Journal of Hydrology 518 (2014) 250–266

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Climate change impacts on groundwater and dependent ecosystems

Bjørn Kløve [a,d,*], Pertti Ala-Aho [a], Guillaume Bertrand [e], Jason J. Gurdak [f], Hans Kupfersberger [g], Jens Kværner [d], Timo Muotka [b,k], Heikki Mykrä [c], Elena Preda [h], Pekka Rossi [a], Cintia Bertacchi Uvo [i], Elzie Velasco [f], Manuel Pulido-Velazquez [j]

[a] *University of Oulu, Water Resources and Environmental Engineering Laboratory, 90014 University of Oulu, Finland*
[b] *University of Oulu, Department of Biology, 90014 University of Oulu, Finland*
[c] *University of Oulu, Thule Institute, 90014 University of Oulu, Finland*
[d] *Bioforsk – Norwegian Institute for Agricultural and Environmental Research, Frederik A. Dahls vei 20, N-1432 Ås, Norway*
[e] *Centro de Pesquisas de Água Subterrânea, Instituto de Geociências, University of São Paulo, Rua do lago 562, Cidade Universitária, CEP 05508-080, São Paulo, Brazil*
[f] *Department of Geosciences, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132, USA*
[g] *Joanneum Research Forschungsgesellschaft mbH. Elisabethsr. 16/II, A- 8010 Graz, Austria*
[h] *University of Bucharest – Splaiul Independentei 91-95, 050095 Bucharest, Romania*
[i] *Water Resources Engineering, Lund University, Box 118, 221 00 Lund, Sweden*
[j] *Research Institute of Water and Environmental Engineering, Universitat Politècnica de València, Cami de Vera s/n, 46022 Valencia, Spain*
[k] *Finnish Environment Institute, Natural Environment Centre, P.O. Box 413, FI-90014 University of Oulu, Finland*

ARTICLE INFO

Article history:
Available online 27 June 2013

Keywords:
Groundwater
Climate
Ecosystems
Global change
Land use
Management

SUMMARY

Aquifers and groundwater-dependent ecosystems (GDEs) are facing increasing pressure from water consumption, irrigation and climate change. These pressures modify groundwater levels and their temporal patterns and threaten vital ecosystem services such as arable land irrigation and ecosystem water requirements, especially during droughts. This review examines climate change effects on groundwater and dependent ecosystems. The mechanisms affecting natural variability in the global climate and the consequences of climate and land use changes due to anthropogenic influences are summarised based on studies from different hydrogeological strata and climate zones. The impacts on ecosystems are discussed based on current findings on factors influencing the biodiversity and functioning of aquatic and terrestrial ecosystems. The influence of changes to groundwater on GDE biodiversity and future threats posed by climate change is reviewed, using information mainly from surface water studies and knowledge of aquifer and groundwater ecosystems. Several gaps in research are identified. Due to lack of understanding of several key processes, the uncertainty associated with management techniques such as numerical modelling is high. The possibilities and roles of new methodologies such as indicators and modelling methods are discussed in the context of integrated groundwater resources management. Examples are provided of management impacts on groundwater, with recommendations on sustainable management of groundwater.

1. Introduction

Groundwater is the major freshwater store acting in the hydrological cycle. It provides water for human consumption, agriculture, industry and many groundwater-dependent ecosystems, especially during droughts. In recent decades the increasing use of groundwater for human consumption and irrigation has resulted in groundwater lowering in large parts of the world (Wada et al., 2010; Treidel et al., 2012). It is well recognised that regional depletion of groundwater resources is a global-scale problem (Konikow and Kendy, 2005). Many groundwater resources are non-renewable on meaningful time scales for both human society and ecosystems. The predicted climate change will exacerbate these concerns in many parts of the world by reducing precipitation and increasing evapotranspiration, both of which will reduce recharge and possibly increase groundwater withdrawal rates (Treidel et al., 2012). Thus, increasing awareness of the importance of wetlands and other groundwater-dependent ecosystems (GDEs) has led to emphasis being placed on a better understanding of groundwater-ecosystem interactions in a changing climate (Kløve et al., 2011a, 2011b).

* Corresponding author. Address: University of Oulu, 90014 University of Oulu, Finland. Tel.: +358 40 5944514; fax: 358 8 553 4507.

E-mail addresses: bjorn.klove@oulu.fi (B. Kløve), pertti.ala-aho@oulu.fi (P. Ala-Aho), guillaume.bertrand@email.com (G. Bertrand), jgurdak@sfsu.edu (J.J. Gurdak), hans.kupfersberger@joanneum.at (H. Kupfersberger), jens.kvarner@bioforsk.no (J. Kværner), Timo.Muotka@oulu.fi (T. Muotka), Heikki.Mykra@oulu.fi (H. Mykrä), elena.preda@g.unibuc.ro (E. Preda), pekka.rossi@oulu.fi (P. Rossi), cintia.uvo@tvrl.lth.se (C.B. Uvo), evelasco@mail.sfsu.edu (E. Velasco), mapuve@hma.upv.es (M. Pulido-Velazquez).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.06.037

While the impacts of groundwater withdrawal and land use on groundwater have been investigated in numerous studies, climate change impacts on groundwater and dependent ecosystems have received less attention (Taylor et al., 2012). Hydrological studies of climate change often address surface water, but fewer studies focus on groundwater (Kundzewicz and Döll, 2009; Green et al., 2011). The predicted impacts of climate warming on groundwater include changes in the magnitude and timing of recharge (e.g. Hiscock et al., 2012), typically with a shift in seasonal mean and annual groundwater levels depending on changes in the distribution of rainfall (Liu, 2011) and snow melt (Jyrkama and Sykes, 2007; Okkonen and Kløve, 2010). The predicted changes in recharge may be larger than the changes in precipitation (Ng et al., 2010). Land use and urbanisation may suppress or amplify groundwater responses to climate change. For example, afforestation can increase recharge (Chaves et al., 2012) and urbanisation can increase consumption (Taylor and Tindimugaya, 2012). In addition to human impacts, natural long-term fluctuations in groundwater levels caused by climate variability must be considered (Hanson et al., 2004; Gurdak et al., 2007; Anderson and Emanuel, 2008).

Sustainable groundwater management in the future requires groundwater to be used in a manner that can be maintained for an indefinite time without having unacceptable environmental, economic or social consequences (Alley et al., 1999). Groundwater sustainability is a value-driven process of intra- and inter-generational equity that balances the environment, society and the economy (Gleeson et al., 2010, 2012). This requires groundwater management to be approached in a holistic way, where all water uses are seen in the context of socio-economic development and protection of ecosystems and ecosystem services (Constanza et al., 1997). The current lack of knowledge on groundwater-ecosystem interactions can be seen as reflecting a neglect of groundwater in integrated watershed management plans (UNEP/CBD, 2010). The European Commission (EC) Groundwater Directive and Water Framework Directive raise concerns about how groundwater use may affect ecosystems. Re-balancing of water allocation between various human uses, as well as to biodiversity and ecosystem functioning, is clearly needed (Showstack, 2004).

This paper focuses on groundwater and associated dependent aquatic and terrestrial ecosystems; climate change effects on groundwater hydrology and geochemistry; and the processes affecting global climate, which in turn influence hydrology, groundwater ecosystem interactions and adaptation policies for groundwater and GDE management. The objective of the paper was to synthesise current knowledge on the complex interactions between climate, groundwater and ecosystems, and to examine integrated groundwater management strategies that account for human and ecosystems needs. Although there are other recent reviews on climate change and groundwater (Earman and Dettinger, 2011; Green et al., 2011; Treidel et al., 2012; Taylor et al., 2012), this is the first to synthesise the effects of climate change on GDE.

2. Review of climate change impacts on GDE

2.1. Climate change and climate variability

Climate change may be perceived as alterations in the local or global climate on different time scales. Cyclical climate changes in a relative short time perspective are called climate variability. For groundwater, this variability can be illustrated as oscillating changes in recharge (P-ET), where the annual recharge varies in a regular or irregular manner that can resemble oscillations (Fig. 1). Several natural phenomena related to atmospheric and (or) oceanic circulation can affect the climate locally or globally, causing changes and (or) variability. Many of these phenomena are related to the circulation of the oceans and (or) of the atmosphere. The Gulf Stream, the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO) are among the best known ones, but other phenomena such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) have been described more recently (e.g. Huss et al., 2010).

ENSO is the result of an interaction between the Pacific Ocean and the atmosphere whereby anomalies in sea surface temperature (SST) co-vary with the intensity of the Southern Oscillation (Rasmusson and Carpenter, 1982; McPhaden et al., 2006), while NAO is an atmospheric phenomenon centred over the North Atlantic (Hurrell et al., 2003). ENSO has a typical quasi-periodic oscillation of 2–7 years, while NAO displays a yearly variability and a decadal quasi-periodic oscillation. PDO has a 10–25 year quasi-periodic cycle that is associated with decadal variability in atmospheric circulation prominent in the North Pacific, where variations in the strength of the wintertime Aleutian Low pressure system co-vary with SST from 20°N polewards (Mantua et al., 1997). AMO is an oceanic-atmospheric phenomenon with a periodicity of 50–70 years that arises from variations in SST in the Atlantic Ocean (Kerr, 2000; Enfield et al., 2001). All these phenomena change the yearly climate regionally and seasonally, so that some regions of the world become seasonally warmer or colder, or drier or wetter, than normal. Associated with the effects of climate variability, oscillations in river runoff have been extensively described in rivers worldwide (e.g. Cullen et al., 2002; Ionita et al., 2012).

The effects of climate variability on groundwater have been less well explored than those on surface water (Green et al., 2011). However, climate variability on interannual to multidecadal time scales, including ENSO, NAO, PDO, and AMO, has also been shown to affect groundwater levels and recharge (Hanson et al., 2004; Pool, 2005; Fleming and Quilty, 2007; Gurdak et al., 2007, 2009; Anderson and Emanuel, 2008; Holman et al., 2009, 2011; Tremblay et al., 2011; Venencio and Garcia, 2011; Perez-Valdivia et al., 2012). It is likely that the signals seen in recharge are also seen in groundwater levels, but as aquifers differ in size, the response to the input signal variability will be more evident in smaller aquifers (Fig. 1).

The increase in greenhouse gas emissions since the industrial revolution has also affected the climate of the Earth. For example, a small but constant increase in mean atmospheric temperature has been observed since then (IPCC, 2007). Human activities can also cause climate change locally by changing land use, water use and vegetation, with consequent impacts on hydrology (e.g. Collischonn et al., 2001). These causes of climate change and variability are continuously acting and interacting with each other. The result of such a complex system is that in some periods their impacts are additive and enhance each other, while in other periods they counteract each other and their impacts decline regionally (see Fig. 1).

Coupled global climate models (GCMs), which describe the circulation of the atmosphere and the oceans, are frequently used to develop scenarios of future climate (rainfall, temperature, radiation, etc.) taking into consideration different scenarios for increases in greenhouse gases. Such scenarios include a constant increase in greenhouse gases for the next 100 years (scenario A2 of IPCC) or a reduction in emissions (scenario B1 of IPCC), or anything in between. In any case, future climate scenarios projected by GCMs in terms of precipitation and temperature may be used to force hydrological models and numerical groundwater flow models in a sequential (e.g. Okkonen and Kløve, 2011) or fully coupled manner (Therrien et al., 2007), in order to predict the impacts of future climate on recharge, groundwater flow and interactions with associated ecosystems.