $10^{\wedge 9}$ m^3 /year for 1988 to 2017) for selected countries. Countries with large RPGw tend to be located in dry, hot climates where the little precipitation is consumed by E_T and groundwater recharge is severely limited. Most of the Middle East and North Africa fall into this class, and watersheds in this region suffer seasonal and dry-year surface and groundwater depletion.

The rapid growth in world population and the associated increase in water demand do not proffer a complete explanation for the massive

Table 1

Synopsis of some selected Groundwater (GW) and Climate Change (CC) review articles within the last decade (2008–2019).

Publication	Study Domain	Framework	Research Gap/Limitations	Proposed Solution(s)
Authors[7,13]	Global	Groundwater dependent ecosystem (GDEs)	Questions remain on how climate change influence recharge, discharge and temperature of GDEs	A multidisciplinary approach to GW, CC and GDEs relationships.
Authors[2-4,7,12-15,17-19, 21-25]	Global[2-4,7,13-15,17-19,23,25], Africa[22,24], Europe[20], Mekong region[4], [UK21], Denmark[11], High latitudes[12]	Methods[2], recharge[3], storage and recharge[4], GDEs[7,13], flow and temperature[12], resources[14-15,17-19,22-25], quality[21], uncertainties[11]	Assumption and methodology limitations[2], uncertainties in prediction using hydro-climatological models. Difficulty in integrating processes in models[23]. Climate, model, parameter and geological uncertainties[11]	Adaptation strategies.[2,15] Integrated approach[2,15] or multidisciplinary approach.[7,13,21] Modelling at a mesoscale with shorter future predictions.[3,24] Development of a more robust hydrological models, GCMs and downscaling techniques.[2,11,14,17,22-23] Creation of long term monitoring network.[2-4,7,11-15,17-19,21-25]
Authors[3,22]	Global[3], Africa[22]	Recharge[3], resources[22]	Lack of knowledge on the magnitude and direction of climate change impacts	Modeling at a mesoscale with shorter future directions[3]. Development of robust hydro-climatological models[22]
Authors[1-4,7,10,12-15,17-19,21-24]	Global[2-3,7,10,12-15,17-19,23,25], Africa[22,24], Europe[20], Mekong region[4], UK2[1], High latitudes[12], Temperate glaciers[1]	Methods[2], recharge[3], storage and recharge[4], GDEs[7,13], flow and temperature[12], resources[14-15,17-19,22-25], quality[10,21], dynamics and evolution[1]	Lack of groundwater data	A groundwater monitoring network is needed because data availability can help reduce uncertainty to some degree. Gathering of GW data will enable characterisation of aquifer systems and allow the validation of comprehensive hydrological models[1]
Author[5-6,9,19,25]	Global, North Africa[6]	Law & Policy[5-6, 9], resources[19,25]	Poor cooperation, leading to weak legislation. Policies and regulation on GW & CC are usually considered separately at local or global scale[9].	"Lack of links between agreement, disparities in outlining climate and water problems, differences in basic norms, disparities in process"[5] Multidisciplinary[5,19,25]. Shared knowledge by stakeholders and researchers leading to proper legislation[19,25].Transition to suitable policies[6]. Collaborations between the relevant organisation, e.g. IPCC, UN etc.; adequate GW legislation[5], strong position should be given to adaptation, rather than emission, in policy formualtion[9]
Author[4,8-10,12,16-18]	Global[10,17-18], Mekong region[4], South Africa[8], Brazil[16], High latitude[12]	Storage and recharge[4], quality, flow and temperature[12], resources[8,16-18], quality[7]	Detailed local or regional hydrogeological studies.	In-depth study of the physical properties of local or regional groundwater processes. Address institutional challenges and fill the knowledge gap in impact assessment[8]
Author[4,10]	Global[10], Mekong region[4]	Flow and temperature[4], resources, quality[1]	Limited knowledge of spatial GW studies	Studies should focus more on the spatial variability of climate change impact and not only temporal. Lack of expertise in the role CC plays in influencing microorganism in shaping aquifer condition.
Author[10,23]	Global[10], United Kingdom[21]	Quality[10,21]	Implications of leaching contaminants to GW resulting from CC are yet to be explored	Local hydrogeological studies and mechanism influencing contaminants (arsenic[10] and nitrate[21]) in the face of climate change.
Author[1,12]	Global,Temperate glaciers[1]	Flow and temperature, dynamics and evolution[1]	Local and regional hydrogeology (aquifer characteristics and dynamics[1]) not well known, lack of studies on GW temperature limits the understanding of CC impact on GW temperature and flow, the sensitivity of fluxes is not well known	Climate and energy transport models should incorporate surface and subsurface flows. Information on the hydrogeology of glacier watersheds should be established and related to surface and atmospheric components[1]

Note: Authors: [1]Vincent et al. (2019), [2]Aslam et al. (2018), [3]Smerdon (2017), [4]Jayakumar and Lee (2017), [5]Gupta and Conti (2017), [6]Kuper et al. (2017), [7]Morsy et al. (2017),[8]Nkhonjera and Dinka (2017), [9]Cullet and Stephan (2017), [10]Bondu et al. (2016), [11]Refsgaard et al. (2016), [12]Kurylyk et al. (2014a), [13]Kløve et al. (2014), [14]Srivastava (2013), [15]Taylor et al. (2013), [16]Hirata and Conicelli (2012), [17]Gun (2012), [18]Earman and Dettinger (2011), [19]Green et al. (2011), [20]Kløve et al. (2011), [21]Stuart et al. (2011), [22]Carter and Parker (2009), [23]Franssen (2009), [24]Taylor et al. (2009), [25]Dragoni and Sukhija (2008).

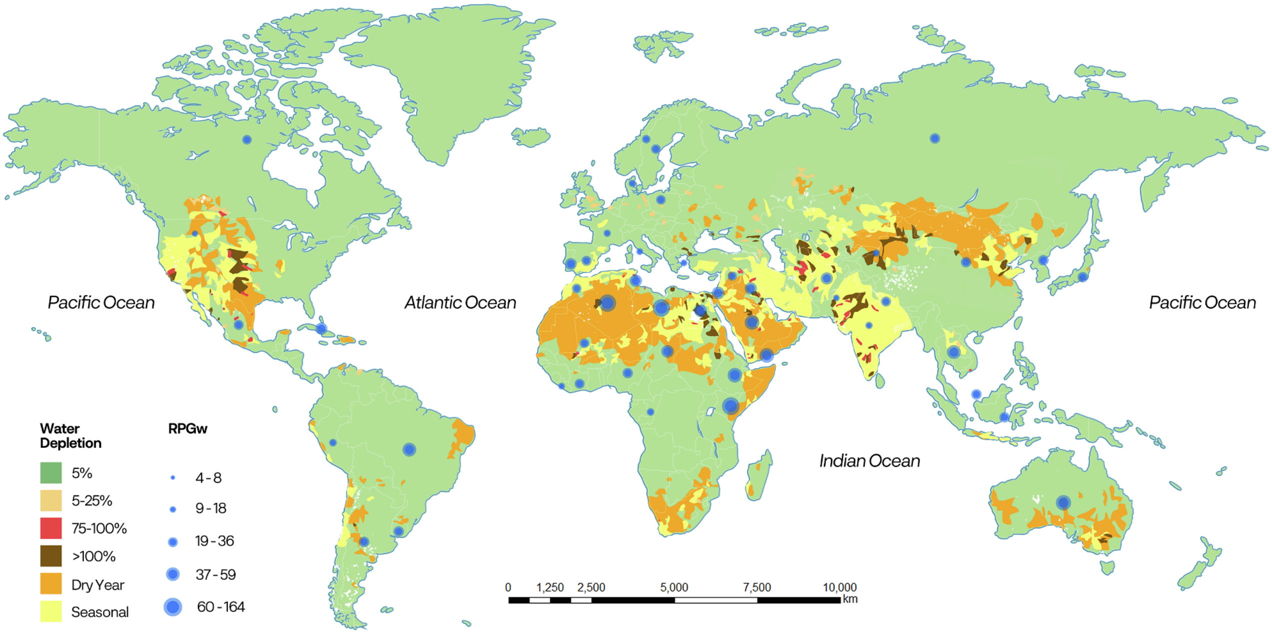


Fig. 2. Ratio of mean annual Precipitation and Groundwater generated internally (RPGw)—(both in 10^9 m^3/yr from 1988 − 2017, although values are similar for all the years considered) (data downloaded from AQUASTAT(AQUASAT-FAO,http://www.fao.org/nr/water/aquastat/main/index.stm/, Accessed December 2019)) for some selected countries superimposed on Global Water depletion. Global Water depletion is the percentage of fresh renewable surface and groundwater fraction available in a watershed (15,091 watersheds delineated in WaterGAP3)(EARTHSTAT, http://www.earthstat.org/water-depletion-watergap3-basins/, Accessed January 2018) used by human activities on seasonal, and inter-annual timescales. Dry-year depletion is included; this increases by a factor of 15 the number of watersheds facing depletion of at least 75%. Global depletion has been modeled by Brauman et al. (2016).

depletion of groundwater storage. Many studies have established correlations between climate perturbations and groundwater levels (Asoka et al., 2017; de Graaf et al., 2017; Kuss and Gurdak, 2014; Russo and Lall, 2017; Sivarajan et al., 2019; Taylor et al., 2013; van der Knaap et al., 2015; van Engelenburg et al., 2018). As global warming and climate change drives more intense and frequent climate extremes, precipitation, evaporation, and surface water will become more variable, making groundwater a threatened and yet critical resource in sustaining ecosystems. Indeed, increasing groundwater demand will characterize future scenarios for water resource management and food security (Gamvroudis et al., 2017; Mustafa et al., 2019; Tong et al., 2016; Zaveri et al., 2016), as it is the only viable means of meeting the water needs of rural areas and arid regions (Lijzen et al., 2014; Melo and Wendland, 2017; Moutahir et al., 2017; Wang et al., 2015).

Climate change, directly (Fig. 3) affects the totality of the groundwater system (da Costa et al., 2019; Jayakumar and Lee, 2017): groundwater-surface water interaction (Scibek et al., 2007; Tague et al., 2008), groundwater flows, groundwater recharge and storage (Asoka et al., 2017; Tillman et al., 2016; Tillman et al., 2017), groundwater discharge, and groundwater quality (Gurdak et al., 2011; Okkonen and Kløve, 2011). Of these, groundwater recharge, from precipitation and leakages from influent streams or other surface water systems, has received the most attention and is dependent on several hydrogeological factors (Russo and Lall, 2017). The impact of climate change on groundwater systems can also be indirect, through changes in groundwater abstraction (Asoka et al., 2017; Gurdak, 2017; Whittemore et al., 2016), and through changes in land use/cover (Fig. 3) (Stoll et al., 2011; Taylor et al., 2013). Climate-induced changes in land use involve changes in vegetation type, evolving agricultural practices and potential increases in crop evaporative water demand, all of which exerts a toll on groundwater (Alam et al., 2019).

Studies of the potential impact of climate change on groundwater assume one of three spatial scopes. Global-scale analyses assess the worldwide pattern of projected recharge trends and groundwater changes. Although they provide a quick snapshot of prevailing conditions, they are often too generic to guide water policy and decision making that is both viable and beneficial on smaller scales (Green et al., 2011; Meixner et al., 2016; Taylor et al., 2013). At the opposite end of spatial scope are basin/aquifer-specific studies that provide a deeper understanding of climate change impacts in a particular river basin or aquifer system. Regional studies, according to Meixner et al. (2016), are a useful compromise between both scales as these evaluate a group of aquifers within a region, with similar or different recharge mechanism.

2. Climate change and the groundwater system

2.1. Recharge

Climate is the primary factor driving spatiotemporal variability in groundwater recharge, and precipitation is the climate element that most directly affects groundwater recharge, irrespective of the recharge pathway. The significance of climate to groundwater is underscored by the universal use of GCMs (and precipitation data) in predicting future groundwater states, and on average, wet conditions often result in increased recharge and storage while drought may cause the opposite effect (Mote et al., 2013; Fu et al., 2019; Zhou et al., 2010). Tillman et al., 2016 and McKenna and Sala (2018) quantified the projected changes in groundwater recharge in the southwestern United States under future climate scenario, and found a net increase in the simulated groundwater recharge mainly due to projected increases in precipitation offsetting a decrease in recharge resulting from projected increased temperatures. Heavy precipitation may not necessarily lead to increasing recharge if intense E_T consumes the excess water (Bellot and Chirino, 2013; Scanlon et al., 2005; Touhami et al., 2013), and in fact, Bloomfield et al. (2019) concluded that groundwater droughts are modulated by changes in evapotranspiration associated with global warming.

Groundwater recharge is also influenced by the intensity of rainfall and not just the amount (Jayakumar and Lee, 2017). E_T may prevent

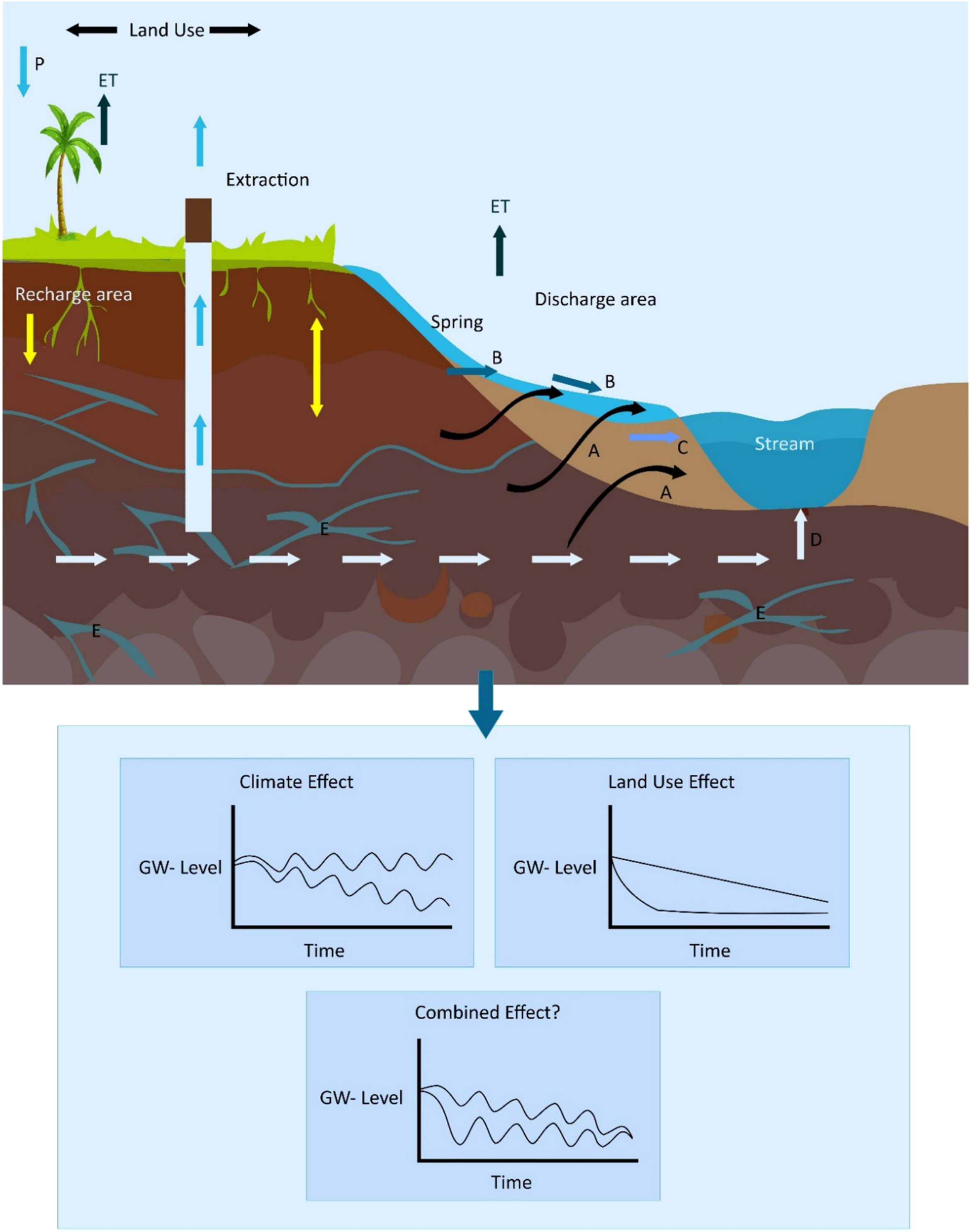


Fig. 3. A conceptual illustration of the potential impacts of climate and land-use change on groundwater. The combined impact will affect all the different processes of groundwater: A-Diffusion, B-Runoff, C- Baseflow, D-Discharge from aquifer and E-Storage in cracks and pores. Groundwater extraction and climate change can affect both regional and global aquifers, but their responses are somewhat different.
Adapted from Kløve et al. (2014)

infiltration below the root zone; therefore, light rainfall is not expected to contribute to groundwater recharge (Frot et al., 2007; Taylor et al., 2013; Tweed et al., 2011). In Uganda, projected recharge estimates under a future climate scenario were found to be extremely sensitive to rainfall intensity (Mileham et al., 2009). In Australia, rainfall intensity was also found to influence recharge estimation, especially diffuse irrigation (Barron et al., 2011). Even in karst topography, findings (Bellot and Chirino, 2013; Touhami et al., 2013) have shown that precipitation events of less than 15 mm are considered negligible for aquifer recharge, while precipitation events equal to or greater than 30 mm produced high enough infiltration to lead to considerable aquifer recharge. Therefore, regions where rainfall intensity is projected to rise may see future recharge increases, provided that rainfall intensity is not too high as to exceed the infiltration capacity of the soil and preclude any extra groundwater recharge.

Furthermore, the type of precipitation event also affects recharge rates (Hughes et al., 2011). Snowmelt is, for the most part, a more efficient creator of recharge than rainfall. All other factors being equal, a move from snow to rain could sometimes bring about lower recharge-to-precipitation proportions (Earman and Dettinger, 2011). Since more precipitation is expected to fall as rain than snow on a warming Earth, cold regions may suffer recharge reductions, otherwise warmer winter temperatures might reduce the depth of ground frost and increase infiltration into the ground, thereby increasing recharge. A warmer winter may also lead to earlier and prolonged snowmelt resulting in ample winter recharge, but reduced spring and summer recharge (Jyrkama and Sykes, 2007; Kløve et al., 2014; Okkonen and Kløve, 2010; Sutinen et al., 2008). Hence, while future groundwater recharge will be influenced primarily by rainfall intensity in the tropics, a shift in the type of precipitation event—from snow to rainfall—will be the primary determinant of future recharge in temperate and cold climates.

Understanding groundwater recharge mechanisms are important for evaluating relations between climate change and groundwater recharge. The combinatory study of eight aquifers in the western US by Meixner et al. (2016), led to the development of a uniform recharge classification scheme which identified four different recharge mechanisms: diffuse, focused, mountain system recharge (MSR) and irrigation. Diffuse recharge occurs through direct infiltration from precipitation that occurs fairly homogeneously over a large area (Scanlon et al., 2002; Sililo and Tellam, 2000; Stamm et al., 1998; Wirmvem et al., 2017). Focused recharge, on the other hand, is concentrated recharge resulting from infiltration from ephemeral and perennial water bodies (Hughes et al., 2011; Meixner et al., 2016; Ren et al., 2019), especially in areas of heterogeneous subsurface characteristics (Hartmann et al., 2017). MSR, the main recharge component in arid and semi-arid basins, involves two related processes: mountain front recharge (MFR) and mountain block recharge (MBR). MFR is recharge from stream runoff at mountain fronts to the adjacent alluvial aquifer while MBR is recharge through mountain bedrock (Houston, 2002; Meixner et al., 2016). Groundwater recharge by irrigation is excess irrigation water which percolates back to the water table. Similarly, some studies have made distinctions such as localised and indirect recharge (Lerner, 1997), and actual and potential recharge (Hendrickx and Walker, 1997).

The study by Meixner et al. (2016) demonstrated that various recharge mechanisms would respond differently to global warming, and the sensitivity of a region to climate change depends on the recharge mechanisms at work in a given aquifer system (Flint et al., 2013; Ng et al., 2010). For the eight aquifers studied, diffuse recharge is expected to drop as a result of the cumulative effects of decreasing precipitation and increasing temperature and E_T. Focused recharge is likely to increase due to the projected increase in precipitation intensity in a warmer climate (Dominguez et al., 2012). MSR is expected to decrease, driven by both reduced winter precipitation and a decline in the proportion of winter precipitation arriving as snow. It is noteworthy that considerable uncertainties exist in these future projections, as seen in the wide range of estimates of recharge changes.

Table 3 summarizes the findings of selected studies on the predicted future impact of climate change on different groundwater components, including recharge. Although estimates of future recharge changes had considerable uncertainty, in all, recharge was found to be decreasing in most of the studies, in both temperate (54%) and tropical (80%) climate regions. Even in the rainy humid tropics, the majority of studies still indicate decreasing recharge by the end of this century, relative to baseline estimates.

Besides the agency of precipitation, climate change may also impact recharge through changes in groundwater use. The excessive abstraction of groundwater, primarily for irrigation can have a significant effect on groundwater, as irrigation accounts for nearly 60–70% of all freshwater extractions and 90% of consumptive uses (Siebert et al., 2010). Typically, groundwater-fed irrigation leads to depletion of groundwater storage, but recharge increases and storage replenishments have been observed in areas of extensive irrigation return flows. For example, in the Republican River Basin of the High Plains aquifer of semi-arid US, where irrigation has become an important supplier of crop water demand, Ou et al. (2018) predicted that irrigation recharge would increase steadily up to 2100 due to the increase in pumping. In regions where irrigation by surface water is dominant, irrigation recharge is also expected to rise (Crosbie et al., 2013; Hanson et al., 2012), but the net effect of excess irrigation is groundwater depletion (Leng et al., 2014; Stanton et al., 2011). In all, the surge in irrigation-led abstraction is likely to continue into the future (Yihdego et al., 2017), driven by climate change-induced seasonal redistribution of precipitation and increased E_T (Kreins et al., 2015). With an increasing population and a consequent rise in demand for food as well as greater economic development, irrigation-led abstraction may even become the most significant mode of climate change impact on groundwater (Russo and Lall, 2017; Whittemore et al., 2016).

Furthermore, land use/land cover can modify the effects of precipitation and groundwater use on groundwater recharge. Many studies have shown significant variation in recharge due to replacing the natural vegetation by arable land or built-up surfaces (Oliveira et al., 2017). Reduction in leaf area, for example, through clearing forests for agriculture, can increase groundwater recharge even if rainfall decreases slightly (Owuor et al., 2016). In contrast, other studies have shown decreases in groundwater recharge from an increase in vegetation density, for instance, through a change from grassland to woodland (Oliveira et al., 2017), or when it involves rapid urbanization and replacement by built-up surfaces. In general, land use/cover change, whether temporary (vegetation change), or permanent (urbanization), can affect recharge by modifying the water balance—evaporation, transpiration, infiltration, and surface runoff processes (Jyrkama and Sykes, 2007; Kundu et al., 2017). These additional influences make it difficult to assess the impacts on groundwater due exclusively, to climate change (Green et al., 2011; Gurdak, 2017; Zhou et al., 2010).

2.2. Discharge

The movement of water from the subsurface to the surface, from an aquifer to a surface-water body, loss to the atmosphere, or withdrawal for human uses represents groundwater discharge (Green et al., 2011). Five major processes of groundwater discharge are identifiable in the literature: (1) spring flow, (2) transpiration by local vegetation, (3) evaporation from soil and open water, (4) subsurface outflow, and (5) withdrawal for various human uses (Green et al., 2011).

Groundwater-fed springs will decrease in discharge going by current forecasts of increasingly arid climate in the southwestern US (Weissinger et al., 2016), the Sikkim Himalaya (Tambe et al., 2012), and in areas of extensive groundwater development as in Niangziguan Springs in Shanxi, China (Hao et al., 2009; Zhong et al., 2016).

A wetter future climate will probably lead to an increase in spring discharge, but this is complicated by the many climate elements often at play. For example, Weissinger et al. (2016) found an inverse relationship between spring discharge on one hand and potential E_T and temperature on the other; whereas, higher winter precipitation led to spring discharge increases. Cervi et al. (2018) corroborate these findings. A better understanding of the interrelationship between climate and spring discharge will not only foster realistic projections of future spring discharge changes resulting from climate change, but will also guide conservation efforts in spring-dependent ecosystems. Besides spring discharges, groundwater discharge is a significant contributor to streamflow, especially in times of little precipitation (Leake and Barlow, 2013). For summer groundwater discharges into adjacent rivers, Kurylyk et al. (2014b) have reported a significant rise in the magnitude of discharge due to projected rises in precipitation and air temperature in New Brunswick, Canada.

The major indirect impact of climate change—extensive groundwater pumping to meet rising water demand for irrigation and other human uses—may substantially lower the elevations of the water table and consequently, baseflow contributions to streamflow. The impacts of groundwater withdrawals can be transmitted to associated lakes, streams, and wetlands through diminished rates of release from the aquifer to these surface water systems (Barlow and Leake, 2012; Leake and Barlow, 2013). Solder et al. (2016) found evidence of declining groundwater discharge attributable to climate variability and change, and to increased water demand.

Further, climate change can potentially impact the temperature of groundwater discharges. From simulations, Kurylyk et al. (2014b), again, reported a rise in groundwater discharge temperature of up to 3.6 °C in their study area in New Brunswick, Canada. Certain fish species are mostly dependent on cold groundwater discharges into streams and rivers to buffer them from temperature extremes and regulate their metabolism, especially in summer months. Deitchman and Loheide (2009), Essaid and Caldwell (2017), and Hare et al. (2017) argue that, given this critical thermal conditioning role, any future climate change impact on groundwater discharge temperature could endanger these already threatened species. The sign of change in groundwater temperature will almost certainly be positive since average global air temperatures are projected to rise, and surface air temperatures and subsurface temperatures have a strong positive correlation, especially in shallow aquifers with greater thermal sensitivities (Gunawardhana and Kazama, 2012; Kurylyk et al., 2013, 2015). Therefore, the probability of surpassing essential temperature thresholds in groundwater-sourced thermal streams may increase considerably under the most extreme future climate scenarios.

2.3. *Flow and storage*

There is much evidence in the literature that groundwater levels in many aquifers around the world are decreasing. Major aquifers in arid and semi-arid regions (Fig. 2) such as the High Plains of the United States (Dong et al., 2019; Longuevergne et al., 2010; Russo and Lall, 2017; Scanlon et al., 2012) and Northwest India are experiencing rapid groundwater depletion (Famiglietti, 2014). Elsewhere, in humid environments such as Bangladesh (Shamsudduha et al., 2012) and Brazil (Foster et al., 2009), a decrease in groundwater storage has also been reported. Groundwater literature over the last few decades have debated the role of groundwater recharge and pumping on the depletion of groundwater storage. It would appear intuitive and logical, that when pumping exceeds natural recharge in an aquifer, then depletion of aquifer storage occurs, and pumping becomes unsustainable. However, this notion, based on some erroneous assumptions spelt out in Devlin and Sophocleous (2005), has been widely discredited as a Water Budget Myth (see Bredehoeft, 2002). Those against this myth argue that natural aquifer recharge is not necessarily a factor affecting sustainable pumping, but the Water Budget Myth continues to persist.

Because groundwater represents the largest store of freshwater on Earth, its depletion will threaten livelihoods and ecological sustainability, especially during periods of drought (Aeschbach-Hertig and Gleeson, 2012; Brauman et al., 2016; Konikow and Kendy, 2005). Storage loss is even deleterious for other reasons. First, it reduces the depth of the water table, thereby increasing the cost of groundwater abstraction from deep boreholes and wells (Aeschbach-Hertig and Gleeson, 2012; Fishman et al., 2011). Second, it reduces groundwater discharge to streams, springs, rivers and other surface water bodies with attendant effects on the well-being of GDEs (Earman and Dettinger, 2011; Giordano, 2009). Third, groundwater depletion has been known to cause land subsidence due to the compaction of soil and open pore spaces that previously held water (Taniguchi et al., 2008; Andaryani et al., 2019). Land subsidence due to groundwater depletion has been found in Venice and Bologna, Italy (Tosi et al., 2015; Modoni et al., 2013), China (Zhu et al., 2015), Iran (Ghazifard et al., 2016), the central valley California (Faunt et al., 2016) and elsewhere.

Groundwater storage is comparatively less sensitive to seasonal or even multi-year climatic variability (Pokhrel et al., 2013; Taylor et al., 2013) and reacts slower than surface water to the effects of direct climate-driven changes in precipitation and recharge rates. In deep aquifer systems, an extended period may be required for direct climate-driven changes in recharge to be evident as a storage change. On the other hand, storage conditions in smaller aquifers with smaller flow paths are probably the most vulnerable to direct changes in storage.

In all, sudden changes in storage may suggest indirect or human-induced depletion, rather than direct climate effects, or an aggressive combination of both, as was found in the Central Valley region of California, where droughts and over-exploitation of groundwater for irrigation led to massive storage depletion (Alam et al., 2019; Xiao et al., 2017). Alam et al. (2019) found that groundwater storage had been depleting since the middle of the 20th century, and climate change will lead to a 31% increase in the rate of groundwater storage loss under RCP4.5 in California's Central Valley.

Scholars generally employ one of three methods of estimating groundwater depletion: 1) the flux-based method (Wada, 2016; Wada et al., 2010) which defines groundwater depletion as an abstraction in excess of recharge, 2) the volume-based method (Konikow, 2011), and 3) the satellite-based method. All methods have their flaws, and estimates are fraught with uncertainties. Nonetheless, assessing the amount of groundwater present in storage has improved since the launching of the Gravity Recovery and Climate Experiment (GRACE), and estimation of changes in groundwater storage at regional scales has been made possible. This satellite-based method detects changes in total water storage (TWS) by measuring temporal variations in the gravity field. The storage changes of groundwater can be evaluated after deducting the remaining TWS changes from GRACE-resultant total TWS changes (Tapley et al., 2019; Wada, 2016). The GRACE satellite data and ground-based observations have been used to ascertain the level of storage depletion in many regions of the world (e.g. California Central Valley (Scanlon et al., 2012); the Amazon (Hu et al., 2017); China (Hao et al., 2019; Lin et al., 2019); and India (Tiwari et al., 2009)). However, although GRACE provides near-in-situ estimates of regional groundwater depletion, its coarse spatial resolution (200,000 km^2 [Longuevergne et al., 2010]) precludes the assessment of small aquifers especially in data-scarce areas (Strassberg et al., 2007; Wada, 2016; Lin et al., 2019). The solution may lie in combining GRACE data with direct groundwater observation and groundwater modelling as Hao et al. (2019) has done.

2.4. *Groundwater quality*

Research on climate change impacts on groundwater quality is sparse, and predictions are fraught with uncertainty. Nonetheless, two modes of impact on groundwater quality in a changing climate are found in the literature: (1) the flushing of chemical compounds into aquifers and (2) over-exploitation of coastal aquifers (Kløve et al., 2014; Treidel et al., 2011). Infiltrating irrigation return flows can flush certain chemical compounds into aquifers, thereby impacting groundwater quality (Merz and Lischeid, 2019; Qin et al., 2011). Severe rainstorms in lowland areas where rates of land-surface loading of contaminants are higher may encourage the downward mobilization of soluble chemicals present in the vadose zone (Dragoni and Sukhija, 2008; Earman and Dettinger, 2011; Gurdak et al., 2007; Kløve et al., 2014). This phenomenon is most characteristic of arid and semi-arid regions where high evaporation rates increase the content of salt in soils and bottom sediments of surface waters and could play an essential role in the salinization of shallow aquifers (Bighash and Murgulet, 2015; Schmidt and Garland, 2012). In mid-/high-latitudes, future climate will be marked by warmer winter temperatures and increased snowmelt, which may increase pollutant capture and solute leaching in the unsaturated zone, thus impacting groundwater quality (Bloomfield et al., 2006;

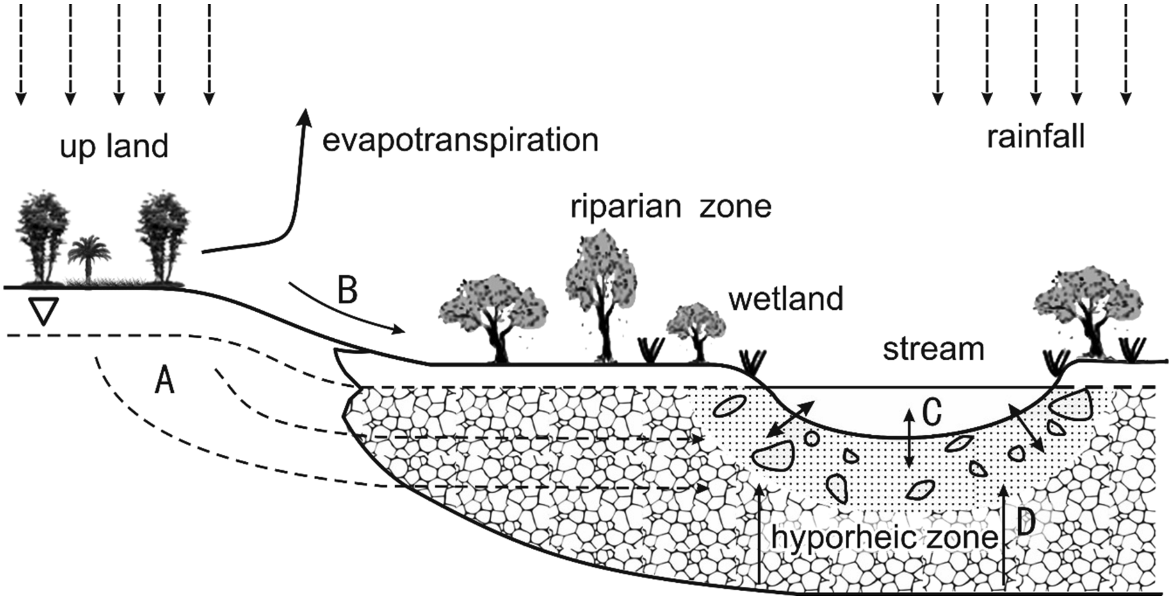


Fig. 4. Schematic representation of surface water-groundwater interaction and major pathways of water interaction is indicated by (A) groundwater flow, (B) overland flow, and (C) hyporheic exchange.
Adapted from Jolly et al. (2008)

Sugita and Nakane, 2007). Also, McGill et al. (2019) found that climate change may worsen sanitary conditions in less developed regions, resulting in the leaching of human waste from pit latrines into groundwater.

Pulido-Velazquez et al. (2015a) have quantified the impact of climate and land use change on groundwater quality related to nitrate concentrations, using the MT3DMS, a three-dimensional multi-species solute transport model (see Zheng et al., 2012) and SWAT model. The result reveals that nitrate concentration in groundwater increased in almost all the study locations across all the climate scenarios. Places that have high irrigation and recharge increases tend to increase nitrate concentrations in groundwater. Poor groundwater quality is a limiting factor for further planned uses, such as drinking or irrigation, and the long-term sustainability of global groundwater resources (Gurdak et al., 2011). Mas-Pla et al. (2019) have detailed the environmental, economic, social, and political concerns that arise from nitrate pollution exacerbated by climate change.

Some studies have reported increasing groundwater discharge temperatures (e.g.Kurylyk et al., 2014b), which is expected to rise even further due to climate change. (Gunawardhana and Kazama, 2011; Kurylyk et al., 2014a; Kurylyk and MacQuarrie, 2013). Increasing groundwater temperature may alter the hydrogeochemical processes that exert control on the mobility and dissolved concentration of chemical contaminants (Pitz, 2016), and thus influence groundwater quality (Riedel, 2019; Hähnlein et al., 2013). Riedel (2019) found that a 1°C increase in groundwater can lead to a 4% decrease in oxygen saturation and a drop of 0.02 in pH value. (Stuart et al., 2011; UNESCO, 2008). Additionally, changes in precipitation and E_T can affect natural groundwater composition. For instance, a rise in E_T following a decline in precipitation may increase geogenic contamination of arsenic and fluoride (Amanambu, 2015; Amini et al., 2008a; Amini et al., 2008b). In contrast, places of excessive rainfall can ease the mobilization of geogenic contaminants (Amanambu, 2015).

The thermal response of groundwater temperature to climate change, in turn, affects the thermal regimes of baseflow-dominated streams or rivers and their hydraulically connected aquifers (Menberg et al., 2014). Also, because the temperatures of the surface and subsurface are intertwined, groundwater temperature may be inferred from surface temperature (Beltrami, 2001; Gunawardhana and Kazama, 2012), and such linkages can provide more insight into the impact of climate change on the subsurface (Menberg et al., 2014). Benz et al. (2017) observed a global link between groundwater temperatures and land surface temperature, with an average offset of 1.2 ± 1.5 °C. The highest differences were found in the coldest and warmest areas of the Earth. They, therefore, attributed the high offset to E_T and snow effect. In cold regions, the impact of climate change on groundwater and soil temperatures is now a significant concern, especially as permafrost thaws (Harden et al., 2012; McGuire et al., 2012).

In any case, the indirect anthropogenic feedbacks to climate change may represent the most critical concern for groundwater quality (Baron et al., 2013; Bloomfield et al., 2013; Green et al., 2011; Li and Merchant, 2013; Pitz, 2016; Stuart et al., 2011; Treidel et al., 2011; Zhou et al., 2010). Excessive pumping or over-exploitation of wells due to increasing water demand and droughts, caused by climate change and compounded by development, especially in coastal areas, may sufficiently lower the water table to create saltwater intrusion (SWI) and the consequent salinization of freshwater (Romanazzi et al., 2015; Stocker, 2014; Van Camp et al., 2014).

Coastal aquifers in low-lying areas are also particularly vulnerable to SWI from sea-level rise due to climate change (Knott et al., 2019). SWI threatens groundwater resources (Ataie-Ashtiani and Ketabchi, 2011; Ketabchi et al., 2016), causing wells to be abandoned and leading to the salinization of vast quantities of fresh groundwater, thus making it unfit for a variety of human uses (Van Camp et al., 2014). As groundwater abstraction increases, wells run dry and must be dug to deeper levels. Consequently, groundwater quality decreases because deeper aquifers in coastal areas tend to produce lower quality water (Famiglietti, 2014; Konikow and Kendy, 2005).

2.5. *Groundwater-Surface water (GW-SW) interactions*

Many studies on groundwater-climate change interaction have concluded that climate change would exert an indirect influence on groundwater as a result of interaction with surface water systems such as lakes and streams, through the groundwater processes of recharge and discharge (Franssen, 2009; Bates et al., 2008; Dragoni and Sukhija, 2008). The interaction between groundwater and surface water is multifaceted (Fig. 4), influenced by the climate and modified by landform, geology, and biotic factors (Sophocleous, 2002). Kløve et al. (2011) identified three possible interactions between lakes and groundwater: 1) groundwater inflow to the entire lake bed (groundwater discharge); 2) groundwater outflow from the whole lake bed (groundwater recharge); and 3) both situations occurring at the same time in different parts of the lake or at different times of the year. In addition, surface water-groundwater connectivity, where present, may exist in various forms: (1) as a connected system—a gaining or losing surface water system; or (2) as a disconnected system—completely disconnected system or a transitional state (Li and Merchant, 2013; Penna et al., 2014). The systems share a common link through recharge and discharge, and their interaction constitutes a vital part of the hydrologic cycle (Jyrkama and Sykes, 2007; Saha et al., 2017). A decrease in surface water availability caused by climate change can affect this interaction (Saha et al., 2017).

In many hydrogeologic settings, natural groundwater discharges help to sustain surface waters during periods of low or no rainfall by sustaining baseflow. In the Upper Colorado River Basin (UCRB), baseflow alone accounts for about 50% of the total annual streamflow in the basin (Rumsey et al., 2015). Therefore, future climate-driven changes in temperature and precipitation, and consequently recharge, may potentially cause changes in baseflow and the magnitude and timing of groundwater discharges to surface water systems (Pitz, 2016; Solder et al., 2016; Sultana and Coulibaly, 2011; Tague and Grant, 2009). Earlier snowmelt, for example, is expected to reduce late-summer recharge and baseflow (Ahiablame et al., 2017; Xie et al., 2008). Changes in flow patterns between surface and groundwater may be amongst the earliest and most obvious direct groundwater-related implications of future climate change (Earman and Dettinger, 2011; Pitz, 2016).

Climate change may also impact GW-SW interaction by increasing the need for groundwater exploitation and development due to drought or an extension of the dry season. When this happens, the water table falls, and groundwater discharge to streams also decreases. This cause and effect relationship is supported by correlation studies linking fluctuations in water table levels to lake water levels (Christensen and Bergman, 2005; Williams and Pelletier, 2015). For example, in the Volta Lake region of Ghana, Yidana et al. (2019) found that increasing groundwater exploitation and climate change will reverse the current situation of net outflows into the Volta Lake. Massive declines in streamflow and lake levels can harm the whole water resources of a particular region (House et al., 2016). Sustaining volumetric flow rates to streams is vital for the survival of aquatic organisms. Groundwater inputs to surface water bodies help to sustain wetlands and associated plant and animal communities (Kløve et al., 2014; Yeakley et al., 2014).

Also, high precipitation may lead to an increase in surface runoff resulting in hydraulic pressures in the lower stream reaches, which may consequently cause a change in the river regime from effluent to influent, permeating its banks and recharging the aquifer, as Brunke and Gonser (1997) discovered. Summarily, an understanding of the possible impact of climate change on the relationship between subsurface and surface water is imperative for effective management of water resources (Barthel and Banzhaf, 2016; Gamvroudis et al., 2017).

3. Models in groundwater hydrology

Assessment of groundwater vulnerabilities in the face of climate change as well as its management for sustainable use will eventually stall unless our knowledge of groundwater systems continues to improve. Numerical modelling of groundwater provides the necessary tools for the continuous expansion of our understanding of groundwater processes (Diersch, 2013; Kumar and Singh, 2011; Pitz, 2016). Indeed, modelling is indispensable to understanding past and present conditions, and in predicting and ultimately controlling the future states of geophysical and Earth systems, including groundwater processes. The relative inaccessibility of aquifers and the complexity of subsurface processes also makes modelling indispensable.

The response of groundwater to important climate variables has been the focus of many studies, using both statistical models (Bierkens et al., 2001; Chen et al., 2002; Okkonen and Kløve, 2010) and complex numerical models (Allen et al., 1998; Brouyère et al., 2004; Cartwright and Morgenstern, 2012; Deng et al., 2013; Hanson and Dettinger, 2005; Jyrkama and Sykes, 2007; Ordens et al., 2014; Scibek et al., 2007; Wood et al., 2015). Here, emphasis is placed solely on numerical models that quantify groundwater flow processes using mathematical equations founded on some simplified assumptions (Kumar and Singh, 2011). The effectiveness of these models hinges on how thoroughly the equations approximate the physical system being modelled, which, in turn, depends on a thorough understanding and characterization of the relevant hydrogeological conditions. The most internationally recognizable groundwater model is the Modular Groundwater Flow Model, *Modflow,* a three-dimensional finite-difference model developed by the US Geological Survey (USGS). Much of its initial scope has been enhanced over the years through integration with other simulations. An example is the particle tracking model, *Modpath,* used in contaminant-transport studies after running a *Modflow* simulation (Mondal and Singh, 2009; Pollock, 2016). Others are *FEFLOW, SUTRA*, etc. (Kumar and Singh, 2011).

In general, groundwater models simulate the natural groundwater flow, solute transport—especially of dissolved chemicals—and aquifer condition (Kumar and Singh, 2011; Qiu et al., 2015). The aim is usually to predict flow under different circumstances and to improve understanding of aquifer behavior and functioning. Other groundwater models probe the chemical quality of groundwater and its susceptibility to varying hydrological and climatic regime, with additional capabilities for designing sustainable water management or remediation schemes, and to provide information about the response of aquifers to alternative courses of action (Bear and Verruijt, 2012). Table 2 summarizes the characteristics of various numerical models used in groundwater studies.

Groundwater flow processes were once thought to be disconnected from the atmosphere and therefore, were not included in most climate models (Taylor et al., 2013). However, many studies (Maxwell and Kollet, 2008) indicate that aquifers do in fact influence the atmosphere, especially in areas of relatively shallow water tables, where dynamic interactions between surface and groundwater can alter the surface water and energy fluxes in the boundary layer (Leng et al., 2014; Maxwell et al., 2011; Qian et al., 2013). Hence, aquifers should be considered part of the lithospheric heterogeneities that climate models must seek to simulate, without which reliable climate prediction—especially of local or regional climate—will remain elusive, and climate-groundwater feedback mechanisms will be poorly understood (Gulden et al., 2007; Maxwell et al., 2011). Accordingly, to better understand the impacts of climate change on groundwater, efforts have been made to represent groundwater processes in land-surface models embedded in GCMs or to couple complete groundwater models to surface water models or larger-scale atmospheric models (e.g. Huang et al., 2019). The recently developed USGS groundwater-surface water code, *GSFLOW*, couples two USGS models: the Precipitation-Runoff Modelling System, PRMS and *MODFLOW* (Hunt et al., 2008; Markstrom et al., 2008). The *GSFLOW* can be applied to more than one watershed, given that it simulates flow across watershed boundaries. *GSFLOW* has been used to simulate flow across the land surface simultaneously and within subsurface saturated and unsaturated materials, in a dense lake district in Wisconsin, USA (Hunt et al., 2008), and in northwest China (Penna et al., 2014; Wu et al., 2015). However, a more comprehensive model which integrates all facets of the hydrosphere—groundwater, surface water, and atmosphere—is the *HydroGeoSphere*, formulated to simulate the whole terrestrial part of the hydrological cycle (Brunner and Simmons, 2012; Maxwell et al., 2015). Others include *CATHY, PAWS, PIHM*, etc. (see Table 2).

Recently, GIS technology has become increasingly harnessed in groundwater modelling. GIS can be used either singly as a map-based tool for gathering and manipulating a large, high-quality hydrogeological database (Rahmati et al., 2016), or fully integrating it with

Table 2
Selected Numerical Groundwater Models and Characteristics.

MODEL	TYPE	BRIEF DESCRIPTION	REFERENCES
GROUNDWATER	● MODFLOW[3,a,c,d,e,f,g]	Sophisticated groundwater model with enhanced capabilities to simulate flow, solute transport, and coupled surface–groundwater flow.	(Bakker et al., 2016; Brunner and Simmons, 2012; Guzman et al., 2015; Kumar and Singh, 2011; Mondal and Singh, 2009; Pollock, 2016)
	● GMS[2,3,a,b,f,g]	A complete modelling package from conceptualization to visualization and can be interfaced with a host of other models,e.g. Modflow.	(Owen et al., 1996; Qiu et al., 2015; Xiaobin, 2003)
	● FEFLOW[2,3,b,c,d,e,f]	A finite element density-dependent groundwater flow, mass and heat transport process modelling system.	(Diersch, 2013; Kumar and Singh, 2011; Trefry and Muffels, 2007)
	● CHEM FLOW[1,a,c,d]	A finite difference model that simulates one-dimensional water and chemical movement	(Kumar, 2012; Rajamanickam, 2011)
	● AT123D[1,2,3,d]	A groundwater transport model for simulating long-term pollutant migration.	(Kumar, 2012)
	● AQUA 3D[3,a,c,d]	A 3-D finite element groundwater flow and contaminant transport simulation model	(Kumar, 2012)
	● SUTRA [2,3,c,d,f]	Simulates density-dependent groundwater flow as well as energy and solute transport	(Kurylyk et al., 2014; Voss and Provost, 2002; Winston and Voss, 2004)
SURFACE/SUBSURFACE COUPLED	● GSFLOW [A,B]	A coupled surface water and groundwater flow model built on the integration of the Precipitation-Runoff Modelling System (PRMS) and MODFLOW	(Markstrom et al., 2008)
	● MIKE SHE [B,C]	A comprehensive and integrated physically-based model capable of simulating the entire land phase of the hydrological cycle.	(Akram et al., 2012; Golmohammadi et al., 2014; Prucha et al., 2016)
	● HydroGeoSphere[B]	A 3-dimensional finite element model designed to simulate the whole terrestrial portion of the hydrological cycle.	(Brunner and Simmons, 2012; Maxwell et al., 2014)
	● OpenGeoSys (OGS)	An object-oriented numerical model which simulates thermo-hydro-mechanical/chemical processes in a porous or fractured media,	(GRÄBE et al., 2012; Kolditz et al., 2012)
	● Parflow[A, B]	An integrated physically-based model which simulates both groundwater and surface water flows.	(Kollet and Maxwell, 2008; Maxwell et al., 2015)
	● PAWS[A, B]	A 3-dimensional model for simulating the entire watershed hydrology: overland, surface and subsurface processes	(Shen et al., 2013)
	● CATHY [A,B]	A physically-based model that integrates surface water and groundwater processes.	(Gauthier et al., 2009; Guay et al., 2013)
	● WaterGap [A,B]	A multipurpose hydrological model simulating water balance, sectoral water use, water quality and recharge	(Brauman et al., 2016; Döll et al., 2001; Portmann et al., 2013; Schumacher et al., 2018)

GROUNDWATER
[1]-1-D
[2]-2-D
[3]-3-D
[a] Finite difference.
[b] Finite element.
[c] Groundwater flow.
[d] Contaminant/Solute transport.
[e] GIS interface
[f] Visualization/graphical tools
[g]Interphase with other models

SURFACE/SUBSURFACE COUPLED
[A] coupled groundwater-surface water.
[B] simulates the entire terrestrial hydrological cycle.[C]GIS interface.

other numerical groundwater models, a process known as *coupling* (Gogu et al., 2001; Gossel et al., 2004; Huo et al., 2007). Integration may be achieved through developing groundwater models that work in a GIS framework, as in *FEFLOW* (Huo et al., 2007) and *MODFLOW.* Gogu et al. (2001) and Ashraf and Ahmad (2012) described this integration, highlighting the unique spatial analysis and visualization capabilities that GIS lends to groundwater modelling. Visualization can help recalibrate numerical models by showing differences between modelled, interpolated, and measured water levels (Gossel et al., 2004). Additionally, multi-layered environmental GIS maps provide decision support tools for better evaluation of management options for the sustainable development of groundwater resources. This ability to overlay disparate environmental data makes GIS indispensable to groundwater management.

3.1. Modelling future climate impacts on groundwater

Regardless of the spatial scales of study, investigating the potential impact of climate change on groundwater involves coupling GCM climate projections with models of groundwater components (Green, 2016; Smerdon, 2017). The process starts with choosing a set of GCMs, GCM output, and a carbon dioxide emissions scenario. These GCM outputs often need to be downscaled to finer scales suitable for hydrological modelling for regional and aquifer-specific studies because of the coarse resolution of GCMs. Downscaled GCM outputs are then coupled with hydrological models to produce estimates of specific groundwater components (Kumar, 2012; Ng et al., 2010; Smerdon, 2017). The whole process involves choosing among a set of GCMs, downscaling methods, and hydrological models, all of which creates uncertainties in outcomes (Crosbie et al., 2013; Green, 2016). Crosbie et al. (2013) and Nkhonjera and Dinka (2017) independently sought to quantify the relative uncertainties in projections of recharge rates from GCMs, downscaling methods, and hydrological models. They found that the choice of appropriate GCM was the most crucial one because it is the most significant source of uncertainties in future projections of recharge. The choice of downscaling methods and hydrological models were the second and next largest source of uncertainties in recharge projections.

In contrast, Kurylyk and MacQuarrie (2013), in their studies in eastern Canada, found that downscaling methods contributed the most

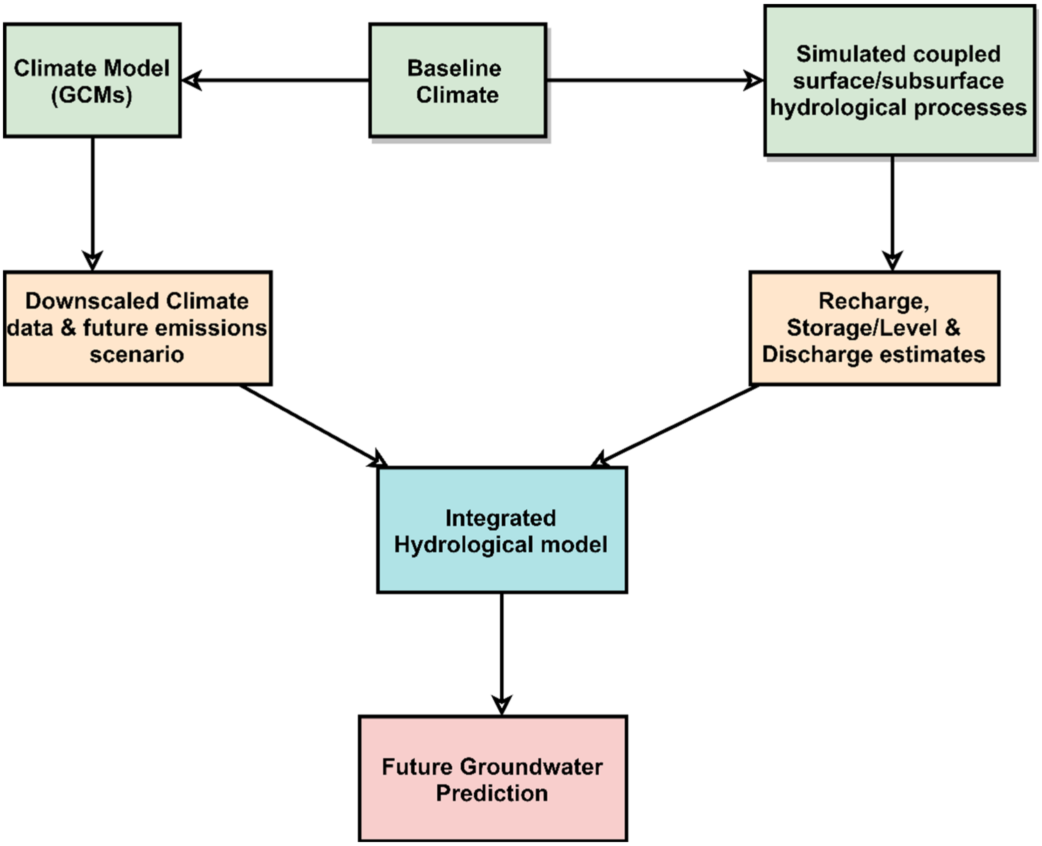


Fig. 5. A generalised framework for Groundwater-Climate change Modeling.

uncertainties to future recharge estimates. Moeck et al. (2016) have also explored uncertainties arising from hydrological models. The different types of downscaling methods and their implications for recharge estimates are discussed in depth by Green et al. (2011) and Holman et al. (2009). To circumvent the problem of GCM and hydrological model selection, many scholars now suggest as best practice the use of an ensemble or range of GCMs and hydrological models to produce the most realistic range of estimates (Crosbie et al., 2013; Holman et al., 2012; Larocque et al., 2019).

A generalized conceptual framework in modelling the future impacts of climate change on groundwater is shown in Fig. 5. A typical modelling framework involves forcing a hydrological model with downscaled GCM climate data and simulated groundwater component variables (using baseline climate data) to generate future estimates for the groundwater component under investigation. Groundwater recharge is understandably the most popular groundwater component for which future predictions are generated. Simulation of groundwater components can range from simplistic numerical models where recharge, for instance, is related exclusively to precipitation (Kirn et al., 2017), through more complex water balance models that take cognizance of temperature and actual E_T, to the most sophisticated simulation of watershed characteristics, including runoff, soil, vegetation dynamics, as well a plurality of climate variables. Some complex watershed simulations, such as that in Alam et al. (2019), model river runoff and reservoir storage and releases, across multiple vertical levels of groundwater flows. The indirect effect of climate on groundwater, which includes the effect of climate on crop evaporative water demand and vegetation evolution, was also accounted for. The use of a heterogeneous subsurface hydrogeology and temporally evolving soil and vegetation dynamics add extra layers of complexity to the simulation of surface–subsurface hydrologic processes, but also permit more realistic estimates of recharge and other groundwater component variables to be made.

The result of potential future groundwater changes for 40 selected studies in the last 5 years is synthesized in Table 3. The studies are subdivided based on the climate of their respective watershed, to assess possible climatic dependencies in future groundwater changes. In our scheme, studies are first broadly classified as either temperate or tropical, before subdividing these classes into smaller recognizable climatic regions. Further, for each study, the groundwater component investigated and the type of climate model and hydrological model used are shown in the table. The size of the study area is shown by color-coding the letters that specify hydrological models, and the future changes in groundwater components produced by the models are provided in the penultimate column. Future predictive changes in groundwater component are relative to baseline conditions, and produced for both the near-term (2020 – 2030/2045) and the distant future (usually 2075 – 2100). The last column shows the SWOT analysis of the predictive models.

As stated above, the future direction of change in groundwater component resulting from climate change was organized by climate region. Fig. 6 summarizes the result for all 40 studies. Of all 33 studies of future recharge change, only eight studies reported an increase over the baseline. The majority of studies found a decrease, with only a few reporting no change. A similar result was found for groundwater level and storage. A breakdown of recharge studies by climate also revealed that, across both temperate and tropical regions (Fig. 6a), recharge and storage are expected to decrease, and, surprisingly, even more acutely in tropical regions (80%). For all 40 studies, increasing temperature and E_T were predicted to increase for the distant future, and these appear to be exacting a stronger influence on recharge and storage, especially in the tropics where some precipitation decreases are predicted. Where rainfall increases occur, recharge may still be limited if light and very heavy rainfall—which has been shown to contribute little to recharge—account for much of that increase. However, rainfall is of course not entirely useless for recharge generation in the tropics.

Table 3

Climate and hydrological modeling studies at varied scales in differing climatic zones with corresponding SWOT overview.

Broad climate zones	**Climatic region(s)**	**Study Framework/ Component**	**Climate and Hydrological Models, Study Size**	**Future Prediction**	**Strengths, Weaknesses, Opportunitiesy and Threats (SWOT)**
Temperate	Medi-terranean^{6,10,38,39,16}	S^{6}, $R^{10,38, 39,16}$, L^{10}	^{6}20 GCMs + *a*, ^{10}1 RCM + *x*, ^{38}7 RCMs + *c*, ^{39}5 GCMs + *e*, ^{16}5 GCMs + *f*	↓ S^{6}, ↑ R^{10}, ↑ L^{10}, ↓ R^{38}, ↓ R^{39}, ↑ Rn^{16}, ↓ Rd^{16}	Strengths i. Increase in credibility of predictions^{31} ii. Inclusion of human system that integrates hazard, susceptibility, and risk to the prediction^{34} iii. Uncertainty in projected outcome was highlighted^{9,32} iv. The use of large ensemble climate models that reduce uncertainty in future predictions$^{6,9,13, 18-19,24,30,31,33, 36,37,38}$ v. Inclusion of several environmental variables in hydrological models for future prediction^{36} vi. The use of complex hydrological models that incorporate processes and mechanisms to reduce uncertainties. vii. The use of regional climate models (RCMs) tends to reduce uncertainties in future predictions^{1,12,3,17,38,20,21,31} viii. Limiting predictions to the near future reduces uncertainty in predictions^{14,32,16,36} ix. Future prediction with smaller spatial scale reduces uncertainties^{2,3,4,17,18,20,23,27,31,32,34,36,37,38,40} Weaknesses i. Complexity in simulated processes often precludes replicability. ii. Using few GCMs/RCMs for future predictions compounds uncertainties $^{1-4,6,8,10,11-12,14,20-23,25,29,30,32, 34,30}$ iii. The use of GCMs rather than RCMs, for regional and local studies, may increase uncertainties$^{11, 8, 29, 30, 14, 34}$ iv. No sensitivity analysis or assessment of results uncertainty for many predictions^{16,26,27,36} v. Using a baseline climate data of less than 30 - 35 years may produce an inaccurate picture of the climate of a study area, and thus lead to spurious relative future changes^{11,20,31} vi. Uncertainty in projected future GW from selected climate models and scenarios show mixed results. vii. Using overly simplistic hydrological model may increase uncertainty^{22,18} viii. Employing very few groundwater data points may be spatially unrepresentative of total watershed characteristics^{22,20} ix. Anthropogenic influence like GW abstraction can amplify uncertainties in prediction^{7} x. Future predictions up to the 2100, while the norm in climate change studies, may be fraught with uncertainties relative to near-term predictions. xi. Providing a complete picture of groundwater response to the changing climate is even more challenging given that the impacts of climate change are often modified by human and indirect agents such as land-use change and over-exploitation of groundwater. xii. Future prediction with larger spatial scale may introduce uncertainties Opportunities i. Improvement in modeling tools by incorporating process and mechanism or by creating a hybrid model from exiting hydrological models. ii. Uncertainty prediction and sensitivity analysis should be incorporated in future predictions iii. Synergetic roles of different climate variables in influencing GW should be investigated^{39} iv. Temporospatial level of uncertainties should be included in future groundwater behavior when including human systems in GW modelling^{34} v. including extremes in complex hydrological model may likely reduce uncertainties in prediction^{9} vi. High resolution remotely sensed data should be developed to monitor GW especially in places that lack data for impact studies. Threats i. Lack of clarity in future uncertainties will limit future policy formulation. ii. Unavailability of GW data may limit our understanding of processes and mechanisms that influence GDEs in the face of climate change. iii. Climate change is likely to affect the future direction of GW components in unknown ways so much so that models may not be able to capture these impacts. iv. Many surface waters and aquifers are hydraulically connected thus GW has threats from surface pollution and overconsumption. These interconnectedness and resultant impact will be harder for future simulation in the face of climate change. v. Inability of several hydrological models to incorporate the hydrogeology of GW will most likely exacerbate uncertainties.
	Climatically diverse^{19,15}	$R^{19,15}$	^{19}11 GCMs + *g*, ^{15}5 RCMs & 4 GCMs + *h*,	↕ R^{19}, ↓ R^{15}	
	Semi-arid steppe^{13,40,28}	$R^{13,40,28}$, L^{13}	^{13}32 GCMs + *b*, ^{40}3 GCMs + j, ^{28}97 GCMs + *k*	↑ R^{13},↓ L^{13}, ↓ R^{40}, ↑ R^{28}	
	Humid/cool continental^{2,7,20,31,25,35,37}	$Q^{2,20}$, $L^{31,37,35, 7}$, U^{31}, $R^{37,7}$, N^{25}	^{2}3 RCMs & WRFe* + *m*, ^{20}1 RCM + *n*, ^{31}6 RCMs + *m*, ^{37}24 GCMs + *k* + *o*, ^{25}4 GCMs + *i* + *o* ^{35}1 RCM + *k* ^{7}4 RCMs & WRFe* + *m*	↓ $Q^{2,20}$, ↓ $L^{31,35}$, ↓ U^{31}, ↓ $R^{37,7}$ ↓ L^{37}, ↑ N^{25}, ↔ R^{7}, ↕ L^{7}	
	Warm temperate^{3,34}	R^{3}, $L^{3,34}$	^{3}3 RCMs + *b* + *f*, ^{34}1 GCM + *d* + *o* + *p*	↓ R^{3}, ↓ $L^{3,34}$	
Tropics	Humid subtropical^{30,36,23}	$R^{30,36}$, $L^{36,23}$, $S_W{}^{23}$	^{30}2 GCMs + *i*, ^{36}1 GCMs + *b* + *k*, ^{23}4 GCMs + *f* + *t*	↑ Rn^{30}, ↓ Rd^{30} ↑ L^{36}, ↓ Rn^{36}, ↑ Rd^{36}, ↓ L^{23}, ↑ $S_W{}^{23}$	
	Humid Tropical$^{1,4-5, 14,18,21,26,27}$	$R^{1,4-5,18,21,26,27}$, $L^{18,26}$, $S^{14,26}$, Q^{4}	^{1}1 RCM + *b*, ^{14}2 GCMs + *i* + *t*, ^{18}10 GCMs + *k* ^{21}1 RCM + *y*, ^{26}5 GCMs + *b* + u, ^{27}10 GCMs + *s* + *t* ^{4}1 GCM + *m* ^{5}12 GCMs + *k*	↑ $R^{1,4,6}$, ↓ $R^{4-5,14,18,21,26,27}$, ↓ $L^{18,26}$, ↑ L^{1} ,↑ S^{1}, ↓ S^{26}, ↓ Q^{4}	
	Dry Subtropical^{9,17,22,29}	$L^{9,29}$, $R^{17,22,29}$, $S^{22,29}$	^{9}20 GCMs + *b*, ^{17}1 RCM + *b* + *q*, ^{22}1 GCM + *k*, ^{29}1 GCM + *b* + *k* + *v*	↓ $L^{9,29}$, ↓ $R^{17,22,29}$, ↓ $S^{22,29}$	
	Tropical montane^{11,12}	B^{12}, $R^{12,11}$, L^{11}, S^{11}, $S_W{}^{11}$	^{12}RCM + *s*, ^{11}1 GCM + *b* + *f* + *t*	↓ B^{12}, ↓ R^{12} , ↓ L^{11}, ↓ S^{11}, ↔ $S_W{}^{11}$	
	Semi-arid/arid^{8,24,32,33}	$R^{8,24, 32,33}$,L^{32}	^{8}1 GCM + *b*, ^{24}10 GCMs + *b* + *k*, ^{32}1 GCM + *b* + *v*, ^{33}7 GCMs + *k*	↓ $R^{8,24,33}$, ↓ Rd^{32}, ↓ Rn^{32}, ↓ L^{32}	

*WRFe—Weather Research and Forecasting ensemble models; GW—groundwater

Framework/component: B = Baseflow, **L** = Level, Nitrogen concentration = N, Q = discharge, S = storage, Salt water concentration = S_W, R = Recharge (n = near future, d = distant future), Uncertainty = U

Future direction of change: ↑ = increasing, ↓ = decreasing, ↕ = increasing/decreasing, ↔ = no change

Study size (km^2) : 🟩 Very small (> 10^2) , 🟦 Small (10^2—10^3), 🟨 Medium (10^3—10^4), 🟥 Large (10^4—10^5), 🟪 Very large (> 10^5), ⬛ Not specified

Hydrological Models: *a*—Central Valley-Surface Water Simulation Model, *b*—Modflow, *c*—Continuous balance model, *d*—HEC-RAS, *e*—Spatially distributed Hydrogeological model, *f*—SWAT, *g*—VIC Model, *h*—Precipitation-recharge Model, *i*—HELP (3), *J*—HYDROBAL, *k*—Soil-Water-Balance/budget, *l*—HEC-HMS, *m*—HydroGeoSphere, *n*—GSSHA (Gridded Surface Subsurface Hydrologic Analysis) mode, *o*—FEFLOW, *p*—HEC-RAS, q— HYDRUS-1D, *s*—WetSpa , *t*—SEAWAT, *u*—WETSPASS, *v* = EARTH, *w*—Qbox, *x*—VISUAL BALAN, *y*—GR2M

Authors: [1]Patil et al. (2020), [2]Persaud et al. (2020), [3]Shrestha et al. (2020), [4]Klaas et al. (2020),[5]Rodríguez-Huerta et al. (2020), [6]Alam et al. (2019), [7]Erler et al. (2019), [8]Ghazavi and Ebrahimi (2019), [9]Goodarzi et al. (2019), [10]Pisani et al. (2019), [11]Akbarpour and Niksokhan (2018), [12]Kahsay et al. (2018), [13]Ou et al. (2018), [14]Pholkern et al. (2018), [15]Pulido-Velazquez et al. (2018), [16]Gemitzi et al. (2017), [17]Kambale et al. (2017), [18]Melo and Wendland (2017), [19]Niraula et al. (2017), [20]Saha et al. (2017), [21]Soro et al. (2017),[22]Toure et al. (2017), [23]Chang et al. (2016), [24]Goodarzi et al. (2016), [25]Paradis et al. (2016), [26]Shrestha et al. (2016), [27]Tam et al. (2016), [28]Tillman et al. (2016), [29]Toure et al. (2016), [30]Beigi and Tsai (2015), [31]Goderniaux et al. (2015), [32]Hashemi et al. (2015),[33]Herrera-Pantoja and Hiscock (2015), [34]Iyalomhe et al. (2015), [35]Jang et al. (2015), [36]Kaur et al. (2015), [37]Lemieux et al. (2015), [38]Pulido-Velazquez et al. (2015b), [39]Sapriza-Azuri et al. (2015), [40]Touhami et al. (2015).

Comparison between studies in the wettest and driest parts of the tropics (Fig. 6b) revealed a better recharge outcome in the former than in the latter, although a majority of studies still reported decreases in recharge and storage.

Like in the tropics, studies in temperate climates also revealed mostly decreasing groundwater recharge and storage; however, these decreases are not as severe as in the tropics. The difference may be due to the effectiveness of snowmelt—which is predicted to increase in a warmer temperate climate—as a recharge generator on seasonal scales (Kløve et al., 2014; Okkonen and Kløve, 2010). But a warmer temperate climate also portends less snowfall and more rainfall, consequently reducing snowmelt over longer periods (Earman and Dettinger, 2011) and thus, reducing recharge. In sum, it should be noted that these 40 studies may not be representative of the broader literature on the subject matter. The presence of uncertainties in estimates also precludes any engagement with these results beyond a tentative, cursory level.

4. Groundwater feedback to the climate system

Vital feedbacks occur between groundwater and atmospheric processes on decadal and longer timescales (Barthel and Banzhaf, 2016; Levy et al., 2018). One such groundwater feedback is the contribution to sea-level rise, where abstracted water from aquifers becomes part of surface water flows until it drains into the ocean. Although some scholars are skeptical about the effectiveness of groundwater abstraction as a cause of sea-level rise, several studies have shown that human-driven changes in land water storage including the direct effects of groundwater abstraction, irrigation, enclosures in reservoirs, wetland drainage, and deforestation play an important role in sea-level changes (Döll et al., 2001; Konikow, 2011; Wada et al., 2012b). Moreover, groundwater depletion strongly affects the trends in regional and global land water storage (Richey et al., 2015). Employing recent developments in satellite measurement of time-variable gravity from NASA's GRACE, Reager et al. (2016) assessed the role of land water storage in sea level changes over the 12 years from 2002 to 2014. The results showed that human-induced groundwater depletion contributed substantially to a gross negative mass trend of –0.97 mm year^{-1} sea-level equivalent.

Another groundwater feedback to the climate is an increase in evapotranspiration (Goodarzi et al., 2019), through increased soil moisture from groundwater-based irrigation. The addition of water to an otherwise dry surface affects the surface energy balance, alters the latent and sensible heat fluxes, and the boundary layer, with likely feedbacks on precipitation (Famiglietti et al., 2011; Leng et al., 2014; Qian et al., 2013). With more soil moisture from irrigation and only energy as the limiting factor, evapotranspiration may occur unabated in summer months, further leading to increases in precipitation and river runoff (DeAngelis et al., 2010; Kustu et al., 2011; Lo and Famiglietti, 2011). Gaining a better understanding of groundwater-climate feedback will require a more detailed representation of groundwater-surface water interaction in the land-surface hydrological phase of GCMs (Taylor et al., 2013; Zaveri et al., 2016).

5. Future considerations

Previous reviews (Table 1) of the past decade have indicated what needs to be done going forward, but there is a need for a clear direction with evidenced examples of what, when (time) where (spatial) and how the path must be. Future considerations are, therefore, tabulated in Table 4, and the sections that follow provide a detailed explanation.

5.1. Physical Basis

5.1.1. The scale of the study

Studies of climate change-groundwater interaction should consider the limitations that spatial scales and subsurface heterogeneities place on their studies. Climatic effects on hydrological components, including groundwater, vary over the Earth surface, and so recharge estimates will vary depending on the spatial scale used in a study. Related to the above is the challenge of controlling for subsurface heterogeneities wwhich significantly alter recharge estimates, yet hydrological models often assume a homogenous layer (Hartmann et al. (2017). Studies of future climate impacts on groundwater will, therefore, benefit from designing studies that allow for subsurface variations. Future projections of changes to groundwater resources should focus more on short-to-medium term forecasts, rather than long-term forecasts which are often beset by uncertainty and inadequate for serious policymaking.

5.1.2. Processes and mechanism

More still needs to be done to comprehend better the complex hydrogeological processes of groundwater on the one hand and how these processes are being affected by climate change on the other. Also, questions remain on the range of mechanisms governing groundwater system and climate change interactions. For example, little is known of advective heat transport in the groundwater system, especially in permafrost areas. Physically-based hydrological models can, to a certain extent, account for processes occurring at scales smaller than the grid-scale. But they do not accurately simulate the role of chemical and biological processes in controlling streambed permeability, and the interaction between rivers and groundwater (Brunner et al., 2017). How does climate change affect the flow rate? What is the future direction and seasonality of potential effects on flow? Answers to these questions can only come through a deeper understanding of processes and mechanisms.

Research on groundwater is process-driven, and the exclusion of these processes usually lead to uncertainties in the modeling approach. Many models do not incorporate complex processes inherent in groundwater and climate change relationships. One limitation in modeling groundwater is the issue of models that cannot integrate the surface–groundwater and the unsaturated zone. When they are available, they are computationally intensive and sometimes fail to incorporate all needed complex processes, increasing uncertainties. Researchers have neglected the rebounding effect of feedback processes while investigating the impact of climate change on the groundwater system. For instance, there is a need for quantitative studies that will examine the influence of climate change on groundwater temperature and flow rates and the consequent effect on riverine and lacustrine thermal regimes and how these resultant effects, in turn, affect groundwater. More work of complex feed-forward and feedback processes is needed, including quantifying the feedback of vegetation on water balance. Future models need to incorporate complex feedback fluxes of the impact of evapotranspiration due to changes in climate.

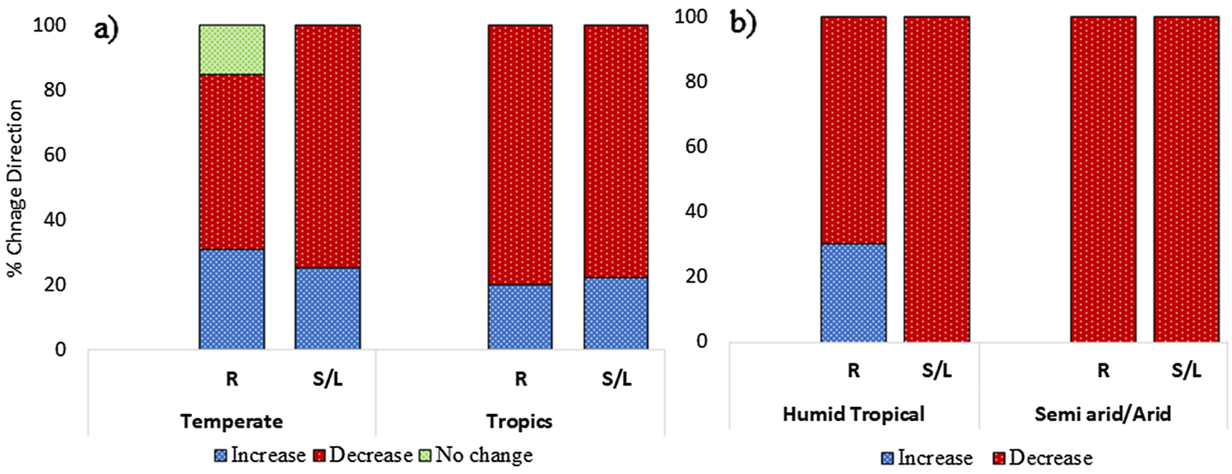


Fig. 6. Summary of the future groundwater changes by climate region based on: a) the 40 studies listed in Table 3; b) a subset of 20 of the 40 studies in the wettest and driest tropics. Recharge—R, Storage—S, Level—L.

For example, changes in climate may lead to a given flora adjusting its transpiration rate because of increased CO_2, and may adapt by altering its vegetation cover and development of a deep root system if CO_2 increases persist (Schaller and Fan, 2009). These processes will have a feedback effect on the groundwater system, and models must be able to capture these processes when simulating climate change impact on groundwater processes. Also, groundwater-land surface feedbacks may impact moisture transport, boundary layer development and precipitation processes at the local and regional scale (Ferguson and Maxwell, 2010; Jiang et al., 2009). More work is required to quantify if regional climate response to a changing climate is dependent on groundwater-land surface feedbacks (Ferguson and Maxwell, 2010).

Models must be robust enough to track and quantify the hidden effects of feedbacks resulting from the dynamic interplay and complex processes of Earth's components. Integrating groundwater processes (land surface-deep hydrological exchanges and groundwater flow) directly into GCM modeling may reduce the uncertainties. While examining complex processes, research on the linearity of groundwater contamination and also the non-linear processes with regards to system response in GDEs should intensify. Aslam et al. (2018) have suggested the use of semi-distributed models in solving the problem of linearity. All these must be done at local to regional scale and outcomes applied to places of similar attributes. We recommend that processes-mechanism, within the context of modelling, should be adopted in groundwater-climate change studies.

5.1.3. *Models*

Groundwater modelling has and continues to open up entire vistas in our understanding of sub-surface processes. It holds the promise of enhancing our understanding of the groundwater-climate relationship, climate change and groundwater feedback mechanisms, and consequently, appropriate management options for sustainable use of water resource. However, models are always at the mercy of a thorough understanding of the operative physical processes, and the ability to characterize and quantify them correctly. Hence, models can differ markedly in their simulations and predictions of the same physical system, and discrepancies in different GCMs results are due to a misunderstanding of subtle atmospheric processes. For example, Zhang et al. (2013) argued that the HadGEM2-ES and other sophisticated climate models often misquantify the relative role of aerosols in cooling the Earth because cloud processes are not adequately resolved. Quantifying aerosol cooling effects through cloud cover simulation is one of the leading causes of uncertainties in climate modeling, and thus a priority for future research since it plays a role in evaluating future scenarios of the climatic element, including precipitation. Indeed, uncertainties in precipitation projections hamper estimates of projected groundwater changes and their potential feedbacks on climate. Models should be robust enough to simulate the complex and dynamic interactions that typify the climate system.

5.1.4. *GCMs and downscaling*

Uncertainties also arise from the choice of GCMs, the choice of downscaling methods, and hydrological models. These uncertainties influence the effectiveness of the results for mapping out appropriate management strategies for groundwater sustainability. The ambiguity of trends and distribution in climatic parameters result in varying predictions of groundwater flow, recharge, storage and discharge, so much so that models cannot predict the magnitude and direction of these processes. Researchers (Chang et al., 2011; Kingston and Taylor, 2010; Zhang, 2015) have recommended multi-model approaches to reduce the impacts of uncertainty. When using any downscaling techniques, there is a need to quantify the uncertainties. For better groundwater-climate change studies, researchers must focus on techniques that are robust enough to consider both climate variability and change. Some downscaling techniques (e.g. Delta change) do not consider variability. The Bias Corrected Spatial Downscaling (BCSD), used in plains areas, does not account for terrain effect (Aslam et al., 2018). Regional Climate Models (RCMs), on the other hand, can account for variability and terrain effect (Andreasson et al., 2003), and are recommended to be utilized for future studies because they produce better future estimates of climate data in smaller domains (Jang et al., 2015). Researchers must also seek to provide better justification for their choice of the downscaling method. In general, there is an urgent and continuous need for better models, as well as improvements in modelling and downscaling techniques.

5.1.5. *Modification by irrigation*

Recent studies (Russo and Lall, 2017; Whittemore et al., 2016) have shown that groundwater levels respond faster to changes in pumping—driven of course by human response to climate variability—than to direct changes in recharge also driven by climate variability. It has also been shown that response to pumping is strongest in irrigated agricultural areas where the water needs are urgent. However, in India, the contributions of groundwater pumping and precipitation to groundwater variability varied regionally, even though irrigation agriculture has increased in most of the country (Asoka et al., 2017). Recently, there has been an increase in research studies on the interactions between climate variability and groundwater (Bouderbala, 2017; Bouderbala, 2018; Durrani et al., 2017; Hartmann et al., 2017; Lorenzo-Lacruz et al., 2017), yet the relative influence of indirect and direct climate variability impact on groundwater levels remains mostly unclear. This complication has considerable implications for groundwater management and should be accounted for in future predictions of climate change impacts on groundwater. Furthermore, hydro-climatological models that consider variability and change like the BCSD and RCM should be considered for future research.

5.2. Socio-Economic Dimension

5.2.1. Multidisciplinary Synergies

The complex subject of groundwater and climate change relationships needs a transdisciplinary approach where biophysical and socio-economic responses are adequately quantified. In doing so, there must be cooperation in research at local and regional levels that will involve shared knowledge. The implication of this is likely to be a new scientific approach to climate change-groundwater studies regarding models that can link climate variability and change, hydrology/hydrogeology, demographic dynamics, socio-economic implications (e.g. water demand), and vegetation dynamics. Morsy et al. (2017) asserted that this approach should be adopted to limit uncertainties through a toad's eye view rather than an eagle's eye view by linking the environment, economic and social aspects. Also, collaboration is critical among stakeholders at all levels and must cut across governments and organizations from the local to the international level. Cooperation will enable proper investigation of the socio-economic and ecological implications of collaborative management of shared aquifers (Albrecht et al., 2017) in the face of climate change, and bridging the gap of groundwater sustainability. Collaboration through a multidisciplinary approach can foster protection and restoration of ecosystems that are vital water resources areas (e.g. wetlands and mountain forests) which protects recharge.

5.2.2. Groundwater monitoring network

While the physical basis and its components, as well as socio-economic dimension, are essential, there is an urgent need for a more enduring long-term groundwater data monitoring. Although expensive, a denser network of groundwater observation sites needs to be created, especially in remote areas and less developed regions to provide more data for detailed study and to supplement other data sources whose spatial resolutions are too coarse for any meaningful local application. GDEs, as well as groundwater contaminations, should be included in groundwater monitoring networks at the local to global level. These detailed records can aid the improvements in the quantification of hydrogeological systems at local to regional scales.

5.2.3. Adaptation

Many studies neglect to investigate the adaptive capacity of people to groundwater systems because indicator-based methodologies are requisite in the quantification of the adaptive capacity of the groundwater system (Aslam et al., 2018; Brooks and Adger, 2003). Cullet and Stephan (2017) notes that policy formulation related to sustainable future groundwater use should shift from traditional emissions reduction to groundwater adaptation strategies.

Kipling et al., (2019) have identified responsibility, scope, optimization, information, and collaboration as important adaptation-specific elements and challenges in modeling climate change impacts for adaptation. While these adaptation elements can represent challenges, they can also serve as strategic considerations in climate change-groundwater modeling for adaptation. Similar to Kipling et al. (2019), five adaptation specific elements—continuous, extent, improve methods, data aggregation and multidisciplinary synergies—have been identified as key elements in modeling climate change impacts for groundwater adaptation. Because climate change is progressive, there should be *Continuous* short-term modeling of climate change impacts (Fig. 7). Here, modelers will most likely achieve a better result through *Multidisciplinary Synergy* that enhances collaboration. It is therefore the responsibility of modelers to constantly communicate the climate

Table 4
Summary of Key Considerations for groundwater climate change research.

Steps	Considerations	Framework	Justification
1	Physical Basis	Scale of Study	Shorter temporal and smaller spatial scales will help curb the problem of uncertainties and better explain inherent processes.
		Process and Mechanism	Climate change impact cannot be well defined if the processes of the groundwater system, as well as the mechanism driving the process, are not well understood.
		Models	Advancement in robust models can provide better explanations and reduce uncertainties.
2	Socio-economic Dimension	Multidisciplinary Synergies	Groundwater is multidisciplinary and should not be subsumed under a few disciplines. Collaboration among a group of related fields is therefore required to produce better scholarship.
		Groundwater monitoring network	More data can help to reduce the uncertainties inherent in Hydro-climatological models considerably.
		Adaptation	Climate change is already part of Earth's processes; understanding this will make us better suited for creating policy and dealing with social changes such as migration related to water scarcity.

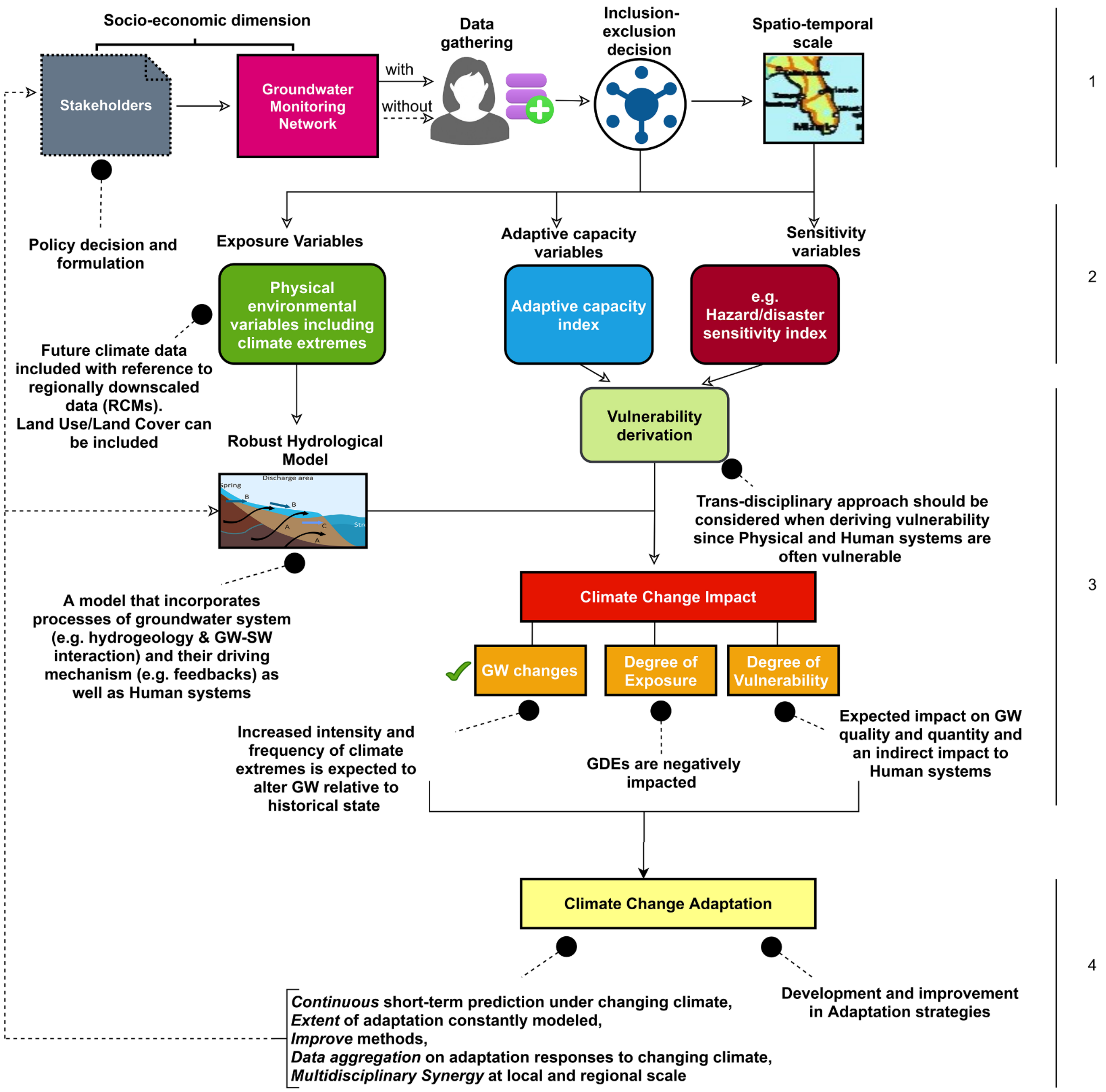


Fig. 7. Directional consideration and framework for continuous Climate Change-groundwater adaptation. Stage 1 involves decision making by stakeholders on groundwater network. Data acquisition can be with/without GW network, decision on data inclusion and spatiotemporal scale of the study domain. Stage 2 involves the derivation of adaptative capacity and sensitivity indices. Stage 3 uses a robust hydrological model to determine climate change impacts with regards to the degree of exposure and changes in GW systems. Stage 4 combines stages 2 and 3 to generate a set of adaptation strategies. The implementation of the aforementioned strategies is used to generate a set of monitoring adaptation specific elements. In stage 5, monitoring variables are fed to stakeholders—to improve decision making and hydrological model—to develop more realistic future GW scenarios.

change outcome to stakeholders for management decision. Cascades of complex feedbacks are generated across multiple sectors as climate change interact with biological and physical systems, making impacts and adaptation studies predominantly complex (Kipling et al., 2019). As such, a decision in modeling the *Extent* (what biophysical systems should be included?) to which climate change affect groundwater systems—given socio-economic and political changes with time—is paramount. The modeling can follow different pathways—depending on the choice of the modeler, and have varying impact on societies and biophysical systems. Thus, pathway adaptive response to climate change constantly explored will lead to a better adaptation strategy from informed decision making.

Developing scenarios for adaptation may be complex because adaptive responses to climate change arepathway-dependent, uncertainties are inherent in data acquisition, and because of changes in choices made by stakeholders. Continuous *Data aggregation* on adaptation responses should be focused on reducing uncertainties. Though uncertainties generally exist in models, the quality of data from human-environment systems is important for modeling climate change-groundwater adaptation. In the face of progressive climate changes, data, uncertainties, and stakeholder decision are expected to change—and modelers must use the information to *Improve* modeling methods for enhanced adaptation strategies (Fig. 7). Adaptation modeling and strategies may be ineffective without *Multidisciplinary Synergy*.

A localized collaboration between researchers within and across regions provide the possibility to consider innovative solutions by cross-pollinating ideas across disciplines, informed by participation of local people such as farmers, fishermen and households whose income, lifestyles and culture are deeply dependent on groundwater resources. The response of local people to climatic changes and their perception of the risks would strongly influence/inhibit future adaptation or mitigation policies

The whole strategy for groundwater and climate change research must be that of integration. The physical and socio-economic dimensions must be well integrated to generate adequate models that will produce results, thereby enabling researchers, and stakeholders to outline adaptive indicators from bottom to top and vice versa. This integration can be effective at both spatial and temporal scales. This conclusion is similar to suggestions made by Aslam et al. (2018), where he proposed the integrated use of impact modelling and index-based methodologies that consider an adaptive capacity for groundwater vulnerability assessment to climate change. Researchers and stakeholders alike must seek to identify the constituents of adaptive indicators (coverage, impact, sustainability and replicability), only then can proper groundwater legislation be created appropriately for adaptive strategies. These strategies may include groundwater conservation, land use protection, protection of groundwater aquifers and transboundary aquifers and other measures such as changing land use and other practices which better sustain societies and GDEs.

6. Conclusion

This paper examines the body of knowledge on the present and future impacts of climate change on groundwater. Differences and similarities in groundwater response to climate change forcing or varied climate change influences on groundwater systems in different regions of the Earth are explored to establish fundamental climatic or geographic controls. The study also exposes pertinent knowledge gaps and possible direction for future research.

The scourge of climate change evidenced and driven by global warming is expected to affect every component of the climate system, including groundwater. A synthesis of 40 modeling studies suggests that the future groundwater changes by climate will result in a decrease in groundwater recharge, storage and levels, particularly in the arid/semi-arid tropics and secondarily the humid tropics. The climate system is a complex web of interactions and feedback mechanisms, and so it is difficult to resolve the whole spectrum of relevant feedbacks for each component in different spatial and time scales. Assessing the climate-groundwater relationship also becomes problematic since groundwater reacts slowly to climate forcing, and it is not readily amenable to scientific probing as surface water systems are. A plethora of studies have shown that groundwater is vulnerable to climate change directly, through recharge replenishments, and indirectly through land use/cover changes and through groundwater-fed irrigation. Hence, to continue to improve our understanding of the impact of climate change on groundwater, two key considerations have been proposed: physical basis and socio-economic dimensions. These strategies provide some guidelines on how research on the impact of climate change on groundwater is to be carried out. The strategies suggest an integrative consideration when assessing groundwater vulnerability to climate change and can provide a quick learning curve to successfully address the limitations in this research area and bridge the gap between science and policy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the commonwealth fellowship program for their support from the period of conceptuion and completion of this Manuscript. The authors are also thankful to the support provided by the Chinese Academy of Sciences-The World Academy of Science (CAS-TWAS) Presidential fellowship while writing this manuscript. Many thanks to Damilola Akinsaya for his input. We thank the Editor and the two anonymous reviewers whose comments have greatly improved this manuscript.

References

Abiy, A.Z., Melesse, A.M., 2017. Evaluation of watershed scale changes in groundwater and soil moisture storage with the application of GRACE satellite imagery data. Catena 153, 50–60.

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

Ahiablame, L., Sheshukov, A.Y., Rahmani, V., Moriasi, D., 2017. Annual baseflow variations as influenced by climate variability and agricultural land use change in the Missouri River Basin. J. Hydrol. 551, 188–202.

Akbarpour, S., Niksokhan, M.H., 2018. Investigating effects of climate change, urbanization, and sea level changes on groundwater resources in a coastal aquifer: an integrated assessment. Environ. Monit. Assess. 190 (10), 579.

Akram, F., Rasul, M., Khan, M.M.K., Amir, M., 2012. A Comparative View of Groundwater Flow Simulation Using Two Modelling Software-MODFLOW and MIKE SHE. In: Proceedings of the 18th Australasian Fluid Mechanics Conference, Launceston, pp. 3-7.

Alam, S., Gebremichael, M., Li, R., Dozier, J., Lettenmaier, D.P., 2019. Climate change impacts on groundwater storage in the Central Valley, California. Climatic Change 157 (3–4), 387–406.

Albrecht, T.R., Varady, R.G., Zuniga-Teran, A.A., Gerlak, A.K., Staddon, C., 2017. Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. Water Security 2, 43–56.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. In: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, 300 (9). FAO, Rome, p. D05109.

Amanambu, A.C., 2015. Geogenic Contamination: Hydrogeochemical processes and relationships in Shallow Aquifers of Ibadan, South-West Nigeria. Bull. Geograp. Phys. Geogr. Series 9 (1), 5–20.

Amini, M., Abbaspour, K. C., Berg, M., Winkel, L., Hug, S. J., Hoehn, E., et al. 2008a. Statistical modeling of global geogenic arsenic contamination in groundwater. Environ. Sci. Technol. 42(10): 3669-3675.

Amini, M., Mueller, K., Abbaspour, K. C., Rosenberg, T., Afyuni, M., Møller, K. N., et al. 2008b. Statistical modeling of global geogenic fluoride contamination in groundwaters. Environ. Sci. Technol. 42(10): 3662-3668.

Andaryani, S., Nourani, V., Trolle, D., Dehghani, M., Asl, A.M., 2019. Assessment of land use and climate change effects on land subsidence using a hydrological model and radar technique. J. Hydrol. 578, 124070.

Andreasson, J., Bergstrom, S., Carlsson, B., Graham, L., 2003. The effect of downscaling techniques on assessing water resources impacts from climate change scenarios. Int. Associat. Hydrol. Sci. Publication(280): 160-164.

Ashraf, A., Ahmad, Z., 2012. Integration of groundwater flow modeling and GIS, Water Resources Management and Modeling, IntechOpen. London, UK (2012), pp. 5957-5973.

Aslam, R.A., Shrestha, S., Pandey, V.P., 2018. Groundwater vulnerability to climate change: a review of the assessment methodology. Sci. Total Environ. 612, 853–875.

Asoka, A., Gleeson, T., Wada, Y., Mishra, V., 2017. Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nat. Geosci. 10 (2), 109–117.

Ataie-Ashtiani, B., Ketabchi, H., 2011. Elitist continuous ant colony optimization algorithm for optimal management of coastal aquifers. Water Resour. Manage. 25 (1), 165–190.

Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Starn, J. J., et al. 2016. Scripting MODFLOW model development using Python and FloPy. Groundwater 54(5), 733-739.

Barlow, P.M., Leake, S.A., 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow. 2330-5703. US Geol. Survey 1376.

Baron, J. S., Hall, E. K., Nolan, B. T., Finlay, J. C., Bernhardt, E. S., Harrison, J. A., et al. 2013. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. Biogeochemistry, 114(1-3), 71-92.

Barron, O., Crosbie, R., Charles, S., Dawes, W., Ali, R., Evans, W., et al., 2011. Climate change impact on groundwater resources in Australia. Summary Report.

Barthel, R., Banzhaf, S., 2016. Groundwater and surface water interaction at the regional-scale–A review with focus on regional integrated models. Water Resour. Manage. 30 (1), 1–32.

Bates, B., Kundzewicz, Z., Wu, S., Palutikof, J., 2008. Climate change and water Technical Paper of the Intergovernmental Panel on Climate Change (Geneva: IPCC Secretariat). Clim. Change 95, 96.

Bear, J., Verruijt, A., 2012. Modeling groundwater flow and pollution, 2. Springer Science

& Business Media.

Beigi, E., Tsai, F.T.C., 2015. Comparative study of climate-change scenarios on groundwater recharge, southwestern Mississippi and southeastern Louisiana, USA. Hydrogeol. J. 23 (4), 789–806.

Bellot, J., Chirino, E., 2013. Hydrobal: An eco-hydrological modelling approach for assessing water balances in different vegetation types in semi-arid areas. Ecol. Model. 266, 30–41.

Beltrami, H., 2001. On the relationship between ground temperature histories and meteorological records: a report on the Pomquet station. Global Planet. Change 29 (3–4), 327–348.

Benz, S.A., Bayer, P., Blum, P., 2017. Global patterns of shallow groundwater temperatures. Environ. Res. Lett. 12 (3), 034005.

Bhanja, S.N., Rodell, M., Li, B., Saha, D., Mukherjee, A., 2017. Spatio-temporal variability of groundwater storage in India. J. Hydrol. 544, 428–437.

Bierkens, M.F., Knotters, M., Hoogland, T., 2001. Space-time modeling of water table depth using a regionalized time series model and the Kalman Filter. Water Resour. Res. 37 (5), 1277–1290.

Bighash, P., Murgulet, D., 2015. Application of factor analysis and electrical resistivity to understand groundwater contributions to coastal embayments in semi-arid and hypersaline coastal settings. Sci. Total Environ. 532, 688–701.

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), 163–177.

J.P. Bloomfield C.R. Jackson M.E. Stuart Changes in groundwater levels, temperature and quality in the UK over the 20th century: an assessment of evidence of impacts from climate change, Living with Environmental Change Report, UK, 14 pp Available at 2013 http://nora.nerc.ac.uk/503271/.

Bloomfield, J.P., Marchant, B.P., McKenzie, A.A.J.H., Sciences, E.S., 2019. Changes in groundwater drought associated with anthropogenic warming. Hydrol. Earth Syst. Sci.. 23 (3), 1393–1408.

Bondu, R., Cloutier, V., Rosa, E., Benzaazoua, M., 2016. A review and evaluation of the impacts of climate change on geogenic arsenic in groundwater from fractured bedrock aquifers. Water Air Soil Pollut. 227 (9), 296.

Bouderbala, A., 2017. Assessment of the impact of climatic variability and human activities on groundwater quality: Case of Mitidja Plain, North of Algeria, Euro-Mediterranean Conference for Environmental Integration. Springer 607–609.

Bouderbala, A., 2018. Effects of climate variability on groundwater resources in coastal aquifers (Case of Mitidja Plain in the North Algeria), Groundwater and Global Change in the Western Mediterranean Area. Springer 43–51.

Brauman, K.A., Richter, B.D., Postel, S., Malsy, M., Flörke, M., 2016. Water depletion: an improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. Elem. Sci. Anth. 4, 000083.

Bredehoeft, J.D.J.G., 2002. The water budget myth revisited: why hydrogeologists model. Groundwater 40 (4), 340–345.

Brooks, N., Adger, N.W., 2003. Country level risk measures of climate-related natural disasters and implications for adaptation to climate change, Working Paper 26, Tyndall Centre for Climate Research, Norwich, University of East Anglia.

Brouyère, S., Carabin, G., Dassargues, A., 2004. Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. Hydrogeol. J. 12 (2), 123–134.

Brunke, M., Gonser, T., 1997. The ecological significance of exchange processes between rivers and groundwater. Freshw. Biol. 37 (1), 1–33.

Brunner, P., Simmons, C.T., 2012. HydroGeoSphere: a fully integrated, physically based hydrological model. Groundwater 50 (2), 170–176.

Brunner, P., Therrien, R., Renard, P., Simmons, C.T., Hendricks Franssen, H.J., 2017. Advances in understanding river-groundwater interactions. Rev. Geophys. 55 (3), 818–854.

Burke, C., Stott, P., 2017. Impact of anthropogenic climate change on the East Asian summer monsoon. J. Clim. 30 (14), 5205–5220.

Carter, R.C., Parker, A., 2009. Climate change, population trends and groundwater in Africa. Hydrol. Sci. J. 54 (4), 676–689.

Cartwright, I., Morgenstern, U., 2012. Constraining groundwater recharge and the rate of geochemical processes using tritium and major ion geochemistry: Ovens catchment, southeast Australia. J. Hydrol. 475, 137–149.

Cervi, F., Petronici, F., Castellarin, A., Marcaccio, M., Bertolini, A., Borgatti, L. 2018. Climate-change potential effects on the hydrological regime of freshwater springs in the Italian Northern Apennines. Sci. Total Environ. 622, 337-348.

Chang, L.C., Ho, C.C., Yeh, M.S., Yang, C.C., 2011. An integrating approach for conjunctive-use planning of surface and subsurface water system. Water Resour. Manage. 25(1): 59-78.

Chang, S.W., Nemec, K., Kalin, L., Clement, T.P., 2016. Impacts of climate change and urbanization on groundwater resources in a barrier island. J. Environ. Eng. 142 (12), D4016001.

Chen, Z., Grasby, S.E., Osadetz, K.G., 2002. Predicting average annual groundwater levels from climatic variables: an empirical model. J. Hydrol. 260 (1–4), 102–117.

Cheng, L., Zhu, J., 2018. 2017 was the warmest year on record for the global ocean. Adv. Atmos. Sci. 35 (3), 261–263.

Christensen, V.G., Bergman, A.L., 2005. Hydrologic Conditions and Lake-level Fluctuations at Long Lost Lake, 1939–2004, White Earth Indian Reservation, Clearwater County, Minnesota. US Geological Survey, Rep. 2005–5181, 18.

Creed, I., Hwang, T., Lutz, B., Way, D., 2015. Climate warming causes intensification of the hydrological cycle, resulting in changes to the vernal and autumnal windows in a northern temperate forest. Hydrol. Process. 29 (16), 3519–3534.

Crosbie, R. S., Scanlon, B. R., Mpelasoka, F. S., Reedy, R. C., Gates, J. B., Zhang, L. 2013. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. Water Resour. Res. 49(7) 3936-3951.

Cullet, P., Stephan, R. M. 2017. Introduction to 'Groundwater and Climate Change: Multi-level Law and Policy Perspectives'. Water Int. 47(6): 641-645.

da Costa, A.M., de Salis, H.H.C., Viana, J.H.M., Leal Pacheco, F.A.J.S., 2019. Groundwater recharge Potential for sustainable water use in urban areas of the Jequitiba River Basin. Brazil. Sustainability 11 (10), 2955.

de Graaf, I.E., van Beek, R.L., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, E.H., Bierkens, M.F., 2017. A global-scale two-layer transient groundwater model: Development and application to groundwater depletion. Adv. Water Resour. 102, 53–67.

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., Robinson, D. 2010. Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. J. Geophys. Res. Atmosph. 115(D15).

Deitchman, R.S., Loheide, S.P., 2009. Ground-based thermal imaging of groundwater flow processes at the seepage face. Geophys. Res. Lett. 36(14).

Deng, Z., Priestley, S.C., Guan, H., Love, A.J., Simmons, C.T., 2013. Canopy enhanced chloride deposition in coastal South Australia and its application for the chloride mass balance method. J. Hydrol. 497, 62–70.

Devlin, J.F., Sophocleous, M.J.H.J., 2005. The persistence of the water budget myth and its relationship to sustainability. Hydrogeol. J. 13 (4), 549–554.

Diersch, H.-J.G., 2013. FEFLOW: finite element modeling of flow, mass and heat transport in porous and fractured media. Springer-Verlag, Berlin, pp. 996.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., et al., 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodynam. 59, 143–156.

Döll, P., Alcamo, J., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S. 2001. The global integrated water model WaterGAP 2.1. EuroWasser, Kassel World Water Series, 5.

Dominguez, F., Rivera, E., Lettenmaier, D., Castro, C., 2012. Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. Geophys. Res. Lett., 39(5): L05803:1-7.

Dong, Y., Jiang, C., Suri, M. R., Pee, D., Meng, L., Goldstein, R. E. R. 2019. Groundwater level changes with a focus on agricultural areas in the Mid-Atlantic region of the United States, 2002–2016. Environ. Res, 171, 193-203.

Dragoni, W., Sukhija, B.S., 2008. Climate change and groundwater: a short review. Geological Society, London, Special Publications, 288(1): 1-12.

Du Plessis, A., 2017. Freshwater Challenges of South Africa and its Upper Vaal River. Springer.

Duan, L., Cao, L., Caldeira, K., 2019. Estimating contributions of sea ice and land snow to climate feedback. Atmosphere 124 (1), 199–208.

Durrani, I.H., Adnan, S., Ahmad, M., Khair, S., Kakar, E., 2017. Observed Long-term climatic variability and its impacts on the ground water level of Quetta alluvial. Iranian J. Sci. Technol. Trans. A: Sci. 1-12.

Earman, S., Dettinger, M., 2011. Potential impacts of climate change on groundwater resources–a global review. J. Water Clim. Change 2 (4), 213–229.

Erler, A.R., Frey, S.K., Khader, O., d'Orgeville, M., Park, Y.J., Hwang, H.T., et al., 2019. Evaluating Climate Change Impacts on Soil Moisture and Groundwater Resources Within a Lake-Affected Region. Water Resour. Res. 55 (10), 8142–8163.

Essaid, H.I., Caldwell, R.R., 2017. Evaluating the impact of irrigation on surface water–groundwater interaction and stream temperature in an agricultural watershed. Sci. Total Environ. 599, 581–596.

Famiglietti, J., 2014. The global groundwater crisis. Nat. Clim. Change 4, 945–948.

Famiglietti, J. S., Lo, M., Ho, S. L., Bethune, J., Anderson, K. J., Syed, T. H., et al. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys. Res. Lett., 38(3).

Fassnacht, S., Cherry, M., Venable, N., Saavedra, F., 2016. Snow and albedo climate change impacts across the United States Northern Great Plains. The Cryosphere 10 (1), 329–339.

Faunt, C.C., Sneed, M., Traum, J., Brandt, J.T., 2016. Water availability and land subsidence in the Central Valley, California, USA. Hydrogeol. J. 24 (3), 675–684.

Ferguson, I.M., Maxwell, R.M., 2010. Role of groundwater in watershed response and land surface feedbacks under climate change. Water Resour. Res. 46(10) W00F02:1-15.

Fishman, R.M., Siegfried, T., Raj, P., Modi, V., Lall, U., 2011. Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation. Water Resour. Res., 47(6) W00L05:1-15.

Flint, L.E., Flint, A.L., Thorne, J., 2013. California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change: US Geological Survey Dataset Report. doi: 10.5066/F76T0JPB.

Foster, S., Hirata, R., Vidal, A., Schmidt, G., & Garduño, H. 2009. The Guarani Aquifer initiative—towards realistic groundwater management in a transboundary context. Sustainable Groundwater Management Series, GW-MATE/World Bank, Washington, 28 pp.

Franssen, H.J.H, 2009. The impact of climate change on groundwater resources. Int. J. Clim. Change Strategies Manage. 1 (3), 241–254.

Francis, J.A., 2017. Why are Arctic linkages to extreme weather still up in the air? Bull. Am. Meteorol. Soc. 98 (12), 2551–2557.

Frot, E., Van Wesemael, B., Vandenschrick, G., Souchez, R., Solé Benet, A., 2007. Origin and type of rainfall for recharge of a karstic aquifer in the western Mediterranean: a case study from the Sierra de Gador-Campo de Dalias (southeast Spain). Hydrol. Process. 21 (3), 359–368.

Fu, G., Crosbie, R.S., Barron, O., Charles, S.P., Dawes, W., Shi, X., et al., 2019. Attributing variations of temporal and spatial groundwater recharge: A statistical analysis of climatic and non-climatic factors. J. Hydrol. 568, 816–834.

Gamvroudis, C., Dokou, Z., Nikolaidis, N., Karatzas, G., 2017. Impacts of surface and groundwater variability response to future climate change scenarios in a large

Mediterranean watershed. Environ. Earth Sci. 76 (11), 385.

Garner, G., Hannah, D.M., Watts, G., 2017. Climate change and water in the UK: Recent scientific evidence for past and future change. Prog. Phys. Geogr. 41 (2), 154–170.

Gauthier, M., Camporese, M., Rivard, C., Paniconi, C., Larocque, M., 2009. A modeling study of heterogeneity and surface water-groundwater interactions in the Thomas Brook catchment, Annapolis Valley (Nova Scotia, Canada). Hydrol. Earth Syst. Sci. 13 (9), 1583.

Ghazavi, R., Ebrahimi, H., 2019. Predicting the impacts of climate change on groundwater recharge in an arid environment using modeling approach. Int. J. Clim. Change Strategies Manage.

Ghazifard, A., Moslehi, A., Safaei, H., Roostaei, M., 2016. Effects of groundwater withdrawal on land subsidence in Kashan Plain, Iran. Bull. Eng. Geol. Environ. 75 (3), 1157–1168.

Gemitzi, A., Ajami, H., Richnow, H.H., 2017. Developing empirical monthly groundwater recharge equations based on modeling and remote sensing data–Modeling future groundwater recharge to predict potential climate change impacts. J. Hydrol. 546, 1–13.

Giordano, M., 2009. Global groundwater? Issues and solutions. Annu. Rev. Environ. Resour. 34, 153–178.

Gleeson, T., Wada, Y., 2013. Assessing regional groundwater stress for nations using multiple data sources with the groundwater footprint. Environ. Res. Lett. 8 (4), 044010.

Gleick, P.H. (Ed.), 1993. Water in Crisis: A Guide to the World’s Freshwater Resources, Oxford University Press, New York pp. 473.

Gloor, M.R.J.W., Brienen, R.J., Galbraith, D., Feldpausch, T.R., Schöngart, J., Guyot, J.L., et al., 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophys. Res. Lett. 40 (9), 1729–1733.

Goderniaux, P., Brouyère, S., Wildemeersch, S., Therrien, R., Dassargues, A., 2015. Uncertainty of climate change impact on groundwater reserves–application to a chalk aquifer. J. Hydrol. 528, 108–121.

Gogu, R., Carabin, G., Hallet, V., Peters, V., Dassargues, A., 2001. GIS-based hydrogeological databases and groundwater modelling. Hydrogeol. J. 9 (6), 555–569.

Golmohammadi, G., Prasher, S., Madani, A., Rudra, R., 2014. Evaluating three hydrological distributed watershed models: MIKE-SHE, APEX, SWAT. Hydrology 1 (1), 20–39.

Goodarzi, M., Abedi-Koupai, J., Heidarpour, M.J.G., 2019. Investigating impacts of climate change on irrigation water demands and its resulting consequences on groundwater using CMIP5 models. Groundwater 57 (2), 259–268.

Goodarzi, M., Abedi-Koupai, J., Heidarpour, M., Safavi, H.R., 2016. Evaluation of the effects of climate change on groundwater recharge using a hybrid method. Water Resour. Manage. 30 (1), 133–148.

Gossel, W., Ebraheem, A., Wycisk, P., 2004. A very large scale GIS-based groundwater flow model for the Nubian sandstone aquifer in Eastern Sahara (Egypt, northern Sudan and eastern Libya). Hydrogeol. J. 12 (6), 698–713.

Gräbe, A., Rödiger, T., Rink, K., Fischer, T., Kolditz, O., 2012. Development of a regional groundwater flow model along the western Dead Sea escarpment. IAHS-AISH Publication 345–350.

Green, T.R., 2016. Linking climate change and groundwater. Integr. Groundwater Manage. 97–141.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., et al., 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405 (3–4), 532–560.

Grogan, D.S., Wisser, D., Prusevich, A., Lammers, R.B., Frolking, S., 2017. The use and reuse of unsustainable groundwater for irrigation: a global budget. Environ. Res. Lett. 12 (3), 034017.

Guay, C., Nastev, M., Paniconi, C., Sulis, M., 2013. Comparison of two modeling approaches for groundwater–surface water interactions. Hydrol. Process. 27 (16), 2258–2270.

Guermazi, E., Milano, M., Reynard, E., Zairi, M.J.M., change, a.s.f.g., 2019. Impact of climate change and anthropogenic pressure on the groundwater resources in arid environment. 24(1): 73-92.

Gulden, L. E., Rosero, E., Yang, Z. L., Rodell, M., Jackson, C. S., Niu, G. Y., et al. 2007. Improving land-surface model hydrology: Is an explicit aquifer model better than a deeper soil profile?. Geophys. Res. Lett. 34(9).

Gun, J.V.D., 2012. Groundwater and global change: trends, opportunities and challenges. UNESCO.

Gunawardhana, L.N., Kazama, S., 2011. Climate change impacts on groundwater temperature change in the Sendai plain, Japan. Hydrol. Processes 25 (17), 2665–2678.

Gunawardhana, L.N., Kazama, S., 2012. Statistical and numerical analyses of the influence of climate variability on aquifer water levels and groundwater temperatures: The impacts of climate change on aquifer thermal regimes. Global Planet. Change 86, 66–78.

Guo, D., Westra, S., Maier, H.R., 2017. Sensitivity of potential evapotranspiration to changes in climate variables for different Australian climatic zones. Hydrol. Earth Syst. Sci. 21 (4), 2107.

Gupta, J., Conti, K., 2017. Global climate change and global groundwater law: their independent and pluralistic evolution and potential challenges. Water Int. 42 (6), 741–756.

Gurdak, J.J., 2017. Groundwater: Climate-induced pumping. Nat. Geosci. 10(2): 71-71.

Gurdak, J.J., Hanson, R.T., McMahon, P.B., Bruce, B.W., McCray, J.E., Thyne, G.D., Reedy, R.C., 2007. Climate Variability Controls on Unsaturated Water and Chemical Movement, High Plains Aquifer, USA. Vadose Zone J. 6 (3), 533–547.

Gurdak, J.J., McMahon, P.B., Bruce, B.W., 2011. Vulnerability of groundwater quality to human activity and climate change and variability, High Plains aquifer, USA. Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations: 145.

Guzman, J. A., Moriasi, D. N., Gowda, P. H., Steiner, J. L., Starks, P. J., Arnold, J. G., Srinivasan, R. 2015. A model integration framework for linking SWAT and MODFLOW. Environ. Modell. Software, 73: 103-116.

Hähnlein, S., Bayer, P., Ferguson, G., & Blum, P. 2013. Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy, 59, 914-925.

Hashemi, H., Uvo, C.B., Berndtsson, R., 2015. Coupled modeling approach to assess climate change impacts on groundwater recharge and adaptation in arid areas. Hydrol. Earth Syst. Sci. 19 (10).

Haine, T.W., Martin, T., 2017. The Arctic-Subarctic sea ice system is entering a seasonal regime: Implications for future Arctic amplification. Sci. Rep. 7 (1), 4618.

Haldorsen, S., van der Ploeg, M., Cendón, D., Chen, J., Chkir Ben Jemaa, N., Gurdak, J. J., et al. 2016. Groundwater and global palaeoclimate signals (G@ GPS).

Hanson, R. T., Flint, L. E., Flint, A. L., Dettinger, M. D., Faunt, C. C., 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).

Hanson, R.T., Dettinger, M.D., 2005. Ground Water/Surface Water Responses to Global Climate Simulations, Santa Clara-Calleguas Basin, Ventura, California. J. Am. Water Resour. Assoc. 41(3): 517-536.

Hao, Y., Wang, Y., Zhu, Y., Lin, Y., Wen, J.C., Yeh, T.C.J., 2009. Response of karst springs to climate change and anthropogenic activities: the Niangziguan Springs, China. Progr. Phys. Geogr. 33 (5), 634–649.

Hao, Z., Zhao, H., Zhang, C., Zhou, H., Zhao, H., Wang, H., 2019. Correlation Analysis Between Groundwater Decline Trend and Human-Induced Factors in Bashang Region. Water 11 (3), 473.

Harden, J. W., Koven, C. D., Ping, C. L., Hugelius, G., McGuire, A. D., Camill, P., et al. 2012. Field information links permafrost carbon to physical vulnerabilities of thawing. Geophys. Res. Lett. 39(15).

Hare, D.K. et al., 2017. Hydrogeological controls on spatial patterns of groundwater discharge in peatlands. Hydrol. Earth Syst. Sci. 21(12): 6031.

Hartmann, A., Gleeson, T., Wada, Y., Wagener, T., 2017. Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. Proc. Natl. Acad. Sci. 114 (11), 2842–2847.

Hegerl, G. C., Black, E., Allan, R. P., Ingram, W. J., Polson, D., Trenberth, K. E., et al. 2019. Challenges in quantifying changes in the global water cycle. Bull. Am. Meteorol. Soc. 100(10).

Helfer, F., Lemckert, C., Zhang, H., 2012. Impacts of climate change on temperature and evaporation from a large reservoir in Australia. J. Hydrol. 475, 365-378.

Hendrickx, J., Walker, G., 1997. Recharge of phreatic aquifers in (semi-) arid areas. Recharge From Precipitation, edited by I. Summers, chap. 2, pp. 19– 111, A.A. Balkema, Brookfield, Vt.

Herrera-Pantoja, M., Hiscock, K.M., 2015. Projected impacts of climate change on water availability indicators in a semi-arid region of central Mexico. Environ. Sci. Policy 54, 81–89.

Hirata, R., Conicelli, B.P., 2012. Groundwater resources in Brazil: a review of possible impacts caused by climate change. Anais da Academia Brasileira de Ciências 84 (2), 297–312.

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 (7), 1629–1641.

Holman, I.P., 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.

House, A., Thompson, J., Sorensen, J., Roberts, C., Acreman, M., 2016. Modelling groundwater/surface water interaction in a managed riparian chalk valley wetland. Hydrol. Process. 30 (3), 447–462.

Houston, J., 2002. Groundwater recharge through an alluvial fan in the Atacama Desert, northern Chile: mechanisms, magnitudes and causes. Hydrol. Process. 16 (15), 3019–3035.

Hu, B., Teng, Y., Zhang, Y., Zhu, C.J.H.j., 2019. The projected hydrologic cycle under the scenario of 936 ppm CO 2 in 2100. 27(1): 31-53.

Hu, K., Awange, J.L., Forootan, E., Goncalves, R.M., Fleming, K., 2017. Hydrogeological characterisation of groundwater over Brazil using remotely sensed and model products. Sci. Total Environ. 599, 372–386.

Huang, Z., Tang, Q., Lo, M. H., Liu, X., Lu, H., Zhang, X., Leng, G. 2019. The influence of groundwater representation on hydrological simulation and its assessment using satellite-based water storage variation. Hydrol. Process. 33(8): 1218-1230.

Hughes, C.E., Cendón, D.I., Johansen, M.P., Meredith, K.T., 2011. Climate change and groundwater, Sustaining Groundwater Resources. Springer, pp. 97–117.

Hunt, R.J., Walker, J.F., Doherty, J., 2008. Using GSFLOW to simulate climate change in a northern temperate climate. MODFLOW and More 109–113.

Huo, Z., Feng, S., Kang, S., Cen, S., Ma, Y., 2007. Simulation of effects of agricultural activities on groundwater level by combining FEFLOW and GIS. N. Z. J. Agric. Res. 50 (5), 839–846.

Iyalomhe, F., Rizzi, J., Pasini, S., Torresan, S., Critto, A., Marcomini, A., 2015. Regional Risk Assessment for climate change impacts on coastal aquifers. Sci. Total Environ. 537, 100–114.

IPCC, 2013. Climate Change 2013: The physical science basis. contribution of working group I to the fifth assessment report of IPCC the Intergovernmental Panel on Climate Change. In: Stocker, T.F. et al. (Eds.). Cambridge University Press.

Jackson, R.B., Le Quéré, C., Andrew, R.M., Canadell, J.G., Peters, G.P., Roy, J., Wu, L., 2017. Warning signs for stabilizing global CO2 emissions. Environ. Res. Lett. 12 (11), 110202.

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.

Jayakumar, R., Lee, E., 2017. Climate change and groundwater conditions in the Mekong

Region–A review. J. Groundwater Sci. Eng. 5 (1), 14–30.

Jia, X., et al., 2019. Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China. Sci. Total Environ. 672, 551–562.

Jiang, X., Niu, G.Y., Yang, Z.L., 2009. Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States. J. Geophys. Res. Atmosph. 114 (D6).

Jolly, I.D., McEwan, K.L., Holland, K.L., 2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. Ecohydrology 1 (1), 43–58.

Jyrkama, M.I., Sykes, J.F., 2007. The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). J. Hydrol. 338 (3), 237–250.

Kambale, J.B., Singh, D.K., Sarangi, A., 2017. Impact of climate change on groundwater recharge in a semi-arid region of northern India. Appl. Ecol. Environ. Res. 15 (1), 335–362.

Kaur, S., Jalota, S.K., Singh, K.G., Lubana, P.P.S., Aggarwal, R., 2015. Assessing climate change impact on root-zone water balance and groundwater levels. J. Water Clim. Change 6 (3), 436–448.

Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., Simmons, C.T., 2016. Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. J. Hydrol. 535, 235–255.

Kingston, D., Taylor, R., 2010. Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. Hydrol. Earth Syst. Sci. 14 (7), 1297.

Kipling, R.P., Topp, C.F., Bannink, A., Bartley, D.J., Blanco-Penedo, I., Cortignani, R., Hutchings, N.J., et al., 2019. To what extent is climate change adaptation a novel challenge for agricultural modellers? Environ. Modell. Software 120, 104492.

Klaas, D.K., Imteaz, M.A., Sudiayem, I., Klaas, E.M., Klaas, E.C., 2020. Assessing climate changes impacts on tropical karst catchment: Implications on groundwater resource sustainability and management strategies. J. Hydrol. 582, 124426.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J.J., Kupfersberger, H., Kværner, J., et al., 2014. Climate change impacts on groundwater and dependent ecosystems. J. Hydrol. 518, 250–266.

Kirn, L., Mudarra, M., Marín, A., Andreo, B., & Hartmann, A. 2017. Improved assessment of groundwater recharge in a Mediterranean karst region: Andalusia, Spain. In EuroKarst 2016, Neuchâtel (pp. 117-125). Springer, Cham.

Kløve, B., Ala-aho, P., Okkonen, J., Rossi, P., 2011. Possible effects of climate change on hydrogeological systems: results from research on esker aquifers in northern Finland. Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations: 305.

Knott, J.F., Jacobs, J.M., Daniel, J.S., Kirshen, P., 2019. Modeling Groundwater Rise Caused by Sea-Level Rise in Coastal New Hampshire. J. Coastal Res. 35 (1), 143–157.

Kolditz, O., Bauer, S., Bilke, L., Böttcher, N., Delfs, J. O., Fischer, T., et al. 2012. OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. Environ. Earth Sci. , 67(2): 589-599.

Kollet, S.J., Maxwell, R.M., 2008. Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. Water Resour. Res. 44(2) W02402: 1-18.

Konikow, L.F., 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. Geophys. Res. Lett. 38(17) L17401: 1-5.

Konikow, L.F., Kendy, E., 2005. Groundwater depletion: A global problem. Hydrogeol. J. 13 (1), 317–320.

Kormos, P. R., Marks, D., Seyfried, M., Havens, S., Hedrick, A., Lohse, K. A., 2016. 31 Years of Spatially Distributed Air Temperature, Humidity, Precipitation Amount and Precipitation Phase From a Mountain Catchment in the Rain-snow Transition Zone., doi: https://doi.org/10.18122/B2B59V.

Kreins, P., Henseler, M., Anter, J., Herrmann, F., Wendland, F., 2015. Quantification of climate change impact on regional agricultural irrigation and groundwater demand. Water Resour. Manage. 29 (10), 3585–3600.

Kumar, C., 2012. Climate change and its impact on groundwater resources. Int. J. Eng. Sci. 1 (5), 43–60.

Kumar, C., Singh, S., 2011. Impact of Climate Change on Water Resources and National Water Mission of India, Proceedings of National Seminar on Global Warming and its Impact on. Water Resour. 1–9.

Kundu, S., Khare, D., Mondal, A., 2017. Past, present and future land use changes and their impact on water balance. J. Environ. Manage. 197, 582–596.

Kundzewicz, Z.W., Doell, P., 2009. Will groundwater ease freshwater stress under climate change? Hydrol. Sci. J. 54 (4), 665–675.

Kuper, M., Amichi, H., Mayaux, P.-L., 2017. Groundwater use in North Africa as a cautionary tale for climate change adaptation. Water Int. 42 (6), 725–740.

Kurylyk, B.L., MacQuarrie, K.T., 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, 244–253.

Kurylyk, B.L., Bourque, C.P.A., MacQuarrie, K.T., 2013. Potential surface temperature and shallow groundwater temperature response to climate change: an example from a small forested catchment in east-central New Brunswick (Canada). Hydrol. Earth Syst. Sci.

Kurylyk, B.L., MacQuarrie, K.T., McKenzie, J.M., 2014a. Climate change impacts on groundwater and soil temperatures in cold and temperate regions: Implications, mathematical theory, and emerging simulation tools. Earth Sci. Rev. 138, 313–334.

Kurylyk, B.L., MacQuarrie, K.T., Caissie, D., McKenzie, J.M., 2015. Shallow groundwater thermal sensitivity to climate change and land cover disturbances: derivation of analytical expressions and implications for stream temperature modeling. Hydrol. Earth Syst. Sci.

Kurylyk, B.L., MacQuarrie, K.T., Voss, C.I., 2014b. Climate change impacts on the temperature and magnitude of groundwater discharge from shallow, unconfined aquifers. Water Resour. Res. 50 (4), 3253–3274.

Kuss, A.J.M., Gurdak, J.J., 2014. Groundwater level response in US principal aquifers to ENSO, NAO, PDO, and AMO. J. Hydrol. 519, 1939–1952.

Kustu, M.D., Fan, Y., Rodell, M., 2011. Possible link between irrigation in the US High Plains and increased summer streamflow in the Midwest. Water Resour. Res. 47(3) W03522: 1-21.

LaFontaine, J.H., Hay, L.E., Viger, R.J., Regan, R.S., Markstrom, S.L., 2015. Effects of climate and land cover on hydrology in the southeastern US: Potential impacts on watershed planning. J. Am. Water Resour. Assoc. 51 (5), 1235–1261.

Larocque, M., Levison, J., Martin, A., Chaumont, D., 2019. A review of simulated climate change impacts on groundwater resources in Eastern Canada. Canad. Water Resour. J./Revue canadienne des ressources hydriques 44 (1), 22–41.

Leake, S.A., Barlow, P.M., 2013. Understanding and managing the effects of groundwater pumping on streamflow. 2327-6932, US Geological Survey.

Lemieux, J. M., Hassaoui, J., Molson, J., Therrien, R., Therrien, P., Chouteau, M., Ouellet, M. 2015. Simulating the impact of climate change on the groundwater resources of the Magdalen Islands, Québec, Canada. J. Hydrol. Regional Studies, 3, 400-423.

Leng, G., Huang, M., Tang, Q., Gao, H., Leung, L.R., 2014. Modeling the effects of groundwater-fed irrigation on terrestrial hydrology over the conterminous United States. J. Hydrometeorol. 15 (3), 957–972.

Lerner, D., 1997. Groundwater recharge. In: Saether OM, de Caritat P(eds) Geochemical processes, weathering and groundwater recharge in catchments. AA Balkema, Rotterdam, pp 109-150.

Levy, Z.F., Rosenberry, D.O., Moucha, R., Mushet, D.M., Goldhaber, M.B., LaBaugh, J.W., et al., 2018. Drought-induced recharge promotes long-term storage of porewater salinity beneath a prairie wetland. J. Hydrol. 557, 391–406.

Li, R., Merchant, J.W., 2013. Modeling vulnerability of groundwater to pollution under future scenarios of climate change and biofuels-related land use change: a case study in North Dakota, USA. Sci. Total Environ. 447, 32–45.

Liesch, T., Wunsch, A., 2019. Aquifer responses to long-term climatic periodicities. J. Hydrol. 572, 226–242.

Lijzen, J.P., Otte, P., van Dreumel, M., 2014. Towards sustainable management of groundwater: policy developments in the Netherlands. Sci. Total Environ. 485, 804–809.

Lin, M., Biswas, A., Bennett, E.M., 2019. Spatio-temporal dynamics of groundwater storage changes in the Yellow River Basin. J. Environ. Manage. 235, 84–95.

Liu, J., Dorjderem, A., Fu, J., Lei, X., Liu, H., Macer, D., Qiao, Q., Sun, A., Tachiyama, K., Yu, L., Zheng, Y., 2011. Water Ethics and Water Resource Management, Ethics and Climate Change in Asia and the Pacific (ECCAP) Project, Working Group 14 Report. UNESCO, Bangkok.

Lo, M., Famiglietti, J., 2011. Irrigation in California's Central Valley strengthens the southwestern US Monsoon, AGU Fall Meeting H24E-06; available at http://adsabs.harvard.edu//abs/2011AGUFM.H24E..06L.

Longuevergne, L., Scanlon, B.R., Wilson, C.R., 2010. GRACE Hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA. Water Resour. Res., 46(11) W11517:1-15.

López-Morales, C.A., Mesa-Jurado, M.A., 2017. Valuation of hidden water ecosystem services: The replacement cost of the aquifer system in Central Mexico. Water 9 (8), 571.

Lorenzo-Lacruz, J., Garcia, C., Morán-Tejeda, E., 2017. Groundwater level responses to precipitation variability in Mediterranean insular aquifers. J. Hydrol. 552, 516–531.

Margat, J., Van der Gun, J., 2013. Groundwater around the world: a geographic synopsis. CRC Press, Taylor & Francis Group, London, UK.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., Barlow, P.M., 2008. GSFLOW-Coupled Groundwater and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). 2328-7055, Geological Survey (US).

Mas-Pla, J., Menció, A.J.E.S., Research, P., 2019. Groundwater nitrate pollution and climate change: learnings from a water balance-based analysis of several aquifers in a western Mediterranean region (Catalonia). Environ. Sci. Pollut. Res. 26(3): 2184-2202.

Maxwell, R., Condon, L., Kollet, S., 2015. A high-resolution simulation of groundwater and surface water over most of the continental US with the integrated hydrologic model ParFlow v3. Geosci. Model Dev. 8 (3).

Maxwell, R.M., Kollet, S.J., 2008. Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nat. Geosci. 1 (10), 665–669.

Maxwell, R. M., Lundquist, J. K., Mirocha, J. D., Smith, S. G., Woodward, C. S., Tompson, A. F. 2011. Development of a coupled groundwater–atmosphere model. Monthly Weather Rev. 139(1): 96-116.

Maxwell, R.M., Putti, M., Meyerhoff, S., Delfs, J.O., Ferguson, I.M., Ivanov, V., et al., 2014. Surface-subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks. Water Resour. Res. 50 (2), 1531–1549.

McGill, B. M., Altchenko, Y., Hamilton, S. K., Kenabatho, P. K., Sylvester, S. R., Villholth, K. G. 2019. Complex interactions between climate change, sanitation, and groundwater quality: a case study from Ramotswa, Botswana. Hydrogeol. J. 27(3): 997-1015.

McGregor, H., 2018. Regional climate goes global. Nat. Geosci. 11 (1), 18.

McGuire, A. D., Christensen, T. R., Hayes, D. J., Heroult, A., Euskirchen, E., Yi, Y., et al. 2012. An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. Biogeosci. Discussions, 9, 4543.

McKenna, O.P., Sala, O.E., 2018. Groundwater recharge in desert playas: current rates and future effects of climate change. Environ. Res. Lett. 13 (1), 014025.

Meixner, T., Manning, A. H., Stonestrom, D. A., Allen, D. M., Ajami, H., Blasch, K. W., et al. 2016. Implications of projected climate change for groundwater recharge in the western United States. J. Hydrol. 534, 124-138.

Melo, D.C., Wendland, E., 2017. Shallow aquifer response to climate change scenarios in a small catchment in the Guarani Aquifer outcrop zone. Anais da Academia Brasileira de Ciências 89 (1), 391–406.

Menberg, K., Blum, P., Kurylyk, B.L., Bayer, P., 2014. Observed groundwater temperature response to recent climate change. Hydrol. Earth Syst. Sci.

Merz, C., Lischeid, G.J.E.E.S., 2019. Multivariate analysis to assess the impact of irrigation on groundwater quality. Environ. Earth Sci. 78 (9), 274.

Mileham, L., Taylor, R.G., 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.

Misra, A.K., 2014. Climate change and challenges of water and food security. Int. J. Sustain. Built Environ. 3 (1), 153–165.

Mo, X., Chen, X., Hu, S., Liu, S., Xia, J., 2017. Attributing regional trends of evapotranspiration and gross primary productivity with remote sensing: a case study in the North China Plain. Hydrol. Earth Syst. Sci. 21 (1), 295.

Modoni, G., Darini, G., Spacagna, R.L., Saroli, M., Russo, G., Croce, P., 2013. Spatial analysis of land subsidence induced by groundwater withdrawal. Eng. Geol. 167, 59–71.

Moeck, C., Brunner, P., Hunkeler, D., 2016. The influence of model structure on groundwater recharge rates in climate-change impact studies. Hydrogeol. J. 24 (5), 1171–1184.

Mondal, N., Singh, V., 2009. Mass transport modeling of an industrial belt using visual MODFLOW and MODPATH: A case study. J. Geograp. Reg. Plann. 2 (1), 001–019.

Morsy, K.M., Alenezi, A., AlRukaibi, D.S., 2017. Groundwater and dependent ecosystems: Revealing the impacts of climate change. Int. J. Appl. Eng. Res. 12 (13), 3919–3926.

Mote, P., Snover, A.K., Dalton, M.M., 2013. Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities. Island Press, Washington.

Moutahir, H., et al., 2017. Likely effects of climate change on groundwater availability in a Mediterranean region of Southeastern Spain. Hydrol. Process. 31 (1), 161–176.

Munday, P.L., Donelson, J.M., Domingos, J.A., 2017. Potential for adaptation to climate change in a coral reef fish. Glob. Change Biol. 23 (1), 307–317.

Mundo-Molina, M., 2015. Climate change effects on evapotranspiration in Mexico. Am. J. Climate Change 4 (02), 163.

Mustafa, S.M.T., et al., 2019. Multi-model approach to quantify groundwater-level prediction uncertainty using an ensemble of global climate models and multiple abstraction scenarios. Hydrol. Earth Syst. Sci. 23 (5), 2279–2303.

Ng, G.H.C., McLaughlin, D., Entekhabi, D., Scanlon, B.R., 2010. Probabilistic analysis of the effects of climate change on groundwater recharge. Water Resourc. Res, 46(7) W07502:1-18.

Nissen, K.M., Ulbrich, U., 2017. Increasing frequencies and changing characteristics of heavy precipitation events threatening infrastructure in Europe under climate change. Nat. Hazards Earth Syst. Sci. 17 (7), 1177.

Niraula, R., Meixner, T., Dominguez, F., Bhattarai, N., Rodell, M., Ajami, H., et al., 2017. How might recharge change under projected climate change in the western US? Geophys. Res. Lett. 44 (20), 10–407.

Nkhonjera, G.K., Dinka, M.O., 2017. Significance of direct and indirect impacts of climate change on groundwater resources in the Olifants River basin: A review. Global Planet. Change 158, 72–89.

Okkonen, J., Kløve, B., 2010. A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. J. Hydrol. 388 (1), 1–12.

Okkonen, J., Kløve, B., 2011. A sequential modelling approach to assess groundwater–surface water resources in a snow dominated region of Finland. J. Hydrol. 411 (1), 91–107.

Oliveira, P.T.S. et al., 2017. Groundwater recharge decrease with increased vegetation density in the Brazilian cerrado. Ecohydrology, 10(1) e1759:1-8.

Omole, D.O., 2013. Sustainable groundwater exploitation in Nigeria. J. Water Resour. Ocean Sci. 2 (2), 9–14.

Ordens, C.M., Post, V.E., Werner, A.D., Hutson, J.L., 2014. Influence of model conceptualisation on one-dimensional recharge quantification: Uley South, South Australia. Hydrogeol. J. 22 (4), 795–805.

Ou, G., Munoz-Arriola, F., Uden, D.R., Martin, D., Allen, C.R., Shank, N., 2018. Climate change implications for irrigation and groundwater in the Republican River Basin, USA. Clim. Change 151 (2), 303–316.

Owen, S.J., Jones, N.L., Holland, J.P., 1996. A comprehensive modeling environment for the simulation of groundwater flow and transport. Eng. Comput. 12 (3), 235–242.

Owuor, S.O., et al., 2016. Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments. Ecol. Process. 5 (1), 16.

Paradis, D., Vigneault, H., Lefebvre, R., Savard, M.M., Ballard, J.M., Qian, B., 2016. Groundwater nitrate concentration evolution under climate change and agricultural adaptation scenarios: Prince Edward Island, Canada. Earth Syst. Dynam. 7 (1), 183–202.

Parry, M., Canziani, O., Palutikof, J., van der Linden, P.J., Hanson, C.E., 2007. Climate change 2007: impacts, adaptation and vulnerability, 4. Cambridge University Press Cambridge.

Patil, N.S., Chetan, N.L., Nataraja, M., Suthar, S., 2020. Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed. Groundwater for. Sustain. Dev. 100323.

Penna, D., Engel, M., Mao, L., Dell'Agnese, A., Bertoldi, G., Comiti, F., 2014. Tracer-based analysis of spatial and temporal variations of water sources in a glacierized catchment. Hydrol. Earth Syst. Sci. 18 (12), 5271–5288.

Persaud, E., Levison, J., MacRitchie, S., Berg, S.J., Erler, A.R., Parker, B., Sudicky, E., 2020. Integrated modelling to assess climate change impacts on groundwater and surface water in the Great Lakes Basin using diverse climate forcing. J. Hydrol. 584, 124682.

Pholkern, K., Saraphirom, P., Srisuk, K., 2018. Potential impact of climate change on groundwater resources in the Central Huai Luang Basin, Northeast Thailand. Sci. Total Environ. 633, 1518–1535.

Pisani, B., Samper, J., Marques, J.E., 2019. Climate change impact on groundwater resources of a hard rock mountain region (Serra da Estrela, Central Portugal). Sustain. Water Resour. Manage. 5 (1), 289–304.

Pitz, C.F., 2016. Predicted impacts of climate change on groundwater resources of Washington State (pp. 1–25). Environmental Assessment Program, Washington State Department of Ecology Olympia.

Pokhrel, Y.N., Fan, Y., Miguez-Macho, G., Yeh, P.J.F., Han, S.C., 2013. The role of groundwater in the Amazon water cycle: 3. Influence on terrestrial water storage computations and comparison with GRACE. J. Geophys. Res. Atmosph. 118 (8), 3233–3244.

Pollock, D.W., 2016. User guide for MODPATH Version 7—A particle-tracking model for MODFLOW. 2331-1258, US Geological Survey.

Portmann, F.T., 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.

Prucha, B., et al., 2016. MIKE-SHE integrated groundwater and surface water model used to simulate scenario hydrology for input to DRIFT-ARID: the Mokolo River case study. Water SA 42 (3), 384–398.

Pulido-Velazquez, M., et al., 2015a. 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.

Pulido-Velazquez, D., García-Aróstegui, J.L., Molina, J.L., Pulido-Velazquez, M., 2015b. Assessment of future groundwater recharge in semi-arid regions under climate change scenarios (Serral-Salinas aquifer, SE Spain). Could increased rainfall variability increase the recharge rate? Hydrol. Process. 29 (6), 828–844.

Pulido-Velazquez, D., Collados-Lara, A.J., Alcalá, F.J., 2018. Assessing impacts of future potential climate change scenarios on aquifer recharge in continental Spain. J. Hydrol. 567, 803–819.

Qian, Y., Huang, M., Yang, B., Berg, L.K., 2013. A modeling study of irrigation effects on surface fluxes and land–air–cloud interactions in the Southern Great Plains. J. Hydrometeorol. 14 (3), 700–721.

Qin, D., et al., 2011. Assessing impact of irrigation water on groundwater recharge and quality in arid environment using CFCs, tritium and stable isotopes, in the Zhangye Basin, Northwest China. J. Hydrol. 405 (1–2), 194–208.

Qiu, S., et al., 2015. Numerical simulation of groundwater flow in a river valley basin in Jilin Urban Area. China. Water 7 (10), 5768–5787.

Rahmati, O., Pourghasemi, H.R., Melesse, A.M., 2016. Application of GIS-based data driven random forest and maximum entropy models for groundwater potential mapping: a case study at Mehran Region, Iran. Catena 137, 360–372.

Rajamanickam, R., 2011. Groundwater quality modeling of Amaravathi river basin of Karur district, Tamil nadu, using visual Modflow. Int. J. Environ. Sci. 2, 91–108.

Reager, J., et al., 2016. A decade of sea level rise slowed by climate-driven hydrology. Science 351 (6274), 699–703.

Refsgaard, J.C., et al., 2016. Climate change impacts on groundwater hydrology–where are the main uncertainties and can they be reduced? Hydrol. Sci. J. 61 (13), 2312–2324.

Ren, X., Zhu, B., Liu, M., Zhang, Y., He, Z., & Rioual, P. 2019. Mechanism of groundwater recharge in the middle-latitude desert of eastern Hunshandake, China: diffuse or focused recharge?.Hydrogeol. J. 27(2): 761-783.

Richey, A.S., Thomas, B.F., Lo, M.H., Reager, J.T., Famiglietti, J.S., Voss, K., et al., 2015. Quantifying renewable groundwater stress with GRACE. Water Resour. Res. 51 (7), 5217–5238.

Riedel, T., 2019. Temperature-associated changes in groundwater quality. J. Hydrol. 572, 206–212.

Rodríguez-Huerta, E., Rosas-Casals, M., Hernández-Terrones, L.M., 2020. A water balance model to estimate climate change impact on groundwater recharge in Yucatan Peninsula, Mexico. Hydrol. Sci. J. 65 (3), 470–486.

Romanazzi, A., Gentile, F., Polemio, M., 2015. Modelling and management of a Mediterranean karstic coastal aquifer under the effects of seawater intrusion and climate change. Environ. Earth Sci. 74 (1), 115–128.

Rumsey, C.A., Miller, M.P., Susong, D.D., Tillman, F.D., Anning, D.W., 2015. Regional scale estimates of baseflow and factors influencing baseflow in the Upper Colorado River Basin. J. Hydrol.: Reg. Stud. 4, 91–107.

Russo, T.A., Lall, U., 2017. Depletion and response of deep groundwater to climate-induced pumping variability. Nat. Geosci. 10 (2), 105–108.

Saha, G.C., Li, J., Thring, R.W., 2017. Understanding the effects of parameter uncertainty on temporal dynamics of groundwater-surface water interaction. Hydrology 4 (2), 28.

Sapriza-Azuri, G., Jódar, J., Carrera, J., Gupta, H.V., 2015. Toward a comprehensive assessment of the combined impacts of climate change and groundwater pumping on catchment dynamics. J. Hydrol. 529, 1701–1712.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10 (1), 18–39.

Scanlon, B.R., Longuevergne, L., Long, D., 2012. Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. Water Resour. Res. 48 (4) W04529:1-9.

Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E., Dennehy, K.F., 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Glob. Change Biol. 11 (10), 1577–1593.

Schaller, M.F., Fan, Y., 2009. River basins as groundwater exporters and importers: Implications for water cycle and climate modeling. J. Geophys. Res. Atmosph., 114(D04103):1-21.

Schmidt, D.H., Garland, K.A., 2012. Bone dry in Texas: resilience to drought on the upper

Texas Gulf Coast. CPL Bibliography 27 (4), 434–445.

Schumacher, M., Forootan, E., van Dijk, A. I. J. M., Schmied, H. M., Crosbie, R. S., Kusche, J., Döll, P. (2018). Improving drought simulations within the Murray-Darling Basin by combined calibration/assimilation of GRACE data into the WaterGAP Global Hydrology Model. Remote Sens. Environ. 204, 212-228.

Scibek, J., Allen, D.M., Cannon, A.J., Whitfield, P.H., 2007. Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. J. Hydrol. 333 (2), 165–181.

Shamsudduha, M., Taylor, R., Longuevergne, L., 2012. Monitoring groundwater storage changes in the highly seasonal humid tropics: Validation of GRACE measurements in the Bengal Basin. Water Resour. Res. 48(2) W02508:1-12.

Shen, C., Niu, J., Phanikumar, M.S., 2013. Evaluating controls on coupled hydrologic and vegetation dynamics in a humid continental climate watershed using a subsurface-land surface processes model. Water Resour. Res. 49 (5), 2552–2572.

Shrestha, S., Bach, T.V., Pandey, V.P., 2016. Climate change impacts on groundwater resources in Mekong Delta under representative concentration pathways (RCPs) scenarios. Environ. Sci. Policy 61, 1–13.

Shrestha, S., Neupane, S., Shanmugam, M., Pandey, V.P., 2020. Mapping groundwater resiliency under climate change scenarios: A case study of Kathmandu Valley, Nepal. Environ. Res. 109149.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation—a global inventory. Hydrol. Earth Syst. Sci. 14 (10), 1863–1880.

Sililo, O.T., Tellam, J.H., 2000. Fingering in unsaturated zone flow: a qualitative review with laboratory experiments on heterogeneous systems. Groundwater 38 (6), 864–871.

Sivarajan, N.A., Mishra, A.K., Rafiq, M., Nagraju, V., Chandra, S., 2019. Examining climate change impact on the variability of ground water level: A case study of Ahmednagar district, India. J. Earth Syst. Sci. 128 (5), 122.

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. J. Hydrol. 555, 125–128.

Smyth, J.E., Russotto, R.D., Storelvmo, T., 2017. Thermodynamic and dynamic responses of the hydrological cycle to solar dimming. Atmos. Chem. Phys. 17 (10), 6439–6453.

Snyder, R.L., 2017. Climate change impacts on water use in horticulture. Horticulturae 3 (2), 27.

Solder, J.E., Stolp, B.J., Heilweil, V.M., Susong, D.D., 2016. Characterization of mean transit time at large springs in the Upper Colorado River Basin, USA: a tool for assessing groundwater discharge vulnerability. Hydrogeol. J. 24 (8), 2017–2033.

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeol. J. 10 (1), 52–67.

Soro, G.E., Yao, A.B., Kouame, Y.M., Bi, T.A.G., 2017. Climate change and its impacts on water resources in the Bandama basin, Côte D'ivoire. Hydrology 4 (1), 18.

Sorokin, L.V., Mondello, G., 2018. Entering the new+ 2 C Global Warming age and a threat of World Ocean expansion for sustainable economic development, Climate Change, Extreme Events and Disaster Risk Reduction. Springer 183–201.

Srinivasan, V., Lele, S., 2017. From Groundwater Regulation to Integrated Water Management. Econ. Polit. Week. 52 (31), 107.

Srivastava, R., 2013. Groundwater resources under a changing climate. J. Indian Inst. Sci. 93 (2), 251–264.

Stagl, J., Mayr, E., Koch, H., Hattermann, F.F., Huang, S., 2014. Effects of climate change on the hydrological cycle in central and eastern Europe, Managing Protected Areas in Central and Eastern Europe Under Climate Change. Springer 31–43.

Stamm, C., Flühler, H., Gächter, R., Leuenberger, J., Wunderli, H., 1998. Preferential transport of phosphorus in drained grassland soils. J. Environ. Qual. 27 (3), 515–522.

Stanton, J. S., Qi, S. L., Ryter, D. W., Falk, S. E., Houston, N. A., Peterson, S. M., et al. 2011. Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009. US Geological Survey Scientific Investigations Report, 5183, 92.

Stocker, T., 2014. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Stoll, S., Franssen, H.H., Butts, M., Kinzelbach, W., 2011. Analysis of the impact of climate change on groundwater related hydrological fluxes: a multi-model approach including different downscaling methods. Hydrol. Earth Syst. Sci. 15 (1), 21.

Strassberg, G., Scanlon, B.R., Rodell, M., 2007. Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). Geophys. Res. Lett. 34 (14).

Stuart, M., Gooddy, D., Bloomfield, J., Williams, A., 2011. A review of the impact of climate change on future nitrate concentrations in groundwater of the UK. Sci. Total Environ. 409 (15), 2859–2873.

Sugita, F., Nakane, K., 2007. Combined effects of rainfall patterns and porous media properties on nitrate leaching. Vadose Zone J. 6 (3), 548–553.

Sultana, Z., Coulibaly, P., 2011. Distributed modelling of future changes in hydrological processes of Spencer Creek watershed. Hydrol. Process. 25 (8), 1254–1270.

Sutinen, R., Hänninen, P., Venäläinen, A., 2008. Effect of mild winter events on soil water content beneath snowpack. Cold Reg. Sci. Technol. 51 (1), 56–67.

Tague, C., Grant, G., Farrell, M., Choate, J., Jefferson, A., 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. Clim. Change 86 (1), 189–210.

Tague, C., Grant, G.E., 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resources Research, 45(7) W07421:1-12.

Tam, V.T., Batelaan, O., Beyen, I., 2016. Impact assessment of climate change on a coastal groundwater system, Central Vietnam. Enviorn. Earth Sci. 75 (10), 908.

Tambe, S., Kharel, G., Arrawatia, M. L., Kulkarni, H., Mahamuni, K., & Ganeriwala, A. K. 2012. Reviving dying springs: climate change adaptation experiments from the Sikkim Himalaya. Mountain Res. Dev. 32(1): 62-72.

Taniguchi, M., Burnett, W.C., Ness, G.D., 2008. Integrated research on subsurface environments in Asian urban areas. Sci. Total Environ. 404(2-3): 377-392.

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., et al. 2019 Contributions of GRACE to understanding climate change. Nat. Clim. Change, 9(5): 358-369.

Taylor, R., 2014. Hydrology: when wells run dry. Nature, 516(7530): 179.

Taylor, R.G., Koussis, A.D., Tindimugaya, C., 2009. Groundwater and climate in Africa—a review. Hydrol. Sci. J. 54 (4), 655–664.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., et al., 2013. Ground water and climate change. Nat. Climate Change 3 (4), 322–329.

Tillman, F.D., Gangopadhyay, S., Pruitt, T., 2016. Changes in groundwater recharge under projected climate in the upper Colorado River basin. Geophys. Res. Lett. 43 (13), 6968–6974.

Tillman, F.D., Gangopadhyay, S., Pruitt, T., 2017. Changes in projected spatial and seasonal groundwater recharge in the Upper Colorado River Basin. Groundwater 55 (4), 506–518.

Tiwari, V., Wahr, J., Swenson, S., 2009. Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys. Res. Lett. 36 (18).

Tong, S., Berry, H. L., Ebi, K., Bambrick, H., Hu, W., Green, D., et al. 2016. Climate change, food, water and population health in China. Bulletin of the World Health Organization, 94(10): 759.

Tosi, L., Strozzi, T., Da Lio, C., Teatini, P. (2015, November). Regional and local land subsidence at the Venice coastland by TerraSAR-X PSI. In NISOLS 2015 (Ninth Symposium on Land Subsidence). Copernicus Publications.

Touhami, I., Chirino, E., Andreu, J.M., Sánchez, J.R., Moutahir, H., Bellot, J., 2015. Assessment of climate change impacts on soil water balance and aquifer recharge in a semiarid region in south east Spain. J. Hydrol. 527, 619–629.

Touhami, I., Andreu, J.M., Chirino, E., Sánchez, J.R., Moutahir, H., Pulido-Bosch, A., et al., 2013. Recharge estimation of a small karstic aquifer in a semiarid Mediterranean region (southeastern Spain) using a hydrological model. Hydrol. Process. 27 (2), 165–174.

Toure, A., Diekkrüger, B., Mariko, A., Cissé, A.S., 2017. Assessment of groundwater resources in the context of climate change and population growth: case of the Klela Basin in Southern Mali. Climate 5 (3), 45.

Toure, A., Diekkrüger, B., Mariko, A., 2016. Impact of climate change on groundwater resources in the Klela basin, southern Mali. Hydrology 3 (2), 17.

Trefry, M.G., Muffels, C., 2007. FEFLOW: A Finite-Element Ground Water Flow and Transport Modeling Tool. Groundwater 45 (5), 525–528.

Treidel, H., Martin-Bordes, J.L., Gurdak, J.J., 2011. Climate change effects on groundwater resources: a global synthesis of findings and recommendations. CRC Press, Taylor & Francis Group, London, UK.

Trenberth, K.E., 2014. Water cycles and climate change. Global Environ. Change 31–37.

Turner, S.W., Hejazi, M., Calvin, K., Kyle, P., Kim, S., 2019. A pathway of global food supply adaptation in a world with increasingly constrained groundwater. Sci. Total Environ. 673, 165–176.

Tweed, S., Leblanc, M., Cartwright, I., Favreau, G., Leduc, C., 2011. Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia. J. Hydrol. 408 (3), 257–275.

UNESCO, I., Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) A Framework Document (GRAPHIC Series No 2008 2).

Van Camp, M., Mtoni, Y., Mjemah, I.C., Bakundukize, C., Walraevens, K., 2014. Investigating seawater intrusion due to groundwater pumping with schematic model simulations: the example of the Dar es Salaam coastal aquifer in Tanzania. J. Afr. Earth Sc. 96, 71–78.

van der Knaap, Y. A., de Graaf, M., van Ek, R., Witte, J. P. M., Aerts, R., Bierkens, M. F., & van Bodegom, P. M. 2015. Potential impacts of groundwater conservation measures on catchment-wide vegetation patterns in a future climate. Landscape Ecol. 30(5): 855-869.

Van Engelenburg, J., Hueting, R., Rijpkema, S., Teuling, A. J., Uijlenhoet, R., & Ludwig, F. 2018. Impact of changes in groundwater extractions and climate change on groundwater-dependent ecosystems in a complex hydrogeological setting. Water Resour. Manage. 32(1): 259-272.

Velis, M., Conti, K.I., Biermann, F., 2017. Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. Sustain. Sci. 12 (6), 1007–1017.

Voss, C., Provost, A., 2002. SUTRA, a model for saturated–unsaturated, variable-density ground-water flow with solute or energy transport. Water-Resour. Invest. Rep. 2002-4231. USGS, Reston, VA. SUTRA, a model for saturated–unsaturated, variable-density ground-water flow with solute or energy transport. Water-Resour. Invest. Rep. 2002-4231. USGS, Reston, VA.

Vincent, A., Violette, S., Aðalgeirsdóttir, G., 2019. Groundwater in catchments headed by temperate glaciers: A review. Earth Sci. Rev. 188, 59–76.

Wada, Y., 2016. Modeling groundwater depletion at regional and global scales: Present state and future prospects. Surv. Geophys. 37 (2), 419–451.

Wada, Y., Beek, L., Bierkens, M.F., 2012. Nonsustainable groundwater sustaining irrigation: A global assessment. Water Resour. Res. 48 (6).

Wada, Y., van Beek, L. P., Sperna Weiland, F. C., Chao, B. F., Wu, Y. H., & Bierkens, M. F. 2012b. Past and future contribution of global groundwater depletion to sea-level rise. Geoph. Res. Lett. 39(9).

Wada, Y., Bierkens, M.F., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9(10): 104003.

Wada, Y., Van Beek, L.P., Van Kempen, C.M., Reckman, J.W., Vasak, S., Bierkens, M.F., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37 (20).

Wang, J., Gao, Y., Wang, S., 2015. Land use/cover change impacts on water table change over 25 years in a desert-oasis transition zone of the Heihe River Basin, China. Water

8 (1), 11.

Weissinger, R., Philippi, T., Thoma, D., 2016. Linking climate to changing discharge at springs in Arches National Park, Utah, USA. Ecosphere, 7(10) e01491:1-12.

Whittemore, D.O., Butler Jr, J.J., Wilson, B.B., 2016. Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers. Hydrol. Sci. J. 61 (1), 134–145.

Williams, Z.C., Pelletier, J.D., 2015. Self-affinity and surface-area-dependent fluctuations of lake-level time series. Water Resour. Res. 51 (9), 7258–7269.

R.B. Winston C.I. Voss SutraGUI: A Graphical User Interface for SUTRA, A Model for Ground-Water Flow with Solute or Energy Transport. U.S. Geological Survey Open-File Report 03–285 2004 Reston, Virginia pp. 114.

Wirmvem, M. J., Mimba, M. E., Kamtchueng, B. T., Wotany, E. R., Bafon, T. G., Asaah, A. N. E., et al. 2017. Shallow groundwater recharge mechanism and apparent age in the Ndop plain, northwest Cameroon. Appl. Water Sci. 7(1), 489-50.

WMO, 2017. The state of the greenhouse gases in the atmosphere using the global observation through 2016. WMO Greenhouse Gas Bulletin (GHG Bulletin), pp. 1-8.

Wood, C., Cook, P.G., Harrington, G.A., 2015. Vertical carbon-14 profiles for resolving spatial variability in recharge in arid environments. J. Hydrol. 520, 134–142.

Wu, B., et al., 2015. Optimizing water resources management in large river basins with integrated surface water-groundwater modeling: A surrogate-based approach. Water Resour. Res. 51 (4), 2153–2173.

Xiaobin, Z., 2003. Groundwater modeling system (GMS) software. Hydrogeol. Eng. Geol. 5, 53–55.

Xiao, M., Koppa, A., Mekonnen, Z., Pagán, B.R., Zhan, S., Cao, Q., et al., 2017. How much groundwater did California's Central Valley lose during the 2012–2016 drought? Geophys. Res. Lett. 44 (10), 4872–4879.

Xie, H., Eheart, J.W., An, H., 2008. Hydrologic and economic implications of climate change for typical river basins of the agricultural Midwestern United States. J. Water Resour. Plann. Manage. 134 (3), 205–213.

Yeakley, J.A., Maas-Hebner, K.G., Hughes, R.M., 2014. Wild salmonids in the urbanizing Pacific Northwest. Springer, New York, pp. 11–29.

Yidana, S.M., Vakpo, E.K., Sakyi, P.A., Chegbeleh, L.P., Akabzaa, T.M., 2019. Groundwater–lakewater interactions: an evaluation of the impacts of climate change and increased abstractions on groundwater contribution to the Volta Lake, Ghana. Environ. Earth Sci. 78 (3), 74.

Yihdego, Y., Webb, J.A., Vaheddoost, B., 2017. Highlighting the role of groundwater in lake–aquifer interaction to reduce vulnerability and enhance resilience to climate change. Hydrology 4 (1), 10.

Zaveri, E., Grogan, D.S., Fisher-Vanden, K., Frolking, S., Lammers, R.B., Wrenn, D.H., et al., 2016. Invisible water, visible impact: groundwater use and Indian agriculture under climate change. Environ. Res. Lett. 11 (8), 084005.

Zhang, R., Delworth, T.L., Sutton, R., Hodson, D.L., Dixon, K.W., Held, I.M., et al., 2013. Have aerosols caused the observed Atlantic multidecadal variability? J. Atmos. Sci. 70 (4), 1135–1144.

Zhang, X., 2015. Conjunctive surface water and groundwater management under climate change. Front. Environ. Sci. 3, 59.

Zhang, L., Nan, Z, Yu, W., Ge, Y., 2016. Hydrological responses to land-use change scenarios under constant and changed climatic conditions. Environ. Manage. 57 (2), 412–431.

Zheng, C., Hill, M.C., Cao, G., Ma, R., 2012. MT3DMS: Model use, calibration, and validation. Trans. ASABE 55 (4), 1549–1559.

Zhong, Y., Hao, Y., Huo, X., Zhang, M., Duan, Q., Fan, Y., 2016. A statistical model for karst spring discharge estimation under extensive groundwater development and extreme climate change. Hydrol. Sci. J. 61 (11), 2011–2023.

Zhou, Y., Xu, Y.J., Xiao, W., Wang, J., Huang, Y., Yang, H., 2017. Climate change impacts on flow and suspended sediment yield in headwaters of high-latitude regions—A case study in China's far northeast. Water 9 (12), 966.

Zhou, Y., Zwahlen, F., Wang, Y., Li, Y., 2010. Impact of climate change on irrigation requirements in terms of groundwater resources. Hydrogeol. J. 18 (7), 1571–1582.

Zhu, L., Gong, H., Li, X., Wang, R., Chen, B., Dai, Z., Teatini, P., 2015. Land subsidence due to groundwater withdrawal in the northern Beijing plain, China. Eng. Geol. 193, 243–255.

Zingaro, D., Portoghese, I., Giannoccaro, G., 2017. Modelling crop pattern changes and water resources exploitation: A case study. Water 9 (9), 685.