Changes in Water Resources Systems: Methodologies to Maintain Water Security and Ensure Integrated Management (Proceedings of Symposium HS3006 at IUGG2007, Perugia, July 2007). IAHS Publ. 315, 2007.

Effects of climate change and population growth on water resources in Korea

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Abstract We assessed the effects of climate change and population growth on freshwater resources in Korea river basins around 2025 using numerical experiments combining regional climate change scenarios, hydrological models, and population and industrial growth scenarios. Our study suggests increasing regional variations of water stress, imposing significant stress in river basins where increasing temperatures and population and industrial growth are likely to occur concurrently. Both the Han River and Nakdong River basins are projected to be more vulnerable than other basins. Climate change alone could decrease mean annual runoff by 2–12% in four major river basins, while climate change could lead to more runoff in the Han River basin. Uncertainty still remains when runoff scenarios are used to assess socioeconomic impacts for each sub-basin that has diverse topographic and economic characteristics. As the first national assessment of climate change, this study will provide a cornerstone for developing sustainable water resource management strategies in Korea.

Key words climate change; growth; vulnerability; water resources

INTRODUCTION

Freshwater resources in Korea have become scarce as the country's population and industry have substantially increased through the last four decades. During the last 35 years (1970–2004), the country's population has grown by more than 15 million and its GDP has increased from \$96 million to \$6 billion (Korea National Statistical Office, 2006). The Korean population is expected to grow to approximately 50 million by 2020, creating a 38 billion ton water demand. Accordingly, the current water resources are projected to fall short by 2.6 billion tons. In addition to population and industrial growth, climate change is posing another stress on freshwater resources in the region, enhancing discrepancies between water supply and demand. Most climate change models suggest that rising temperatures and increases in rainfall variability are likely to increase runoff variability for river basins in Korea (Min *et al.*, 2006). Floods and droughts would become more frequent than in the past under changing climate conditions. Here we assess the combined effects of climate change and population growth on Korean water resources. Our efforts will provide a guideline for sustainable water resources planning and management practices in Korea.

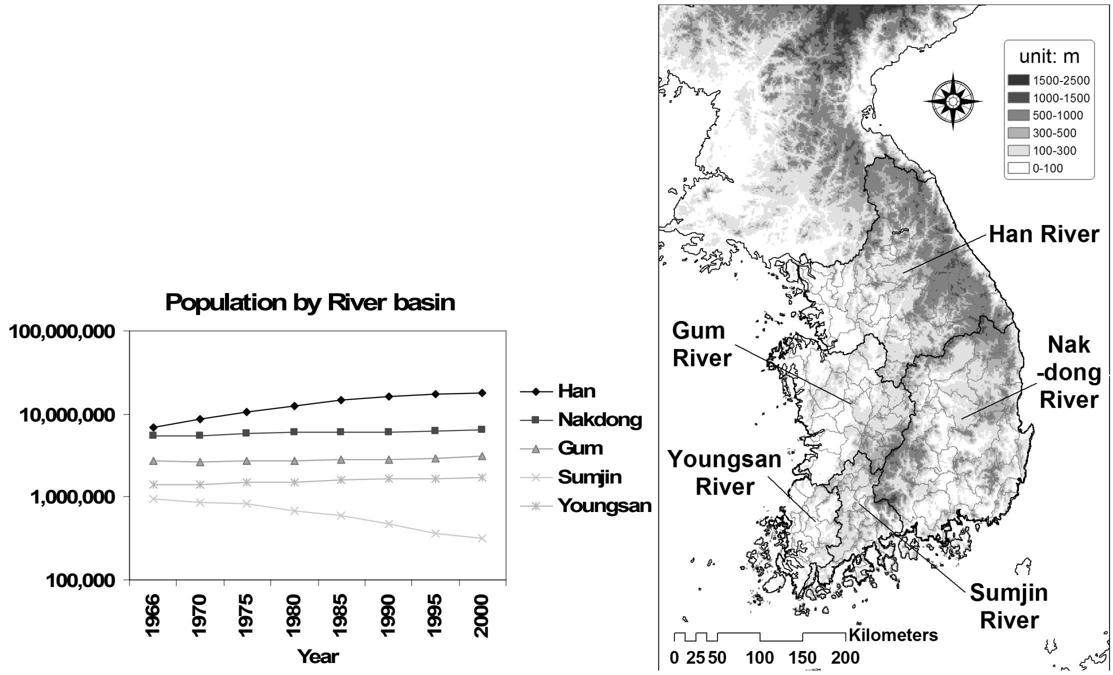

Fig. 1 Population change in major river basins of Korea between 1966 and 2000.

DATA AND METHODS

We compiled historical water use by sector between 1966 and 2001 and regional gross domestic product data from the Korea Water Management Information System (KWMIS) for five major river basins (see Fig. 1). Historical and projected future population data and other socioeconomic data were obtained from the National Statistics Office.

We used a nonparametric Kendall's tau statistic to determine any statistical significance in monotonic changes in trend analysis. Trend analysis was used for extrapolating future water use subsequently. Pearson's correlation coefficient and forward multiple regressions were used to sort out significant explanatory variables for water use by each sector and region. Future water use by each sector is projected based on regional-specific historical patterns and population and industrial growth scenarios.

We produced fine scale regional climate change scenarios based on the IPCC SRES A2 and B2 emission scenarios. For simulating climate information over the Korean peninsula, regional climate models, MM5 (Oh *et al.*, 2004) and RegCM3 (Im *et al.*, 2006) have been applied to ECHO-G A2 and B2 global fields, respectively. The climate data sets used in this study are temperature and precipitation simulated by MM5 and RegCM3 at 27 km and 20 km grid spacing (mother domain = 60 km), respectively. Further details of the high resolution climate change scenarios are described in Oh *et al.* (2004) and Im *et al.* (2006). Figure 2 illustrate the baseline (1971–2000) mean annual precipitation and temperature from RegCM3 b2 simulation.

For hydrological impact assessment, we divided the five major basins into 139 sub-basins and generated monthly runoff scenarios. We used USGS's PRMS model to estimate long-term runoff between 1971 and 2040. The PRMS model parameters were derived from GIS layers (e.g. DEM, land cover data) and published literature. The hydrological model was calibrated for gauged basins with the Nash-Sutcliff efficiency

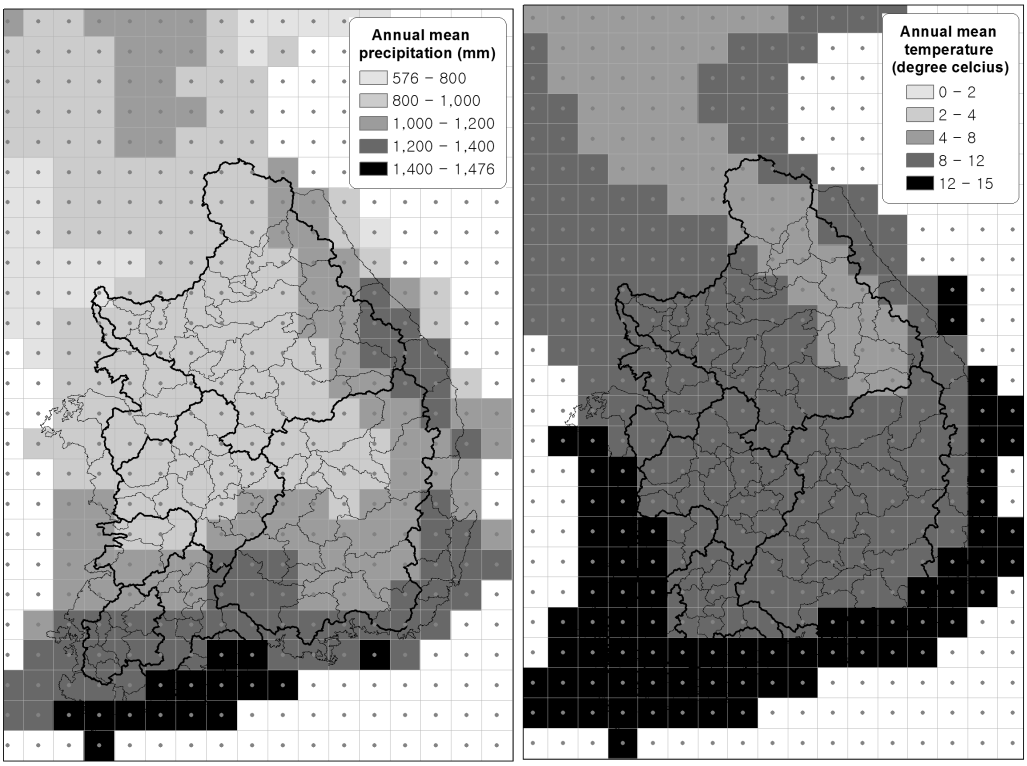

Fig. 2 Modelled mean annual precipitation and temperature at the nested domain (27 km), 1971–2000.

ranging from 0.64 to 0.88 and percent error in volume ranging from 0.3% to 11.5%. The regionalization method was then used for estimating runoff for ungauged basins (Bae *et al.*, 2007). The runoff scenarios for 2025 (2011–2040) are based on 30-year averages.

For vulnerability assessment, we used water scarcity index (WSI), the ratio of freshwater withdrawals to available renewable freshwater resources (Vörösmarty *et al.*, 2000; Oki & Kanae, 2006). Water use sectors include domestic, industrial, and agricultural water use. Values in the order of 0.2 to 0.4 illustrate medium to high stress, while those greater than 0.4 show severe water limitation (United Nations, 1997).

RESULTS AND DISCUSSION

Changes in climate

The projected surface warming is pronounced at higher latitudes and during winter seasons. In contrast to the temperature change, the change in precipitation shows a distinct seasonal variation and a substantial regional variability. While the northern central region is projected to be wetter than the baseline period, the majority of other regions are projected to be drier than the baseline period (1971–2000) under the A2 scenario (see Fig. 3). Basins located in southern part of Korea are projected to be drier. In general, basins are projected to be wetter under the B2 scenario than under the A2

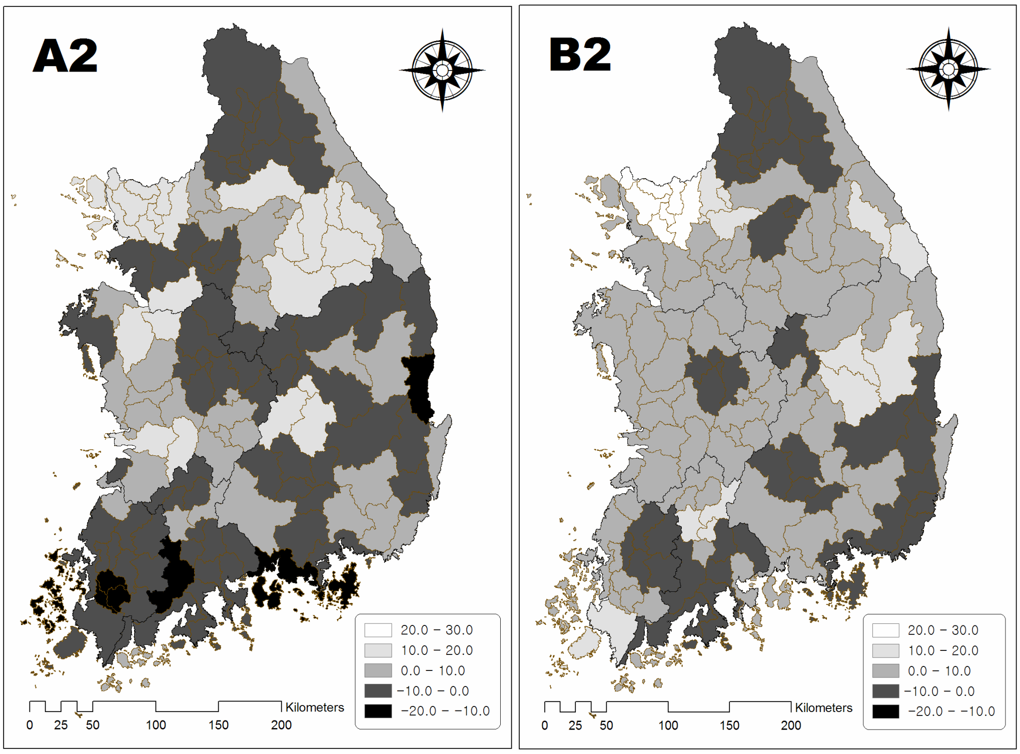

Fig. 3 Percent changes in mean annual precipitation from the baseline period (1971–2000) for 2025s under the A2 and B2 climate change scenarios.

scenario. The number of frost days (minimum temperature < 0ºC) markedly decreases, and the number of hot days (maximum temperature > 32ºC) increases in the B2 scenario compared to the present day. The regional distribution of warm rain episodes changes considerably, indicating changes in flood vulnerable regions (Im *et al*., 2006).

Changes in runoff

With projected warming and increased evapotranspiration, mean annual runoff is projected to decrease in all major river basins except in the Han River basin where the influence of increasing precipitation surpasses increases in evapotranspiration. The hydrological impacts are more pronounced at high elevations where snow cover is projected to decline significantly (Bae *et al*., 2007). Figure 4 shows changes in mean annual runoff for 139 sub-basins of Korea. While there is a disagreement between the outputs of the A2 and B2 scenarios, sub-basins located in the southern part of Korea are likely to have less runoff in 2025 than in the baseline period. In particular, runoff in summer months decreased 8 to 40% in southern river basins.

Water use pattern

Historical patterns of water use indicate that there are strong positive correlations between population size and domestic water use for most regions. While per capita

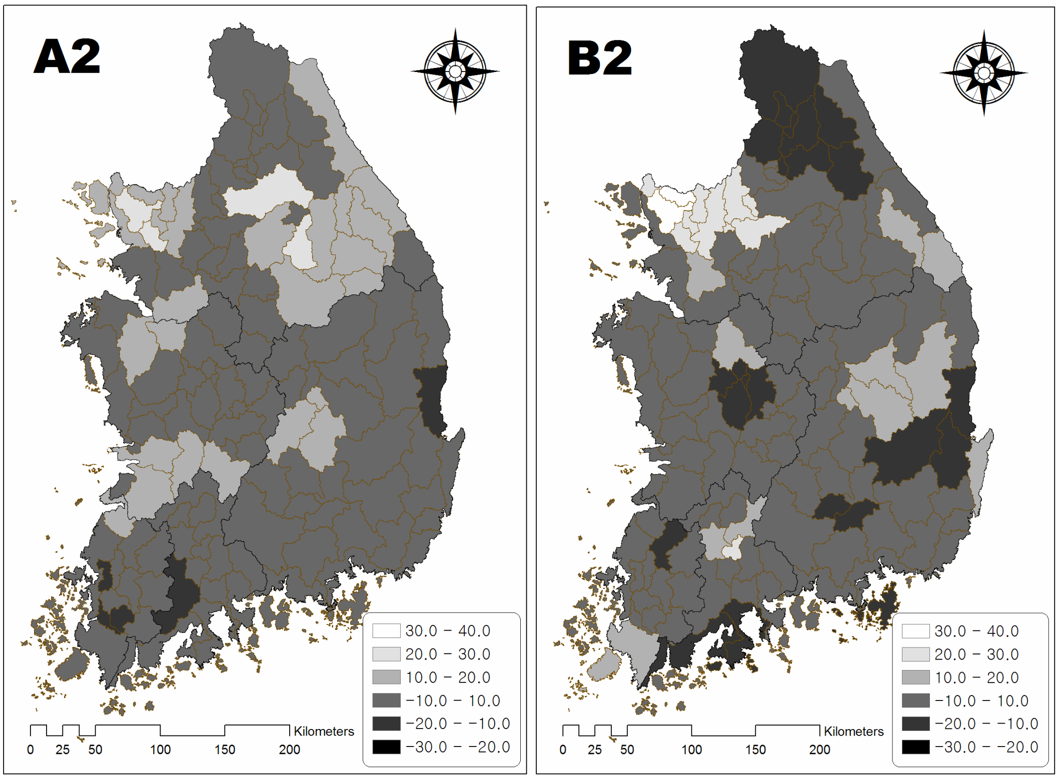

Fig. 4 Percent change in mean annual runoff from the baseline period (1971–2000) for 2025 under the A2 and B2 climate change scenarios.

water use has declined in major cities since the late 1990s, it has increased in all other regions with rising income and changes in lifestyles. Based on historical patterns and population projections, domestic water use is projected to increase in major metropolitan areas; however, it is estimated to stabilize in rural areas because of out migration to towns and cities. These region-specific water use patterns are taken into account for estimating future water demand for five major river basins (see Table 1). Only the Han River basin is projected to have increases in domestic water use by 2025.

Agricultural water use has continuously declined as the importance of the agricultural industry diminishes in the national economy. However, water use for livestock has increased with increases in population. Irrigation water use is positively associated with agricultural area and temperature, suggesting that future water use could be determined by these two factors. Rising temperature might cancel the effect of decreases in agricultural land on irrigation water use. Given this uncertainty, we hold future agricultural water use constant at the year 2000 level.

Table 1 Changes in domestic and industrial water use for five major river basins, 2000–2025 (unit: million m^3).

Water use	Year	Han	Nakdong	Gum	Youngsan	Sum
Domestic	2000	3616	2074	1026	1233	348
	2025	4250	1881	1006	953	296
Industrial	2000	510	1289	241	13	31
	2025	1000	2375	506	27	64

Industrial water use shows an increasing trend and is positively associated with total regional production output, but is not related to the number of industries or the size of the industrial complex. Future industrial water use is estimated based on projected industrial production, with an annual growth rate of 2.5% and current industrial water use per production. In all river basins, industrial water use is projected to increase in the future (see Table 1).

Future water resource vulnerability

We developed three environmental change scenarios for assessing the vulnerability of future water resources in Korea. The first scenario was based on future population and industrial growth without climate change. The second scenario was based on the projected climate change only, and the third scenario was based on the combination of climate change and growth scenarios. Under the baseline period, water scarcity index (WSI) range from 0.03 to 0.38, somewhat lower than the previous estimate of 0.45 for Korea (OECD 1994). Our estimates, however, did not include water use for mining and reserves for maintenance.

Under the growth scenario, the Han and Nakdong River basins experience more significant stresses than other basins, particularly under the A2 climate change scenarios. The WSI increased from 0.28 to 0.32 for the Han River basin and from 0.38 to 0.41 for the Nakdong River basin (see Fig. 5). Similar to precipitation changes, predicted climate changes could reduce mean annual runoff by more than 10% for basins located in the south. The Nakdong River basin is projected to experience the highest stress (WSI > 0.4) at 2025. The Han River basin, however, could have increases in annual runoff by 4.5% with more precipitation under climate change scenarios. When climate change and growth occur currently, all regions experience further reduction in the relative availability of water as reflected by increases in WSI.

The numerical experiments suggest that the regional variation of water stress in Korea is likely to increase under the changing environmental scenarios. The Han River basin and the Nakdong River basin already have high population densities and contain major industries. With relatively low population density and depopulation in rural areas, the other three basins may remain less vulnerable to these environmental

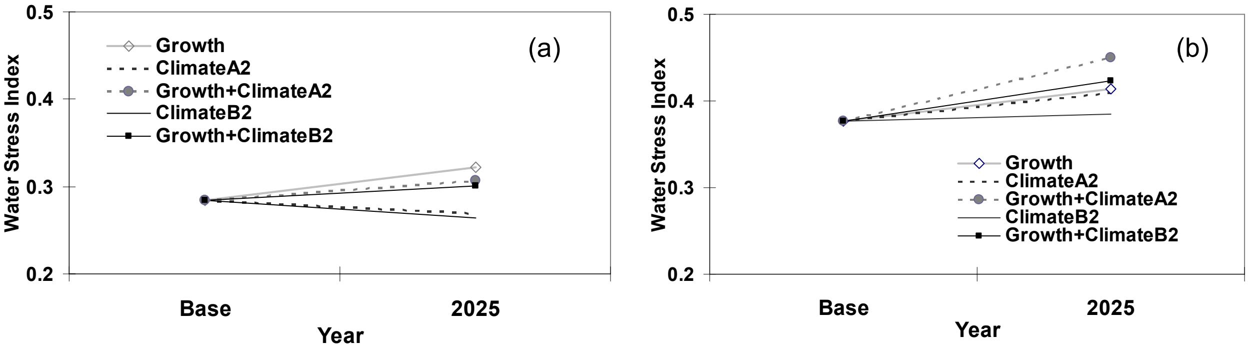

Fig. 5 Changes in the ratio of water use to runoff under different climate change and growth scenarios for (a) the Han River basin and (b) the Nakdong River basin.

changes. If these spatial patterns of demographic and economic trends continue in the future, a major water diversion plan might be needed to meet the needs of water for growing regions.

CONCLUSIONS

Assessing future water vulnerability based on projected changes in water demand and climate change is a complex task, requiring integrated knowledge in climate science, population growth, water economy, and decision-making. While climate change alone may not pose as big a stress on water resources as industrial growth on a national scale, southern basins are projected to experience significant changes by climate change. These potential regional disparities should be considered for the sustainable water resource management of Korea.

Acknowledgements This research was supported by a grant (code# 1-9-2) from the Sustainable Water Resources Research Center of the 21st Century Frontier Research Program in Korea.

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