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Survey Article

An Overview of the Potential Impacts of Climate Change on Groundwater Resources

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Abstract. Climate change has been consistently observed over the past decades to be associated with changes and/or modifications of components of the hydrological systems. Observational records and global and regional climate projections indicate that both surface-water and groundwater resources are vulnerable to climate change and variability. Thus, understanding the impacts of climate change and variability on groundwater systems is integral to better planning and efficient management of groundwater resources. However, assessing and predicting the effects of climate change on groundwater systems is relatively difficult due to the uncertainties associated with the spatial and temporal prediction of future climates. This review provides an overview of the key components of groundwater hydrology in relation to climate change. The effects of changes in climate on groundwater in soil, deep vadose and saturated zones are assessed. The responses of groundwater recharge, discharge, quality and changes in storage to climate change are assessed on inter-annual to multi-decadal or longer geologic time scales.

Keywords. Climate change; Global and regional; Hydrological systems; Groundwater resources; Potential impacts

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1. Introduction

Groundwater may be regarded as all forms of water in the subsurface; this includes water in the soil root zone (soil moisture), deeper vadose zone and saturated zone (confined and unconfined aquifers). Groundwater, one of the most important natural resources globally, provides much of the public and domestic water supply; most rural population around the world obtain potable water from domestic (private) wells, usually for drinking, cooking and washing, particularly in areas where surface-water is either scarce or contaminated. Many terrestrial processes including hydrologic processes are controlled by climate. Thus, changes in climate, which occurs in space and on all time scales, will results to changes and variability in Earth's processes (Velasco *et al*. [88]). Climate change may results from the influence of natural processes and anthropogenic activities on terrestrial climates and hydrologic cycle (IPCC [51]; Dragoni and Sukhija [25]; Aizebeokhai [7]). Hydrologic cycle is linked with changes in atmospheric temperature and radiation balance. Global warming has been consistently associated with changes in components of the hydrologic cycle such as increasing evapotranspiration, changes in atmospheric water vapour, changing precipitation patterns, etc. (Bates *et al*. [11]; IPCC [50], Jimenez Cisneros *et al*. [53]). Such changes will influence subsurface hydrologic dynamics and cause changes in groundwater quality, recharge, discharge and storage in many aquifers (Green *et al*. [37]; Aizebeokhai [6]).

Understanding the impacts of climate change on the complex processes influencing the availability and sustainability of surface-water and groundwater resources is crucial (Dragoni and Sukhija [25]). The effects of climate change on surface-water resources are well recognized; studies of climate change and climate projections indicate that freshwater resources are vulnerable. The availability and sustainability of groundwater in many aquifers is threatened due to depletion of the resource resulting from human and climatic stresses (Alley *et al*. [5]; Bovolo *et al*. [12]; Green *et al*. [38]). The vulnerability of groundwater to climate change has not been adequately studied. Understanding the potential impacts of climate change on groundwater resource availability and sustainability is required for efficient management of the resource. Climate change may directly or indirectly affect groundwater systems in many ways; the magnitude and direction of the changes may be difficult to quantify due to associated uncertainty at all stages of the assessment process (Dettinger and Earman [23]; Kundezwicz *et al*. [57]). This review presents an overview of the key components of groundwater hydrology in relation to changes climate. The responses and vulnerability of groundwater systems to projected climates are assessed. The potential impacts of climate change on recharge and discharge as well as groundwater storage and quality are evaluated. The essence of this review is to draw greater attention to the vulnerability of groundwater systems to climate change.

2. Global Climate Projections

Greenhouse gasses are the major driver of much of the contemporary global and regional climate change; the concentration of CO_2 in the atmosphere is the primary indicator of greenhouse gases and thus, the primary regulator of climate change (Green *et al*. [38]; IPCC [50], Jiménez Cisneros *et al*. [53]). Climate models are used for studying climatic behaviour in response to increasing concentration of green house gases in the atmosphere. Climate models range from simple climate models (SCMs) of the energy balance type to earth system models of intermediate complexity (EMICs) to comprehensive three-dimensional (3D) general circulation models or global climate models (GCMs). GCMs are generally considered as the most sophisticated and reliable climate models for simulating current global climate and predicting future climate scenarios (IPCC [51]; Green *et al*. [50]). However, the inherent uncertainties in climate models make the outputs at best a rough approximation under various assumptions of green house gases emissions (Zhang *et al*. [96]; Schneider [77]). Climate projections are required to quantify the potential effects of climate change and variability on groundwater systems.

Climate change projections for the 21st century are consistent in indicating significant global warming due to rising air temperature and alterations in frequency and intensity of precipitation (Mearns *et al*. [64], Aizebeokhai [7]; IPCC [50], Jiménez Cisneros *et al*. [53]). Climate projections for the 21st century include increased warming in high latitudes than in the tropics; increasing precipitation in high latitudes and parts of the tropics; and decreasing precipitation in some subtropical and lower mid-latitude regions. Increasing air temperature will result to more evapotranspiration and uneven distribution of precipitation, both in timing, frequency and intensity; increasing global average temperature will results to rise in sea level. The changes in climate will have significant impact on hydrological cycle and thus surface-water and groundwater resources (Gurdak *et al*. [39]; Vicente-Serrano *et al*. [89]; IPCC [50], Jiménez Cisneros *et al*. [53]).

3. Climate Change and Groundwater Hydrology

The understanding of the potential effects of climate change on surface-water resources has greatly improved; only few studies have focused on climate induced changes in groundwater resources. Groundwater systems may be directly or indirectly affected by climate induced changes on surface-water and precipitation. The direct impacts include groundwater responses to changes in temperature and precipitation due to increasing concentration of greenhouse gases (Figure 1). The indirect impacts arise from changes in land use and anthropogenic activities, surface-water supplies, and increasing demand for water due to increasing population. Climate change will affect various components of the global hydrologic cycle in space, time, and frequency domains (Milly *et al*. [66]; Bates *et al*. [11]; Aizebeokhai [6]; Toure *et al*. [85]). Changes in atmospheric and surface components of the hydrologic cycle will likely cause changes in the subsurface components of the hydrologic cycle (Van Dijck *et al*. [86]). However, the potential impacts of climate change on groundwater systems are poorly understood due to the complex relation that exists between groundwater and climate variables (Green *et al*. [37]; [38]; Earman and Dettinger [26]).

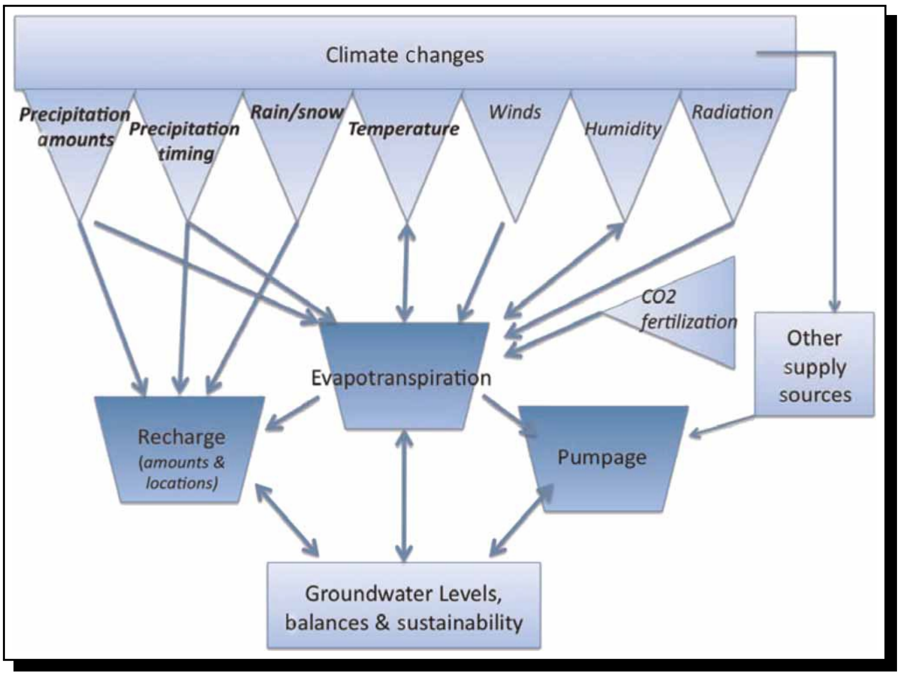

Figure 1. A conceptual relations between climate variables and groundwater hydrology (Earman and Dettinger [26])

Anthropogenic activities including groundwater abstraction resulting to decline in storage, and the capture of natural discharge are often on the same time scale as some climate change. Thus, distinguishing between anthropogenic and climate induced changes in groundwater systems is often difficult. For example, the magnitude and phase relation of El Nino-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO) cycles may result in average or extreme climate conditions that may affect precipitation, drought, infiltration, recharge, discharge, storage and quality of groundwater resources (De Vita *et al*. [24]; Velasco *et al*. [88]). Subsurface hydrological response to climate change may be characterized on inter-annual to multi-decadal time scales because variability on these time scales has the most tangible implications for groundwater resource management (Hanson *et al*. [45]; Gurdak *et al*. [40]; IPCC [50], Jiménez Cisneros *et al*. [53]; Velasco *et al*. [88]). Climate variability on these time scales is often the result of ENSO, PDO and AMO, and can have substantial influence on groundwater systems (Hanson *et al*. [44]; Kuss and Gurdak [58]).

3.1 Precipitation, Evapotranspiration and Surface-Water

There is a general agreement that anthropogenic activities are contributing greatly to the natural greenhouse (IPCC [51]; [50], Jiménez Cisneros *et al*. [53]). The spatial variability of projected precipitation indicates both positive and negative changes which can affect both surface-water and groundwater processes. Projected warming trends will significantly affect global and regional evapotranspiration patterns with direct implications for the sustainability of surface-water and groundwater resources. There is relatively little agreement on the direction and magnitude of predicted evapotranspiration patterns (Barnett *et al*. [9]). Higher air temperatures will increase evapotranspiration and reduce runoff and soil moisture. Small changes in precipitation and/or evapotranspiration may lead to large changes in soil moisture and recharge in many semi-arid and arid regions (Sandstrom [76]; Earman *et al*. [27]). Groundwater recharge is likely to increase with increasing precipitation in some regions. Also, the proportion of land surface that will experience extreme drought is predicted to increase especially in the sub-tropics, and mid-latitudes (Bates *et al*. [11]; Miller *et al*. [65]). Different aquifers and different locations within a given aquifer would experience varied climate induced changes depending on the spatial variability of the hydraulic properties. Many studies indicate substantial alteration in the hydrologic cycle in snowmelt-dominated regions through seasonal shifts in stream flow (Cayan *et al*. [18]; Mote *et al*. [68]; Barnett *et al*. [9]; Jiménez Cisneros *et al*. [53]). Groundwater use may increase to offset the shortage of surface-water in seasons when demands for water are typically higher.

3.2 Surface and Subsurface Hydrological Interactions

Climate change has substantial implications for surface-water processes, including surface-water and groundwater interactions. Climate change will result to less availability of surface-water and thus increase the need for groundwater development (Chen *et al*. [19]). Surface-water storage structures play a vital role in augmenting recharge. Surface-water and groundwater interactions may be the most vulnerable to climate change in most settings. Most gaining streams are relatively shallow compared to the aquifer thickness and receive inflows mainly from the uppermost parts of the aquifers. A decrease in recharge will lower the water-table in unconfined aquifers and reduce inflow to surface-water bodies. Similarly, increase in recharge will result to rising groundwater levels and increased inflow to surface-water bodies.

Small but important feedbacks exist between groundwater and atmospheric processes on decadal and longer time scales (Cohen *et al*. [21]). The hydrologic sensitivity of watersheds to climate change depends on feedbacks between groundwater, overland flow, surface-water and energy balance. The magnitude and seasonality of groundwater feedbacks to surface hydrologic processes is highly sensitive to climate change (Zhou *et al*. [97]). Many ecosystems that depend on hydrological systems are vulnerable to changes in surface-water and groundwater interactions. Springs, wetlands, riparian and estuary systems, which are responsive to the fluctuations in flows to and/or through them, will be affected by climate induced changes in precipitation events and evapotranspiration (Kimmerer [55]). Understanding climate projection is crucial for groundwater/surface-water resources close to the limits of sustainability. Stream flows during dry periods can be strongly affected by groundwater withdrawer. Thus, it is important to accurately understand the links between climate change and the cycles of supply and demand that drive groundwater recharge and withdrawal. Also, accurate projections of climate change and simulations of the responses in the water-resources system are required (Hanson and Dettinger [43]).

3.3 Soil Moisture and Vadose Zone

Projected climate is expected to have profound effects on soil and vadose zone hydrology. Soil moisture and temperature are important factors in terrestrial climates, biogeochemical reactions, and land and atmosphere interactions. Variability in vadose zone hydrology, shallow water tables, and groundwater resources are affected by soil moisture and temperature (Fan *et al.* [31]). Spatial variations in soil moisture influence atmospheric processes, such as the cumulus convective rainfall. Some soil types such as hydromorphic soils may exhibit higher climate change feedback potential than well-aerated soils (Jungkunst *et al.* [54]). Climatic variables that influence soil moisture include spatiotemporal patterns in precipitation, evapotranspiration and surface-water conditions. Other factors include land use, soil texture, slope, and other biological, chemical, and physical characteristics (Jasper *et al.* [52]; Seneviratne *et al.* [78]). Complex interactions between thermal, hydrologic and geochemical processes that can affect groundwater quantity and quality commonly occur in the vadose zone (Glassley *et al.* [35]). The vadose zone of some semi-arid and arid regions has slowly evolving dynamic characteristics that pose important challenges for long-term understanding of the effects of climate change.

3.4 Saturated Zone

Many aquifers around the world have large storage capacity and are potentially less sensitive to changes in climate than surface-water bodies. Groundwater can potentially mitigate droughts and support surface-water in meeting the demand for water particularly in semi-arid and arid regions. Changes in palaeo-climatic conditions and responses in recharge, discharge and changes in storage are preserved in the records of groundwater major and trace-elements chemistry, stable and radio-isotopes composition, and noble gas content (Fan *et al.* [31]; Edmunds and Milne [29]; Castro *et al.* [17]). Other important components of the hydrogeological systems include groundwater-fed lakes in arid and semi-arid regions, pore-water chemistry of the vadose zone, and subsurface-thermal regimes (Taniguchi [83]; Miyakoshi *et al.* [67]; Taniguchi *et al.* [83]). Groundwater archives act as low-pass filters and provide low resolution time-series of reconstructed temperatures and atmospheric-moisture transport patterns (Gasse [33]). More palaeo-hydrological researches are required to develop chronologies and analyze mechanisms for water storage and losses in aquifers, obtain quantitative reconstructions of hydrological cycles, and identify atmospheric-moisture transport patterns at regional and basin scales.

A number of non-climatic forcings such as contamination, reduction in stream flow and recharge, and lowering of the water table and loss of storage due to withdrawer can affect groundwater resources. Climate induced changes in groundwater to date are relatively small compared with non-climate drivers because groundwater systems often respond more slowly and have substantial temporal lag to climate change than surface-water systems (Hanson *et al.* [44]; Gurdak *et al.* [40]; Aribisa *et al.* [8]). Persistent and severe dry periods can significantly alter the hydraulic properties of aquifers. Current vulnerabilities in water resources strongly correlate with climate variability, due largely to variability in precipitation (Kundzewicz *et al.* [57]; Ouysse *et al.* [72]). Variability in groundwater levels correlate more strongly with precipitation than with temperature, but temperature is more important in shallow aquifers.

3.5 Aquifers Recharge

The dynamic processes affecting aquifers recharge are fundamental to the assessment of climate induced changes in groundwater quality and quantity (Dragoni and Sukhija [25]; Gurdak *et al*. [41]; Toure *et al*. [85]). Groundwater recharge is a sensitive function of climatic factors, local geology and soil type, topography, vegetation, surface-water hydrology and land use. Any variation in precipitation, temperature and evapotranspiration will generally affect recharge (Dragoni and Sukhija [25]; Green *et al*. [38]). The understanding of the controls on recharge has improved significantly, but the knowledge of recharge rates and mechanisms is relatively poor. Excess rainfall or runoff not used or stored in reservoirs ultimately becomes part of the soil or groundwater systems or flow to oceans. Climate projections are expected to have numerous effects on recharge rates and mechanisms, which may not necessarily be negative in all aquifers (Kundzewicz *et al*. [57]; Holman *et al*. [48]; Toure *et al*. [85]); recharge may increase, decrease or unchanged depending on a number of climate variables. Under projected climate scenarios, recharge tends to increase in subtropical regions and remains relatively unchanged or reduced in some regions (Eckhardt and Ulbrich, 2003; Green *et al*. [37]; Holman *et al*. [48]).

The spatiotemporal responses of recharge to precipitation variability due to changes in climate may affect aquifer yield and discharge, and may modify groundwater flow networks such that gaining streams suddenly become losing streams and groundwater divides change position (Winter [93]; Dragoni and Sukhija [25]). In permafrost regions, aquifer recharge may increase in areas of permafrost thaw; long-term stream flow records can indicate the general trend in groundwater contribution to stream flow due to permafrost thawing (Kitabata *et al*. [56]; Walvoord and Striegl [90]; Haldorsen *et al*. [42]). In some regions, groundwater flow may contribute more to permafrost degradation than changes in climate; degrading permafrost may cause lowering of regional groundwater table leading to falling lake stages, shrinking wetlands, and degenerating grasslands. Soil moisture may decrease with degrading permafrost and thus, increase the likelihood of desertification in the region (Cheng and Wu [20]). Snow cover and soil frost will be reduced in some regions leading to increased winter floods, aquifer recharge and water levels in shallow unconfined aquifers (Okkonen *et al*. [70]). Climate related parameters affecting recharge often trigger slope instability and landslide. Variability in precipitation and air temperature has substantial control on future landslide activities. Changes in recharge, which directly affect groundwater levels, have implications for slope stability, geomorphology, and other engineering considerations. Increase in recharge and thus increased groundwater levels will likely increase slope instability (Soldati *et al*. [80]).

Since groundwater is a critical component of the global hydrologic cycle, more attention should be paid to climate change effects on recharge. The necessary tools and data required to predict recharge responses to projected climate scenarios in most environments are currently lacking. Recharge response to projected climates in many regions is presently not well known due to the uncertainties in predicting future responses of recharge to a given climate-change scenario (Dragoni and Sukhija [25]). The changing conditions of the location and timing of recharge and associated effects on groundwater supplies are not sufficiently understood under projected climate scenarios (Sophocleous [81]; Gurdak *et al*. [40]). However, there is abundant evidence that water resources are vulnerable to climate change effects, especially if recharge conditions change or worsen (Barthel *et al*. [10]; Novicky *et al*. [69]). In water stressed regions, the use of groundwater to offset declining surface-water availability will be hampered by declining recharge rates (Kundzewicz *et al*. [57]).

3.6 Groundwater Discharge

Usually, groundwater depletion occurs when rates of recharge are less than rates of discharge in a given aquifer. Groundwater depletion may results from direct or indirect effects of climate change and/or anthropogenic activities, such as pumping, land use or urbanization. Changes in global groundwater discharge have contributed to rise in sea-level during the past century. Sea-level rise due to global warming and climate change would have been greater if substantial quantity of water had not been stored in land-surface reservoirs or channelled into aquifers by irrigation return-flow (Sahagian *et al*. [74]; Green *et al*. [38]). Groundwater resources could still be substantially affected by climate change even if the present pumping rates are not increased (Loaiciga *et al*. [60]; Yusoff *et al*. [95]). Direct or indirect effects of climate related changes in groundwater discharge include soil degradation, changes in water demand, and changes in irrigation or land-use practices (Brouyere *et al*. [14]). The notable increase in groundwater depletion is consistent with population growth and advances in technology in many regions. The technological advancement include development of high resolution geophysical techniques for delineating aquifers and the development of high-capacity well pumps used to meet the increasing demand for water. Declining base flow that correlates with soil texture has also been observed in some regions (Wang *et al*. [91]).

The effects of groundwater discharge often take many years to manifest; thus, there is a tendency to neglect data collection and analysis required to support informed decisions for efficient groundwater resource management (Alley [2]; Hsu *et al*. [49]). Groundwater resources are usually non-renewable as aquifer discharge usually exceeds recharge, especially in arid and semi-arid regions. Under wet climate scenarios, runoff will be the most sensitive hydrologic component, and when combined with the predicted increases in groundwater discharge, may result in rising groundwater levels and winter precipitation that will increase the risk of flooding (Croley and Luukkonen [22]; Woldeamlak *et al*. [94]). Similarly, under dry climate scenarios, aquifer recharge which will be the most sensitive hydrologic component decreases in all seasons, resulting to declining groundwater levels (Allen *et al*. [1]). This may adversely affect aquatic life in wetlands and riverine ecosystems which rely on groundwater discharge to support base flow (Woldeamlak *et al*. [94]).

3.7 Groundwater Flow and Storage

The importance of groundwater storage is critical in successfully dealing with climate related effects on groundwater resources. Groundwater storage has been and will continue to be used to modulate the effects of droughts on surface-water resources as surface-water storage will become more limited due to climate change (Mall *et al*. [62]; Toure *et al*. [85]). Under projected climate scenarios, groundwater storage will decrease significantly in many regions due to simulated severe droughts (Toure *et al*. [85]). This will further threaten access to groundwater resources. However, some regions may have sufficient and reliable groundwater storage. Groundwater depletion will likely be compounded by global population growth, which correlates with higher groundwater abstraction that further threatens groundwater availability and sustainability (Loaiciga [60]). Population growth and associated increase in the demand for water resources coupled with reduction in groundwater storage will result to substantial land-subsidence (Taniguchi *et al*. [84]). Changes in infiltration rates will also significantly affect groundwater storage; storage may likely in regions with high rates of infiltration.

The complex nature of natural climate variability, which occurs on multiple time scales, is often a major obstacle to reliable characterisation of climate change resulting from anthropogenic activities (Ghil [34]; Aizebeokhai [6]). Anthropogenic effects on aquifers, such as pumping resulting to loss in storage, are often on the same time scale as some natural climate variabilities (Hanson *et al*. [46]; Mayer and Congdon [63]). The natural variability in climate can have profound effects on surface-hydrologic cycle due to the magnitude and phase relation that can cause average or extreme climate forcings (Caruso [16]; Hanson and Dettinger [43]; IPCC, [50]; Jiménez Cisneros *et al*. [53]). Many questions remain with regard to the control of natural climate forcings on subsurface hydrologic processes and how anthropogenic warming affects the frequency and magnitude of these forcings (Gurdak *et al*. [39]). Additional studies on climate variability may help to advance groundwater resource management practices.

3.8 Groundwater Quality

Most studies of climate change effects on groundwater resources have been focused on recharge, discharge, changes in storage and the associated processes governing the flow of groundwater. Relatively few studies have focused on processes affecting groundwater quality. Groundwater quality depends on the chemical, physical and biological characteristics of the resource; thus, it responds to changes in climate and associated anthropogenic activities due to the influences of recharge, discharge, and land use on groundwater systems. Even if climate change does not cause any significant changes in groundwater quality, changes in the amount of groundwater entering other water systems will change the quality of groundwater and those of other water systems (Earman and Dettinger [26]). Groundwater quality assessment is commonly based on a value specific concept related to specific water-use standards. Groundwater quality has direct implications for the health standards of drinking-water (Alley [4]). Usually, groundwater quality is a major limiting factor for its use. The sustainability of water supplies under future climate scenarios depends on the quantity and quality of groundwater resources as well as the physical, chemical, biological and hydrogeological characteristics of the aquifers.

The projected variability in precipitation patterns will likely affect the quality of groundwater under future climate scenarios in many ways (Alley [3]; Dragoni and Sukhija [25]). Changes in recharge rates, mechanisms and locations will affect contaminant transport, and spatial and temporal variability in groundwater quality. Since precipitation is chemically dilute, majority of the dissolved material in most aquifers are derived from the interactions between rock formations and groundwater. Climate change may likely alter the amount of time for the interaction or the chemical conditions during the interaction; this will degrade the quality of groundwater. Also, the spatiotemporal variability in precipitation patterns will result to substantial infiltration events. Large, pore-water salt reservoirs in the vadose zone, mainly chloride and nitrate, will likely be flushed into many aquifers leading to increased groundwater salinization (Sugita and Nakane [82]; Gurdak *et al*. [40]). Thus, groundwater quality in many aquifers may likely deteriorate substantially if these large chemical reservoirs reach the aquifer.

Sea-level rise, spatial and temporal variability in precipitation patterns and evapotranspiration, which affect recharge and increase groundwater abstraction, will result to increased saline-water intrusion into fresh groundwater (Sherif and Singh [79]; Ranja *et al*. [73]; IPCC [51]; Oude Essink *et al*. [71]; Jiménez Cisneros *et al*. [53]). The increasing sea-level rise will lead to increased groundwater flow towards low-lying inlands areas and decrease groundwater flow towards the sea (Vandenbohede *et al*. [87]; Jiménez Cisneros *et al*. [53]). Increased recharge in coastal aquifers will lead to increased groundwater flow towards both low-lying inland areas and the sea. Thus, brackish and saline-water in low-lying areas will be pushed back and saline-water intrusion may increase in the low lying areas; this will increase salinization and degrade groundwater quality in most low-lying areas and hence effects its ecology and drainage systems (Vandenbohede *et al*. [87]). Over withdrawer of groundwater combined with increasing dry periods may lead to substantial decline in groundwater quality in many coastal aquifers (e.g. Lambrakis and Kallergis [59]).

4. Conclusions

Abundant evidence exists that water resources are vulnerable to the effects of climate change. Climate change effects on surface-water resources are widely recognised but not much is known about climate change effects on groundwater resources. Subsurface hydrology is intimately coupled with surface hydrology and atmosphere; the responses of groundwater hydrology to climate change have been assessed. Contemporary groundwater and climate systems are not in equilibrium due to the long memory of deep groundwater system with long flow part and large storage. Changes in climate have implications for groundwater quantity and quality in many aquifers; the responses of aquifer recharge, discharge and changes in storage to climate change are assessed on inter-annual to multi-decadal or longer geologic time scales. Groundwater resources are vulnerable to changes in storage due to variability in precipitation patterns, evapotranspiration, fluctuations in surface-water and groundwater interactions, and over withdrawer arising from climate change.

A deeper understanding of the effects of climate change on groundwater resources over long term is integral for better planning and efficient groundwater management. Information about climate related effects on groundwater resources is inadequate, especially with respect to groundwater quality and ecosystems, and socio-economic dimension. Climate induced changes in hydrological variables and their impacts on groundwater systems are limited by uncertainties inherent in the assessment processes which relate to climate change effects on groundwater recharge, discharge, quality and storage. Current tools to facilitate integrated appraisals of adaptation and mitigation options across multiple water-dependent sectors are also inadequate. Thus, more research on the effects of climate change on hydrologic variables and systems are required to improve the understanding and modelling of climate change at spatial and temporal scales relevant to decision making. The relation between groundwater quality and climate change together with the role of groundwater storage in adapting to climate change should is established. Techniques to predict and control climate change effects on groundwater at regional and basin scales are required. The tools to effectively quantify climate change effects on groundwater resources at different spatial and temporal scales are also required. Models for saline-water intrusion due to rising sea level and ocean encroachment, and salt dissolution within bedrock formations at regional, sub-regional and basin scales should be developed.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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