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Groundwater and Dependent Ecosystems: Revealing the Impacts of Climate Change

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Abstract

Groundwater resources and groundwater dependent ecosystems are threatened by a changing climate. This paper is an assessment for the current knowledge of the impacts of climate change on these climatic scenarios and the adaptation options for management. Based on the growing body of evidence, given current climate projections, unsteadiness in temperature and rainfall may be the primary threats to groundwater and groundwater dependent ecosystems. Variations of temperature and precipitation will impact these ecosystems by altering recharge of groundwater sources and endangering the survival of biological communities by disrupting key biological processes. Predicting these impacts are just as uncertain as predicting climate trends as they are vary over time and space. Despite these uncertainties, there are numerous attempts at all levels of government and society to develop favorable policy environments, build resilient management institutions, synthesize available science, and increase the consciousness and participation of communities to protect and promote the sustainable use of groundwater and groundwater ecosystems.

Keywords: Groundwater, temperature, precipitation, ecosystems, climate.

INTRODUCTION

Water is essential for human survival and ecosystem health. However, freshwater comprises only a tiny fraction of the global water pool and most of it is locked in frozen glaciers and the polar ice caps (Gleeson et al. 2012). The most accessible freshwater is found either as surface water or groundwater. Historically, the pressures to these accessible freshwater resources have been due to consumptive uses for drinking, irrigation and industry as well as non-extractive uses related to recreation, transportation, and waste disposal. Groundwater, in particular, has numerous benefits to society, yet its use has sometimes resulted in undesirable, often unintended, consequences that include storage depletion, land subsidence, saltwater intrusion, reductions in stream flow, and loss of wetland and riparian habitats. Now and into the coming century, the accumulating pressures of direct-use on groundwater and its dependent ecosystems will likely be exacerbated by a rapidly changing climate. Now and into the coming century, the accumulating direct-use pressures on groundwater and groundwater dependent ecosystems will likely be exacerbated by a rapidly changing climate (IPCC, 2007) as shown in the conceptual framework given in figure 1. The long-term fluctuations in temperature, precipitation, wind and other climate parameters will dramatically alter the hydrologic cycle and will not only alter the spatial and temporal availability of freshwater but also the aerial extent, diversity and health of the ecosystems that depend on it. The Intergovernmental Panel on Climate Change (IPCC, 2007) has estimated the increase in global average surface temperature by 0.74ºC from 1906 to 2005 and it will affect the renewable groundwater resources and its level. This warming in the temperatures has direct impacts on the hydrological cycle with the associated changes in precipitation and evapotranspiration which can indirectly impacts on the flux and storage of water in surface and groundwater reservoirs (Kumar, 2012).

While all water resources are threatened, groundwater and groundwater dependent ecosystems are particularly at risk. Because it is not seen and because of the inherent time lag between the stress and a detectible system response, groundwater has been most vulnerable to anthropogenic stress. Additionally, the impacts of climate change on ground water and its dependent ecosystems are less clearly understood due to lack of sufficient scientific studies (Candela et al, 2009; Risbey et al, 2007 and Klove et al., 2011). Hydrological studies of climate change primarily focus on surface water, but only few studies give emphasis on groundwater (Kundzewicz and Döll, 2009; Green et al., 2011). Those which focus on groundwater, primarily studied the impacts of groundwater withdrawal and land use change (Green et al., 2011) but the studies on impacts of climate change on groundwater quantity and quality and cascade effects on groundwater dependent ecosystems (GDEs) have received less attention (Taylor et al., 2012 and Treidel et al., 2012).

Many GDEs support surprisingly high biodiversity and exhibit high levels of endemism (Goldscheider et al., 2006; Boulton et al., 2008), and thus being of considerable conservation value. And in order to conserve biodiversity and ensure the continued benefits of groundwater and GDEs to society, it is imperative to assess the potential impacts of climate change to these systems and to develop strategies to protect them (Dams et al., n.d.). It is in this regard, we reviewed the current state of knowledge regarding the impact of climate change on groundwater and GDEs. We identify the parameters of GDEs that will be most impacted. These impacts then determine the evaluation of promising groundwater management strategies from the policy to the community level. We also identify key research needs that will be critical in meeting the needs of current and future adaptive management of ground water resources and dependent ecosystem.

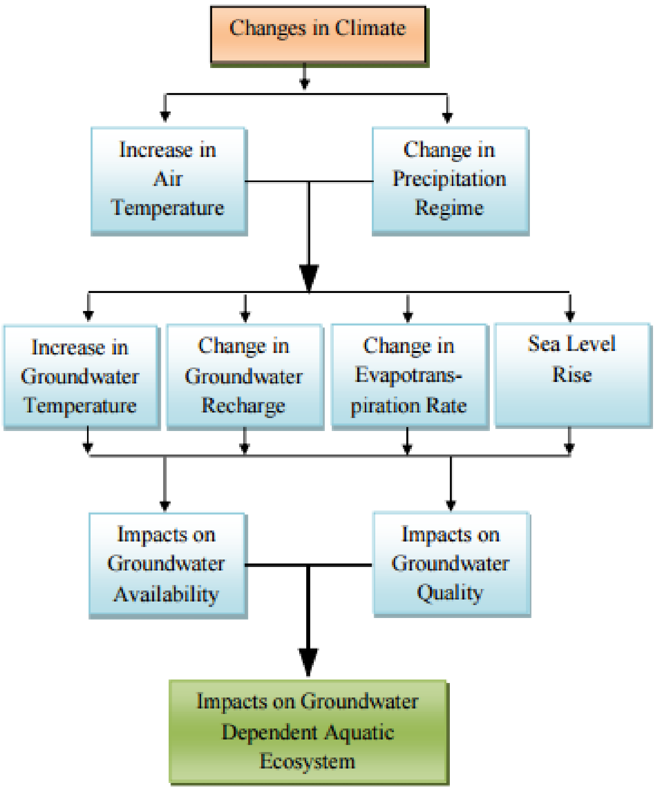

Figure 1: Conceptual diagram on impacts of climate change on groundwater dependent aquatic ecosystem

IMPACTS OF CLIMATE CHANGE ON GROUNDWATER AVAILABILITY AND QUALITY

The changes in climate have directly or indirectly affected the groundwater resources in many different ways (Holman, 2006; Earman and Dettinger, 2011). Recharge of an aquifer is notable as it provides permanency of rainfall quantity of groundwater forever. Recharge of an aquifer depends largely on the type of soil, vegetation, distribution, amount and timing of precipitation, surface temperature, wind speed, evapotranspiration, runoff, dis-charge patterns and land use land cover change. The sensitivity of recharge relate with how the temperature and precipitation are associated. Warmer winter is responsible for increased groundwater recharge (Klove et al., n.d. and Scibek et al., 2007). Klove et al, 2011 noted variations in groundwater level since the 1980s in Northern Finland due to the variations in climate variability which have also affected water levels in groundwater dependent lakes situated on the esker. Candela (2009) also estimated that the aquifer water balance will become slightly negative and spring flow discharge will decrease from 17 mm^3 /yr to as low as 13 mm^3 /yr by 2025 in Inca-Sa Pobla, Spain. Likewise, Candela et al. (2012) projected a 17% reduction in recharge for the first quarter of the 21st century in the wetlands of Majorca, Spain.(Todd, 1980) noted the particular defenselessness of the soil water zone that associates vegetation and biogeochemical reactions, to improve temperature that lead to higher evapotranspiration. Similarly, groundwater in the saturated zone are also more vulnerable to climate change as this zone responds by showing changes in its quantity, quality and flow of water depending on the trends of precipitation, evapotranspiration, recharge and discharge (Schwartz and Zhang, 2003).

The climate change may have the impacts on groundwater quality in many different ways (Alley, 2001 and Dragoni and Sukhija, 2008) by changes in recharge rates, mechanism and location (Alley, 2001). Due to increase in surface temperature, groundwater temperature will increase which will affect water chemistry, residence time and volume of water in matrix and fractures, and thus the composition of the water. The groundwater value depends on the physical, chemical and biological properties of the aquifers, which are organized by climatic fluctuations. During the wet scenario, increased infiltration can mobilize large pore-water chloride and nitrate reservoirs in the vadose zone of semiarid and arid regions (Gurdak and Hanson, 2007). Increase in recharge leads to the dissolution of carbonates, increase in Calcium content may increase the stiffness of groundwater. During a dry situation, the increase in total dissolved solids may get worse the groundwater quality by increased salt include.

Impacts on Groundwater Dependent Ecosystem

The impacts of climate change on ecological processes of aquatic ecosystem depend upon the rate and magnitude of change in temperature and precipitation (Poff et al, 2002) both of which will reduce recharge and possibly increase groundwater withdrawal rates (Treidel et al., 2012) making adverse effects on groundwater dependent environment. Several indicators of physic-chemical, biological and hydrological parameters can be used to understand the changes in groundwater depth, pressure, quality, flow rate, land-use, structure, composition and functioning of GDE and loss of GDEs ecosystem services (Preda et al., 2013) and all the groundwater indicator aims to identify the areas where GDE habitats are likely to be more sensitive to changing climate and where more detailed investigations are likely to be required. However, unlike Preda et al. (2013), we are broadly dealing with the impacts on groundwater dependent aquatic ecosystem rather than going in-depth with all the indicators.

DISCUSSION OF IMPACTS OF INCREASE IN TEMPERATURE

The alteration on air temperature and river temperatures may also affect groundwater temperatures (Taylor and Stefan, 2009) and dissolved oxygen (DO) concentrations (Figura et al., 2011; Kløve et al., 2012; Haldorsen et al., 2012). Some fish species and invertebrates are harmfully influenced when the DO concentration goes below 5 mg/l (Delvin et al., 2007) and most fishes are negatively affected if it drops down below 2.5 mg/l (Frodge et al., 1990). Similarly, lower DO concentration for a long period may slows down the rates of nitrification and denitrification process (Kemp et al., 1990 as cited in Preda (2013). Taylor and Stefan (2009) explain that groundwater temperatures would increase by up to 40C in a temperate climate zone under a doubling of CO2 climate situation. The growth and reproduction of many species directly related to the thermal regime including extreme temperatures, diurnal range and seasonal change in temperature and hence controls vital life processes (Poff et al., 2002). Drying of climate has significantly impacted groundwater dependent ecosystem in south-western Australia projected to be further more risk under the dry future climate scenario (Barron et al., 2012). Figura et al. (2011) detected a significant shift in groundwater temperatures across the Swiss Plateau. Changes in groundwater temperature and subsequent dissolved oxygen concentrations would likely have important implications for temperature dependent reaction rates and reduction–oxidation (redox) reactions that directly affect many biogeochemical processes, including those in the nitrogen and carbon cycle in soil and groundwater. Because many biogeochemical operations in groundwater are temperature dependent, climate-induced changes that influence groundwater temperature may adversely affect the quality of groundwater (Figura et al., 2011). Increase in temperature might influence pesticide leaching in groundwater (Klove et al, 2011) but the processes are complex and mainly related to the land use changes driven by climate change (Bloomfield et al., 2006).

Impacts of Change in Precipitation

The changes in precipitation can have large effects on water quality because wetlands can trap elements such as sulphate (Devito and Hill, 1997), nitrogen, phosphorous (Devito and Dillon, 1993) and methylmercury (Branfireun et al., 1996). According to Klove et al., (n.d), several studies (Brække, 1981; Wieder, 1985; Bayley et al., 1986; Van Dam, 1986) have identified the acidification of stream caused by release of SO4 2- from wetlands after droughts, and this can be linked to fish mortality (Gosling and Baker, 1980; Holopainen and Oikari, 1992). Poff et al., (2002) also pointed out that the pattern of precipitation dictates the changes in volume of water in an aquatic ecosystem over time and this seasonal variation in water volume strongly determines the kind of species existence in an aquatic ecosystem. A study carried out by Chambers(2013) in Jewel Cave of Western Australia showed a remarkable decline in groundwater level from 1958 to 2012 and found that groundwater has reached to its lowest level yet resulting into the decrease in the species richness of the area. The loss of groundwater in cave systems accelerated by the climate change induced rainfall decline in Southwest Western Australia (Eberhard, 2004) is the primary threat to the Stygofaunal communities (Chambers, 2013). The survival of Stygofauna depends on a sustainable source of ground water (Eberhard, 2004; English, 2000 and Jasinka, 1997) and hence the groundwater is the most crucial factor influencing the presence and absence or Stygofauna (Chambers, 2013). Climate change further accentuated the degradation of spring biota by causing changes in the precipitation and evapotranspiration regimes (Runhaar et al., 2002) with increased risk of floods and droughts, and potentially cascading effects on groundwater quality (IPCC, 2007).

A decrease in the groundwater level also enhance soil aeration and organic matter oxidation (Klove et al., 2013) which can lead to nutrient rich environment through production of NO^{3-} and $PO_4{}^{3-}$, which are generally the limiting nutrients in GDE (Wassen et al., 2005). In aerobic conditions, $PO4\ ^{3-}$ may become toxic due to its fixation with the oxidized form of iron (Fe3+) in the root zone (Boomer and Bedford, 2008). An increase in groundwater flow may result in waterlogged conditions, anoxic processes and associated fluxes of contaminants (Werner and Zedler, 2002; Olde Venterink et al., 2006) which may create the nutrition unbalance situation. Changes in groundwater recharge rates and mechanisms may also increase the mobilisation of pesticides and other pollutants in the unsaturated zone and reduce groundwater quality (Bloomfield et al., 2006). Studies on natural soil and agricultural processes in the United Kingdom reported a range of nitrate leaching rates from a slight increase to possibly high nitrate concentrations in groundwater by 2100 because of climate change (Stuart et al., 2011). Similarly, recharge during dry periods may have higher concentration of salts and total dissolved solids (TDS) however recharge during damp periods may have lesser concentration of TDS (Sukhija et al., 1998).

Impacts of Change in Sea Water Level and Saltwater Intrusion

Coastal ecosystem can be highly impacted by salt water intrusion due to sea level rise and reduced groundwater flow

(Werner et al., 2013 and Klove et al., 2013). Von Igel (2006) predicted the increase in intrusion of seawater and decline of piezometric level up to 2 m. Groundwater contamination is also expected in low elevation coastal zones due to sea level rise (IGES, 2008). In some vulnerable zones, such effects on groundwater resources may provide the only available freshwater reserve unreachable or incompatible for use in the near coming times (IPCC, 2007). The sea level rise led destruction of coastal wetlands can have direct negative impacts on coastal fisheries. Long-term changes in the frequency, intensity, timing, and distribution of strong storms would most likely alter the species composition of coastal marshes, as well as the rates of important ecosystem processes such as nutrient cycling and primary and secondary productivity (Michener et al., 1997).

INTEGRATED WATER MANAGEMENT AS A RESPONSE TO CLIMATE CHANGE

The goal of management is to optimize sustainable use of groundwater resources without compromising future use and ensuring the persistence of GDEs, the associated ecosystem services they provide to society. The growing number of groundwater stressors and the competing demands are making groundwater management increasingly complex. Experts who have studied groundwater use around the world tend to agree that too little is known about the institutions and policies that govern the use of these resources (Mukherji and Shah, 2005). Nevertheless, innovative approaches to groundwater management have been developing in many parts of the world over the past decade (de Gooijer et al., 2009). These innovative approaches feature a variety of instruments to manage groundwater (Theesfeld, 2010; Kemper, 2007). Management of groundwater and surface water has usually been two distinct areas being implemented by different government and non-government institutions. Although science has long had the understanding that surface waters are natural extensions of groundwater systems, only when water became scarce, did the need to use these resources conjunctively and therefore integrate their management emerged. The increased pressures on groundwater resources require a new cohesive management method that brings clearly into account groundwater, dependent ecologies and their ecosystem services. This approach is based on new technologies for sustainable groundwater exploitation, considering their support capacity and interactions with dependent ecosystems at wider spatial scales (watershed, national and regional scales), as well as involvement of stakeholders in the management and decision making processes (MEA, 2005).

APPROACHES TO MANAGE GROUND WATER AND GROUNDWATER DEPENDENT ECOSYSTEM OF CLEAR AND CONSISTENT POLICY FRAMEWORKS THAT ARE INCLUSIVE OF GDE

The UN’s Food and Agriculture Organization (FAO, 2011) define policy framework as, a set of decisions which are oriented towards a long term purpose or to a particular problem.‖ Some call attention to the need for consistent policies, legislation and legal frameworks, strategic management planning, and resource administration capacity regarding groundwater management (Foster and Loucks, 2006; Pandey et al., 2011; Puri et al., 2001). These policies need to be consistent across relevant sectors and provide clear guidance for implementation such as enacting new laws and establishing permit systems, creating economic incentives and civil society actions (Theesfeld, 2008). To keep the productive capability of aquifers needs steady monitoring of groundwater quantity and quality and includes aquifer protection. Resulting from the notion of the importance of environmental sustainability, some forward-thinking groundwater resources managers have begun to include the management of GDEs as part of their management activities such as European Union’s Water Framework Directive (WFD, 2000/60/EC and the Groundwater Directive (GWD, 2006/118/EC) have specified the role of GDEs and evaluated by quantitative and chemical status assessment. This acknowledgement and inclusion of GDEs in groundwater policies needs to be more explicit. Aquifer protection policies like those operationalized through the Groundwater Directive of the European Union Water Framework Directive oblige states to take measures to avoid aquifers being contaminated by land use activities and also the maintenance of GDEs.

Effective Institutions with Sufficient Capacity and Designed to Function at Multiple Scales and Across Sectors

Policy and legal frameworks are boundaries within which groundwater management occurs. Management is then tasked to national or local institutions that are mandated to policy decisions to desired outcomes. The Organization for Economic Cooperation and Development (OECD) has pointed out major lack of capacity at the local level within these management institutions (OECD, 2011). Effective management calls for a close match between the scale of ecological processes and the institutions that govern groundwater resources (Cumming et al., 2006). Given the broader trends in ecological and water governance toward multi partnerships and hybrid approaches, it is also leading to build capacity through the multiple and disparate governance level (Kerr, 2007). In addition, interplay between both formal and informal institutions, and across and within scales is seen as important institutional and political elements of governance (Cash et al., 2006; Young, 2002). In particular, the management of transboundary aquifers can only be pursued by establishing the appropriate scales of decision making and involving an assortment of stakeholders as well as state institutions that are designed to operate in multiple scales (Linton and Brooks, 2011). Increasingly, research has also emphasized the need for institutional capacity to adapt to uncertainty and change in order to be resilient within a social-ecological system (Folke et al., 2005; Gallopin, 2006; Young, 2009; Dietz et al., 2003).

Groundwater Recharge Estimation

Groundwater recharge estimations are essential for the management of groundwater aquifers, providing information for sustainable use of groundwater resources. It involves a complete methodology that includes all factors influencing recharge such as soil wetness, precipitation, runoff, evapotranspiration, and land cover (Morsy, 2016; AlRukaibi and McKinney, 2010). During floods and strong storm happenings, these water can be taken to recharge the groundwater in order to give the GDEs instead of losing it as runoff. Modeling helps to estimate the amount of water used by GDEs and checking whether it is sufficient or not, by comparing the soil moisture levels in the rhizosphere with and without the presence of groundwater recharge. Groundwater models are computer programs of groundwater flow systems for the estimation of groundwater flux and head. Thus, such models give approximate estimates, yet they are useful investigation tools.

Further Researches Based on Toad’s Eye Science

Future researches should focus on effect of climate change on groundwater resources and dependent ecosystems. Climate change mapping on different resources will provide better outcomes and results about the vulnerability and dangers involved over time for an exact region. Study should also be advanced to bring superior results from the positive effects of climate change, with the aim of reducing the negative effects. Special attention should be paid to the role of climate change on timing of recharge and discharge and temperature in GDE. This knowledge is needed to protect and manage the various services that groundwater provides to both ecosystems and society.

Currently, most monitoring programs focus on rivers, lakes, and groundwater. GDEs should also be included in national monitoring networks and future monitoring should be carried out at the ecosystem scale. An environmental knowledge of the assessment of GDEs must be complemented with an acquaintance of the commercial and social impacts of groundwater adjustment. This will only be achieved through a multidisciplinary approach and toad’s eye view instead of just looking with eagle’s eye view which links environmental, economic and social assessment and provide local level management techniques.

Community Participation

The involvement of non-state actors and diverse stakeholders such as communities in decision-making is a common component of most successful resource management approaches (Biermann and Pattberg, 2008). Partnerships that create a management network comprised of government authorities, scientists, and water users are catalysts for effective management of resources (Ross and Martínez-Santos, 2010).

Participation has shown to yield a number of benefits ranging from more informed decisions to outcomes that are better complied with, to mobilizing self-regulatory capacity, where appropriate (Hodgson, 2006; Garduño et al, 2010). Hence, all the approaches should consider the active participation of water users and the local people to embrace the overall importance of wetlands and other GDEs.

CONCLUSION

Groundwater and dependent ecosystem have been providing valuable services for humans and ecosystems. However, there has been limited emphasize by governments, nongovernment organizations and academic institutions on the study of impacts on these ecosystems. The changes in climate, particularly variations in temperature and precipitation, have considerable impacts on groundwater resources and GDEs and these impacts vary greatly over time and space. Variations in temperature impact recharge rates and ultimately, quantity and quality of groundwater. Changes in temperature and precipitation impact abundance, diversity, and distributions of biotic components of groundwater dependent ecosystems.

Managing this variability and complexity will require a multidisciplinary approach at all levels of society to develop scale-specific adaptation strategies. Science will need to address the challenge of synthesizing the results of research and employing numerical models to supply managers and policymakers with clear, science-based management scenarios. Another role of science is to support the monitoring of the response of the resource to specific management actions. Finally, it is essential to note that active consideration of non-climatic stressors is vital for future ecosystem resilience.

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