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≪ **Review Paper** ≫

Challenges of Groundwater as Resources in the Near Future

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ABSTRACT

Groundwater has been a very precious resource for human life and economic development in the world. With increasing population and food demand, the groundwater use especially for agriculture is largely elevated worldwide. The very much large groundwater use results in depletion of major aquifers, land subsidences in many large cities, anthropogenic groundwater contamination, seawater intrusion in coastal areas and accompanying severe conflicts for water security. Furthermore, with the advent of changing climate, securing freshwater supply including groundwater becomes a pressing and critical issue for sustainable societal development in every country because prediction of precipitation is more difficult, its uneven distribution is aggravating, weather extremes are more frequent, and rising sea level is also threatening the freshwater resource. Under these difficulties, can groundwater be sustaining its role as essential element for human and society in the near future? We have to focus our efforts and wisdom on answering the question. Korean government should increase its investment in securing groundwater resources for changing climate.

Key words : Climate change, Extreme drought, Sea level rise, Seawater intrusion, Groundwater depletion

1. Groundwater Use in the World

Groundwater has long served human and society with a variety of ways including drinking, domestic use, irrigating crops (agriculture), business and industries and it is the natural material that the annual production is the largest (Struckmeier et al., 2005). Worldwide annual groundwater abstraction is in the range of 600-1,100 km^3 per year, being 20-33% of total global freshwater abstraction for the various uses (Zektser and Everett, 2004; Shah et al., 2007; Döll, 2009; Siebert et al., 2010). Among them, the irrigation is the dominant use (Siebert et al., 2010), accounting for about 60% of groundwater abstraction and groundwater is supplying 25-40% of drinking water (but 80% in Europe and Russia) in the world (Vrba and van der Gun, 2004; Struckmeier et al., 2005; NGWA, 2013).

According to Wada et al. (2010), the global groundwater abstraction was 312 km^3/year in 1960 (this figure is not that much reliable because the global groundwater use data were not existing then and also now), but it steadily increased to 734 km^3/year in 2000 (Fig. 1(a)), which is 135% increase for the period. Now in 2013, the groundwater abstraction is estimated to be about 982 km^3/year (Margat and van der Gun, 2013). The large groundwater abstractions are led by 15 countries including India, China, United States (US) and Bangladesh (NGWA, 2013; Table 1). Except only some nations like Indonesia, Russia, Japan, and Thailand, most countries consume groundwater dominantly for agricultural irrigation (Shah, 2009; Margat and van der Gun, 2013).

India's groundwater use has been exploding since 1960 (Fig. 1(b)) and thus there is a growing concern regarding this kind of water scavenging economy (Shah, 2009). Even though India receives a large amount of annual rainfall (averagely 2,000 mm/year but it is not equally distributed, 200-4,000 mm/year over the country), the irrigation area is also greatly increasing (e.g., tripled to 33.1 Mha for 1970-1999; Rodell et al., 2009) and thus meeting this irrigation water demand is causing a severe groundwater depletion and water crisis (Rodell et al., 2009). The intensively irrigation dependent country is on the brink of economic collapse without essential mitigation measures, especially in this era of climate change.

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Table 1. Top 15 nations with the largest estimated annual groundwater abstraction as of 2010 (Margat and van der Gun, 2013; NGWA, 2013) and groundwater use in Korea (as of 2011; NGIC, 2015)

Country	Population (×1000)	Area (km^2)	Groundwater use (km^3/yr)	Groundwater use per person (m^3/yr)	Groundwater use per area (m^3/km^2/yr)	Usage		
						Irrigation	Domestic	Industry
India	1,224,614	3,287,260	251.00	205	76,355	89%	9%	2%
China	1,341,335	9,596,960	111.95	83	11,665	54%	20%	26%
USA	310,384	9,826,680	111.70	360	11,367	71%	23%	6%
Pakistan	173,593	796,095	64.82	373	81,422	94%	6%	0%
Iran	73,974	1,648,200	63.40	857	38,466	87%	11%	2%
Bangladesh	148,692	143,998	30.21	203	209,795	86%	13%	1%
Mexico	113,423	1,964,380	29.45	260	14,992	72%	22%	6%
Saudi Arabia	27,448	2,149,690	24.24	883	11,276	92%	5%	3%
Indonesia	239,871	1,904,570	14.93	62	7,839	2%	93%	5%
Turkey	72,752	783,562	13.22	182	16,872	60%	32%	8%
Russia	142,985	17,098,200	11.62	81	680	3%	79%	18%
Syria	20,411	185,180	11.29	553	60,968	90%	5%	5%
Japan	126,536	377,915	10.94	86	28,948	23%	29%	48%
Thailand	69,122	513,120	10.74	155	20,931	14%	60%	26%
Italy	60,551	301,340	10.40	172	34,513	67%	23%	10%
Korea (south)	51,360	99,720	3.91	76	39,210	49%	46%	5%

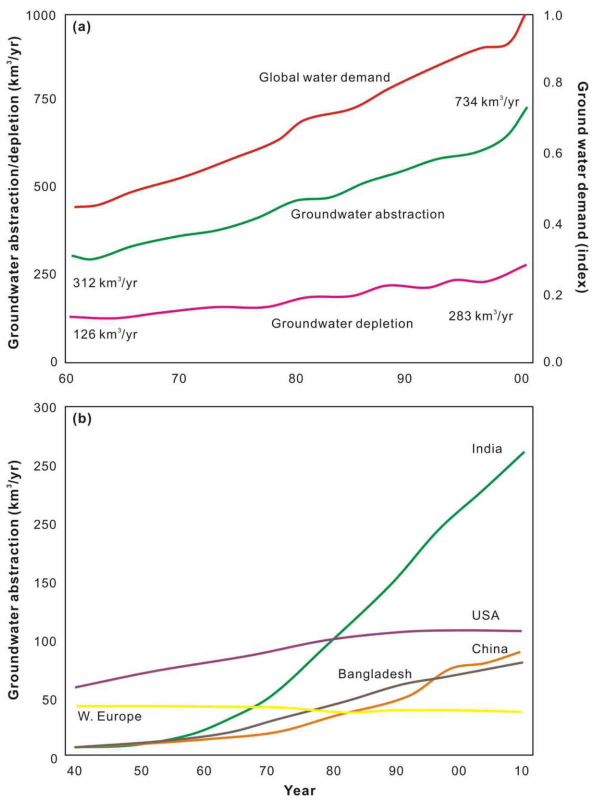

Fig. 1. (a) Global groundwater abstraction and depletion and (b) groundwater abstraction for some selected countries. The figures are from Wada et al. (2010) and Shah et al. (2007), respectively, but they are modified for this paper.

Viewing the increasing patterns of groundwater use (see Fig. 1(b)), future of China is not that much optimistic. Compared with India (89%), its groundwater abstraction for irrigation purpose is very low (54%) but total groundwater pumping is steadily increasing through 1960-2000. In the meanwhile, the groundwater use in the sector of industry is very notable (26%). The China's economy is rapidly developing and expanding cultivated irrigation and water supply for urban and industrial development, resulting in overdraft of groundwater (Changming et al., 2001). Recently, shale gas development aggravates this water situation because the new technology, called fracking, applied for the gas development requires a large quantity of freshwater injection (20 million liters of water into each gas well; Howarth et al., 2011). China is the top country having technically recoverable shale gas resource and thus the energy source never be given up (Lee et al., 2015).

Even though the groundwater use in the US is also large, its trend is much different from the countries above. The groundwater abstraction was steadily increasing until 1990 but after then it was not elevated until 2010 (see Fig. 1(b)). But the US is one of the largest agricultural production countries including China, Brazil, India, and Argentina (USDA, 2015) and thus irrigation purpose is predominant

Table 2. Estimates of global scale and continental scale groundwater depletion (GD) and equivalent sea level rise (SLR) (Taylor et al., 2013)

Region	Flux based method		Volume based method	
	GD (km^3/yr)	SLR (mm/yr)	GD (km^3/yr)	SLR (mm/yr)
World	204 ± 30	0.57 ± 0.09	145 ± 39	0.40 ± 0.11
Asia	150 ± 25	0.42 ± 0.07	111 ± 30	0.31 ± 0.08
Africa	5.0 ± 1.5	0.014 ± 0.004	5.5 ± 1.5	0.015 ± 0.004
N. America	40 ± 10	0.11 ± 0.03	26 ± 7	0.07 ± 0.02
S. America	1.5 ± 0.5	0.0042 ± 0.0014	0.9 ± 0.5	0.002 ± 0.001
Australia	0.5 ± 0.2	0.0014 ± 0.0006	0.4 ± 0.2	0.001 ± 0.0005
Europe	7 ± 2	0.02 ± 0.006	1.3 ± 0.7	0.004 ± 0.002

(71%; see Table 1). Especially, the total water withdrawals in California and Texas are over 20,000 million gallons per day (USGS, 2014). So for the agricultural sector, securing freshwater for irrigation is very critical for their business. Recent (2013-2014) severe drought in California (Aghakouchak et al., 2014) resulted in devastating groundwater pumping increase (5 million acre-feet), and in damaging the state agriculture, total economic loss of 2.2 billion dollars and 1,7100 job losses (Howitt et al., 2014).

Groundwater depletion occurs when the abstraction exceeds its recharge, resulting in insustainability of water supplies, land subsidence and seawater intrusion (Wada et al., 2010). So the long-term groundwater over-exploitation indicated above has caused groundwater depletion in the world (Konikow and Kendy, 2005; Rodell et al., 2009; Famiglietti, 2014). And many of depleted aquifers are not renewable. According to Taylor et al. (2013), the worldwide total groundwater depletion is 145 to 204 km^3 per year (Table 2). Among many continents, Asia has led this large depletion (73.5-76.5%) because it is mainly related with the great groundwater abstraction in India, China, Pakistan, and Bangladesh for agriculture. It is very disappointing that this depletion rate is steadily increasing (see Fig. 1(a) ; Wada et al., 2010). Even the groundwater depletion affects substantially the sea level rise (Konikow, 2011).

The widely known Ogallala aquifer in High Plains of US has been intensively pumped for crop irrigation and this caused a drastic water level decline up to 50 m (Gleeson et al., 2010). The lowered water levels have not been recovered, causing increase of crop production cost and reducing agricultural revenue. The residence times of groundwater in aquifers like Ogallala are commonly over 11,000 years and thus once the aquifers are depleted, their renewals are practically not possible within a reasonable time frame (Gleeson et al., 2010). All these groundwater abstraction and its depletion problem give us a question, how long does this use can be possible without our discretion on this problem?

2. Climate Change and Groundwater

Even though there are still disputes on causes of the global warming by either natural or anthropogenic, we generally reach a consensus that the climate is changing both globally and locally. So the climate extremes (droughts and floods) are common (Easterling et al., 2000; Lee et al., 2015). With context of water resources management, the most important thing we must consider in this stage is to predict precipitation over time and space with enough spatial resolution and reliability. Our efforts for this seem a little bit successful under low and high CO_2 emission scenarios using various climate models even though the spatial resolution is not that much good (USGCRP, 2009; USEPA, 2015).

For example, for the end of this century (~2100) under high emission scenario, in the winter, the precipitation will increase by 5-40% in the middle and north US, and Canada while the south US will get a less precipitation by 5-40%, than the recent precipitation (USGCRP, 2009). But in summer, the precipitation will decrease in the south US and even in middle US while the increase by 5-30% will be shown only in north Canada (USGCRP, 2009). It is summarized that the upper US and Canada will have more precipitation and the lower US will have less precipitation in the end of this century. Viewing the Korean Peninsula for RCPs

Table 3. Summary of some selected studies for impacts of climate change on groundwater

Region	Scenario/recharge model	Period	Predicted results	Reference
High Plains, USA	Five GCMs/SWAP	~2075	Rainfall:-25% ~ +20%; recharge: -75% ~ +35%	Vaccaro (1992)
Ogallala, USA	Three GCMs/HUMUS	–	Precipitation: -28% ~ +16%; recharge: +8 ~ -77%	Rosenberg et al. (1999)
Geer basin, Belgium	Seven GCMs /MOHISE	2010~2099	Decrease in GWL and recharge	Brouyère et al. (2004)
Grote-Nete, Belgium	NATCC/WetSpass, MODFLOW	2050~2100	Precipitation: -10% ~ +14%; recharge: -40% ~ +14%; GWL: -52 ~ +16 cm	Woldeamlak et al. (2007)
Alicante, SE Spain	-/ERAS	1900~2100	Recharge: -2% ~ -30%	Aguilera and Murillo (2009)
East Anglia, England, Scotland	GCMs/SMBM	2011~2100	Precipitation:+16% ~ +65%; recharge: -20%, -40%, -7% for three regions	Herrera-Pantoja and Hiscock (2008)
River Mitano, Uganda	RCMs/SMBM	2070~2100	Precipitation: +14%; recharge: +53%; runoff: +137%	Mileham et al. (2009)
Dill, Germany	GCMs/SWAT	2070-2099	Precipitation: -23% ~ +13%; recharge: -3.0% ~ -7.5%; streamflow: -4.1% ~ -6.9%	Eckhardt and Ulbrich (2003)
British Columbia, Canada	CGCM1/HELP, MODFLOW	2010~2099	Recharge: +2% ~ +25% GWL: -0.025 m ~ +0.05 m	Scibek and Allen (2006)
Ontario, Canada	GCM/HELP3	40 years	Precipitation: +5% ~ +20%; recharge: +100 mm/yr	Jyrkama and Sykes (2007)
Bievre-Valloire, France	Two GCMs/ANSWERS	27 years (~2023)	Decrease in recharge and GWL	Bouraoui et al. (1999)
Namoi, Howard, Scottsdale, Australia	GCMs/WAVES	112 years	Rainfall:-10% ~ +10%; recharge: -40% ~ +120%	McCallum et al. (2010)
Murray-Darling, Australia	15 GCMs/WAVES	1990~2030	Recharge: -12% ~ +32%	Crosbie et al. (2010)
Korea (south)	RCMs/recharge equation	2000-2100	Rainfall: +32 ~ +33%: GWL: -2.3 m ~ -3 m	Jang et al. (2015)

GCM (General Circulation Model), SWAP (Soil-Water-Atmosphere-Plant), HUMUS (Hydrologic Unit Model for U.S.), MOHISE (integrated hydrological model) GWL (groundwater level), NATCC (North Atlantic Thermohaline Circulation Change), ERAS (Estimation of Recharge in Over-exploited Aquifers), SMBM (soil moisture balance method), RCM (Regional Climate Model), SWAT (Soil and Water Assessment Tool), CGCM (Canadian Global Coupled Model), HELP (Hydrologic Evaluation of Landfill Performance), WAVES (Soil-Vegetation-Atmosphere-Transfer Model)

4.5 and 8.5, the precipitation in winter will be 3.0-7.2% increase while that in summer will be 2.8-5.6% increase for the period of 2006-2049, but a wide spatial variation is noted (KMA, 2014). However, nevertheless of the above predictions for US and Korea, the reliability of the results cannot be guaranteed because the prediction uncertainties were not quantified (Taylor et al., 2013). But that is the best at this time.

Then, how about the groundwater? If climate, especially precipitation, changes, what will happen with groundwater? Can we go further about the groundwater with the so called plausible precipitation projections? Taylor et al. (2013) indicated that climate change influences the groundwater both in direct (recharge) and indirect (change in groundwater use) ways. Here, I want to introduce some direct effects because they determine the latter (Table 3). Eckhardt and Ulbrich (2003) projected groundwater recharge for 2070-2099 using greenhouse gas emission scenarios and SWAT model in the Dill catchment in Germany. The study said that groundwater recharge and streamflow will be reduced by up to 50%, which can be a threat to water availability, water quality, and hydropower generation.

The Ogallala aquifer is one of the most productive water resources in the U.S. and about 30% of irrigation groundwater is from this aquifer (Rosenberg et al., 1999). Rosenberg et al. (1999) predicted reduction of groundwater recharge up to 77% for three climate models, which will greatly aggravate the water situation in this depleting aquifer

(Jyrkama and Sykes, 2007). Woldeamlak et al. (2007) conducted a meaningful study on effect of climate change on groundwater system in the Grote-Nete catchment of Belgium. They used wet, cold, and dry climate scenarios and WetSpass model for groundwater recharge projection. The study indicated that groundwater level will decrease by 0.5 m on average (up to 3.1 m). And it stressed that the maximum water level drop will threaten shrubs and crop production in this area.

Jang et al. (2015) conducted a notable study on impact of climate change on groundwater resource in Korea (south). Using regional climate models (with RCPs 4.5 and 8.5) and a simple precipitation-recharge-groundwater level equation, they predicted the groundwater level changes in four river basins for 2000-2100. They concluded that the groundwater levels will be decreasing at all the basins with the two climate scenarios even though rainfall is projected to increase. This result gives us some implications for water resources management strategy. In that case, we have to seriously consider less water consuming agricultural practices, especially in high land cool vegetable fields and intensive agricultural areas (Lee et al., 2012).

All the above studies indicate that groundwater recharge and groundwater level are largely varying (decreasing or increasing) responding to climate change and their variations will be much different with locations. But the prediction reliability largely depends on the climate models and thus they should be refined. Based on the improved climate models, the projections on the groundwater must be downscaled to practical application.

3. Threats in Coastal Areas

Recent global warming and climate change result in a worldwide sea level rise (Fig. 2; Parris et al., 2012) due to thermal expansion of seawater, water addition into oceans from melt glaciers and ice sheets, water input from groundwater depletion, etc. (Rahmstorf, 2007; Lee and Song, 2009; Konikow, 2011). This kind of sea level rise is accelerated in the 20th century, which gives us a confirmation that a large portion of the rise is anthropogenic (Church and White, 2006; Nicholls and Cazenave, 2010). According to USEPA (2014), the global average sea level rise for 1880-2013 is about 9 inches (22.86 cm). Korea is not that much different from this trend but it is confronting rather worse situation. The sea level rise rate around Korean peninsula for 1968-2007 is averagely 2.16 mm/year, which is much greater than a global average of 1.8 mm/year for a similar period (1961-2003) (Kim et al., 2009).

And then, what are the effects of the rising sea level on people and the environment? It will cause a devastating damage to coastal areas. Historically and now, many large cities with big population have been developed in the coastal areas in the world because water is relatively easily available there and the near sea provides a cheap and facilitated transportation route. So residents in the coastal areas will experience frequent land subsidence, flood due to groundwater inundation (Rotzoll and Fletcher, 2012), and

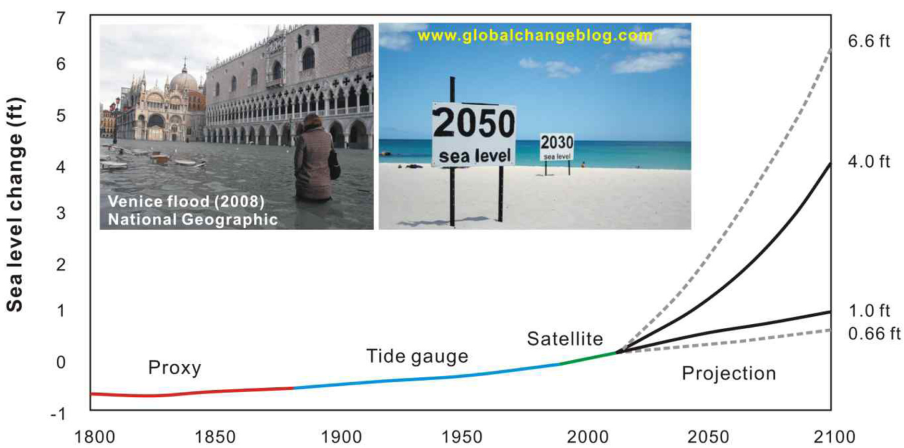

Fig. 2. Global sea level changes (past and projection). This figure is from Parris et al. (2012) and it is modified for this paper. The two inset photos are from National Geographic and globalchangeblog.com, respectively, which are open to the public.

eventually lose their lands, homes and jobs (businesses) due to the rising sea level (Nicholls et al., 1999; USEPA, 2014). The lessened beach will not provide a space for a variety of beach recreational activities and the rising sea level will expel coastal plants and animals, and destroy the coastal ecosystems. We cannot be provided further valuable eco-services by this spoiled coastal nature.

What will happen with coastal groundwater? In coastal area, seawater is intruding the lands due to density difference. The interface between freshwater and saltwater is given by the Ghyben-Herzberg relation (Verrjuit, 1968), assuming sharp interface, as follows:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h$$

where z and h are the thicknesses of the freshwater zones below and above the sea level, respectively, and ρ_f and ρ_s are the densities of freshwater and saltwater, respectively. If the sea level rises (the saline water heads are increasing), h becomes smaller at a fixed surface point and thus z is also becoming smaller, which means that the interface is much retreating landward. If the sea level rise becomes larger, the retreat is much greater. This kind of the saltwater encroachment poses a substantial threat to coastal crop production due to increased salinity of irrigation water, especially in western agricultural areas of Korea (Lee and Song, 2007).

So the sea level rise causes a big loss in groundwater resources. According to Nicholls and Cazenave (2010), the coastal areas of Africa and most southern Asia at low elevations are the most vulnerable to this sea level rise. Because the southern part of Asian continent including India, Vietnam and China is heavy cropping area where irrigation is largely depending on groundwater, they may not meet a large proportion of worldwide food supply. Ranjan et al. (2005) said that the sea level rise at a 2.0 mm/year will cause 5% loss of fresh groundwater in western US and that of 0.9 mm/year in Bengal Bay will cause 3% freshwater loss in Bangladesh. Masterson and Garabedian (2007) provided an interesting study result on effects of the sea-level rise on groundwater flow in coastal aquifers of eastern US Simulations of sea-level rise of 2.65 mm/year for 1929-2050 predicted decrease in 2% of thickness of fresh water lens away from streams while its decrease of 22-31% near streams, which means a great groundwater loss in coastal cities of US.

It can be summarized that the sea level rise derived from global warming and climate change is a big threat to groundwater resources in coastal areas in the world. Thus, without appropriate mitigation measures, we will face devastating consequences including loss of water supply, groundwater inundation, and land subsidence.

4. Discussion

It is fairly certain that there are some pressing groundwater issues that we have to pay attention to, including changing climate, groundwater depletion, and sea level rise (Gorelick and Zheng, 2015). Korea is also facing most of these problems such as changing precipitation (Jang et al., 2015), sea level rise (Kim et al., 2009), and seawater intrusion especially in western coastal areas (Lee and Song, 2007; Song et al., 2007). Surface water is the most vulnerable to climate change, unlike groundwater. Nevertheless of this, Korean government has insisted so called surface water oriented water policy for a long time. It is known that this country is depending on groundwater at 11.5% (3.91 billion m^3 per year) among total water use (NGIC, 2015). But the Korean government has only invested its budget (on water) in groundwater below 0.5%, the left is all allocated to surface water management. Korean people do not have any belief in quality of surface water or piped water (Lee et al., 2013), so they usually boil the piped water for drinking or they buy bottled waters made of groundwater. But it is much disappointing that government officials and people do not recognize the values of the precious groundwater as resources.

In the era of climate change, the groundwater is the last resort to water resources. But it must overcome many challenges like climate extremes, over-exploitation, and sea level rise, for sustainable use. Most importantly, it is pressing to teach people and government officials to know the groundwater's value. As seen above, the overdraft is surely a big problem but the underutilization of groundwater is also causing many problems like uneconomic abandonment of the precious water resource, urban inundation, etc. (Lee and Koo, 2007; Giordano, 2009). Will the groundwater be still promising in the future? It depends on efforts of relevant communities including university professors, researchers in institutions, and groundwater professionals in many companies. Without due attention, they will lose groundwater and also their job and business.

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References

Aghakouchak, A., Feldman, D., Stewardson, M.J., Saphores, J.D., Grant, S., and Sanders, B., 2014, Australia's drought: lessons for California, *Science*, **343**, 1430-1431.

Aguilera, H. and Murillo, J.M., 2009, The effect of possible climate change on natural groundwater recharge based on a simple model: a study of four karstic aquifers in SE Spain, *Environ. Geol.*, **57**, 963-974.

Bouraoui, F., Vachaud, G., Li, L.Z.X., Le Treut, H., and Chen, T., 1999, Evaluation of the impact of climate changes on water storage and groundwater recharge at the watershed scale, *Clim. Dyn.*, **15**, 153-161.

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

Changming, L., Jingjie, Y., and Kendy, E., 2001, Groundwater exploitation and its impact on the environment in the North China Plain, *Water Int.*, **26**(2), 265-272.

Church, J.A. and White, N.J., 2006, A 20th century acceleration in global sea-level rise, *Geophy. Res. Lett.*, **33**(1), L01602.

Crosbie, R.S., McCallum, J.L., Walker, G.R., and Chiew, F.H.S., 2010, Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia, *Hydrogeol. J.*, **18**, 1639-1656.

Döll, P., 2009, Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment, *Environ. Res. Lett.*, **4**, 035006.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., and Mearns, L.O., 2000, Climate extremes: observations, modeling, and impacts, *Science*, **289**, 2068-2074.

Eckhardt, K. and Ulbrich, U., 2003, Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range, *J. Hydrol.*, **284**, 244-252.

Famiglietti, J.S., 2014, The global groundwater crisis, *Nat. Clim. Change*, **4**, 945-948.

Giordano, M., 2009, Global groundwater? Issues and solutions, *Annu. Rev. Environ. Resour.*, **34**, 7.1-7.26.

Gleeson, T., VanderSteen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen, D.M., and Zhou, Y., 2010, Groundwater sustainability strategies, *Nat. Geosci.*, **3**, 378-379.

Gorelick, S.M. and Zheng, C., 2015, Global change and the groundwater management challenge, *Water Resour. Res.*, doi: 10.1002/2014WR016825.

Herrera-Pantoja, M. and Hiscock, K.M., 2008, The effects of climate change on potential groundwater recharge in Great Britain, *Hydrol. Process.*, **22**, 73-86.

Howarth, R.W., Ingraffea, A., and Engelder, T., 2011, Natural gas: Should fracking stop?, *Nature*, **477**, 271-275.

Howitt, R., Medellin-Azuara, J., MacEwan, D., Lund, J., and Sumner, D., 2014, Economic Analysis of the 2014 Drought for California Agriculture, Center for Watershed Sciences, University of California, Davis, California, 20 p.

Jang, S., Hamm, S.Y., Yoon, H., Kim, G.B., Park, J.H., and Kim, M.S., 2015, Predicting long-term change of groundwater level with regional climate model in South Korea, *Geosci. J.* , DOI 10.1007/s12303-015-0002-9.

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

Kim, K.H., Shin, J., Koh, E.H., Koh, G.W., and Lee, K.K., 2009, Sea level rise around Jeju Island due to global warming and movement of groundwater/seawater interface in the eastern part of Jeju Island, *J. Soil. Groundw. Environ.*, **14**(3), 68-79 (in Korean with English abstract).

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

Konikow, L.F. and Kendy, E., 2005, Groundwater depletion: A global problem, *Hydrogeol. J.*, **13**, 317-320.

Korea Meteorological Administration (KMA), 2014, Korea Climate Change Assessment Report 2014: Summary for Policymakers, KMA, Seoul, 52 p.

Lee, J.Y., Jeon, W.H., Park, Y., and Lim, H.G., 2012, Status and prospect of groundwater resources in Pyeongchang, Gangwon-do, *J. Geol. Soc. Korea*, **48**(5), 435-444 (in Korean with English abstract).

Lee, J.Y. and Koo, M.H., 2007, A review of effects of land development and urbanization on groundwater environment, *J. Geol. Soc. Korea*, **43**(4), 517-528 (in Korean with English abstract).

Lee, J.Y., Park, Y., Kim, N.J., and Jeon, W.H., 2013, Status of community drinking water in Korea: implications for appropriate management. *J. Soil Groundw. Environ.*, **18**(6), 56-68.

Lee, J.Y. and Song, S.H., 2007, Evaluation of groundwater quality in coastal areas: implications for sustainable agriculture, *Environ. Geol.*, **52**(7), 1231-1242.

Lee, J.Y. and Song, S.H., 2009, Discussion on "Sea Level Rise Around Jeju Island due to Global Warming and Movement of Groundwater/seawater Interface in the Eastern Part of Jeju Island", *J. Soil Groundw. Environ.*, **14**(5), 1-4 (in Korean).

Lee, J.Y., Weingarten, M., and Ge, S., 2015, Induced seismicity: The potential hazard from shale gas development and CO_2 geologic storage, *Geosci. J.* (in press).

Margat, J. and van der Gun, 2013, Groundwater Around the World, CRC Press, Balkema.

Masterson, J.P. and Garabedian, S.P., 2007, Effects of sea-level rise on ground water flow in a coastal aquifer system, *Ground Water*, **45**(2), 209-217.

McCallum, J.L., Crosbie, R.S., Walker, G.R., and Dawes, W.R., 2010, Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge, *Hydrogeol. J.*, **18**, 1625-1638.

Mileham, L., Taylor, R.G., Todd, M., Tindimugaya, C., and 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.

National Ground Water Association (NGWA), 2013, Facts About Global Groundwater Usage, www/ngwa.org, 2 p.

National Groundwater Information Center (NGIC), 2015, Groundwater use in Korea, www.gims.go.kr.

Nicholls, R.J. and Cazenave, A., 2010, Sea-level rise and its impact on coastal zones, Sciences, **328**, 1517-1520.

Nicholls, R.J., Hoozemans, F.M.J., and Marchand, M., 1999, Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses, *Global Environ. Change*, **9**(S1), S69-S87.

Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., Horton, R., Knuuti, K., Moss, R., Obeysekera, J., Sallenger, A., and Weiss, J., 2012, Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Tech Memo OAR CPO-1, National Oceanic and Atmospheric Administration, Silver Spring, MD, 37 p.

Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise, *Science*, **315**, 368-370.

Ranjan, P., Kazama, S., and Sawamoto, M., 2005, Effect of sea level rise on the loss of fresh groundwater resources: case studies of western American coast and bay of Bengal, *Annual J. Hyd. Eng.*, **49**, 97-102.

Rodell, M., Velicogna, I., and Famiglietti, J.S., 2009, Satellite-based estimates of groundwater depletion in India, *Nature*, **460**, doi:10.1038/nature08238.

Rosenberg, N.J., Epstein, D.J., Wang, D., Vail, L., Srinivasan, R., and Arnold, J.G., 1999, Possible impacts of global warming on the hydrology on the Ogallala aquifer region, *Clim. Change*, **42**, 677-692.

Rotzoll, K. and Fletcher, C.H., 2012, Assessment of groundwater inundation as a consequence of sea-level rise, *Nat. Clim. Change*, **3**, 477-481.

Scibek, J. and Allen, D.M., 2006, Modeled impacts of predicted climate change on recharge and groundwater levels, *Water Resour. Res.*, **42**, W11405.

Shah, T., 2009, Climate change and groundwater: India's opportunities for mitigation and adaptation, *Environ. Res. Lett.*, **4**, 035005.

Shah, T., Burke, J., and Villholth, K., 2007, Groundwater: a global assessment of scale and significance, *Water For Food, Water for Life*, Colombo, Sri Lanka, pp. 395-423.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Doll, P., and Portmann, F.T., 2010, Groundwater use for irrigation-a global inventory, *Hydrol. Earth Syst. Sci.*, **14**, 1863-1880.

Song, S.H., Lee, J.Y., and Park, N., 2007, Use of vertical electrical soundings to delineate seawater intrusion in a coastal area of Byunsan, Korea, *Environ. Geol.*, **52**, 1207-1219.

Struckmeier, W., Rubin, Y., and Jones, J.A.A., 2005, Groundwater-Reservoir for a Thirty Planet? IUGS, Norway, 16 p.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblance, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I., and Treidel, H., 2013, Ground water and climate change, *Nat. Clim. Change*, **3**, 322-329.

United States Department of Agriculture (USDA), 2015, World Agricultural Production, Circular Series WAP 2-15, 26 p.

United States Environmental Protection Agency (USEPA), 2014, Climate Change Indicators in the United States, Third Edition, EPA 430-R-14-004, http://www.epa.gov/climatechange/indicators.

United States Environmental Protection Agency (USEPA), 2015, Future Climate Change, USEPA, http://www.epa.gov/climatechange/science/future.html.

United States Geological Survey (USGS), 2014, Estimated Use of Water in the United States in 2010, Circular 1405, USGS, Reston, Virginia, 64 p.

United States Global Change Research Program (USGCRP), 2009, Global Climate Change Impacts in the United States, Cambridge University Press, New York.

Vaccaro, J.J., 1992, Sensitivity of groundwater recharge estimates to climate variability and change, *J. Geophy. Res*., **97**, 2821-2833.

Verrjuit, A., 1968, A note on the Ghyben-Herzberg formula, *Bull. Int. Assoc. Sci. Hydrol.*, **13** (4), 43-46.

Vrba, J. and van der Gun, J., 2004, The World's Groundwater Resources, International Groundwater Resources Assessment Centre, 10 p.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., and Bierkens, M.F.P., 2010, Global depletion of groundwater resources, *Geophy. Res. Lett.*, **37**, L20402, doi: 10.1029/2010GL044571.

Woldeamlak, S.T., Batelaan, O., and De Smedt, F., 2007, Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium, *Hydrogeol. J.*, **15**, 891-901.

Zektser, I.S. and Everett, L.G., 2004, Groundwater Resources of the World and Their Use, UNESCO IHP-VI Series, UNESCO, Paris.