ESTIMATION OF IRRIGATION WATER SUPPLY FROM NONLOCAL WATER SOURCES IN GLOBAL HYDROLOGICAL MODEL

S. Kitamura[1], S. Yoshikawa[2], and S. Kanae[3]

[11] Tokyo Institute of Technology, kitamura.s.ag@m.titech.ac.jp:
[2] Tokyo Institute of Technology, sayajo@chikyu.mei.titech.ac.jp:
[3] Tokyo Institute of Technology, kanae@cv.titech.ac.jp:

ABSTRACT

The terrestrial water cycle is being altered by human activity such as water diversion and withdrawal for agricultural use. In this study, the total irrigation water requirement all over the world was estimated using global hydrological model H08. In order to analyze the sustainability of water resources, the model was enhanced to quantify four major sources: river, reservoirs, nonlocal water sources and nonrenewable water sources. Geographical data of water diversion systems were made to estimate the amount of water supplied from nonlocal water sources. The simulated result showed that nonlocal water resources have large contribution to irrigated crops.

Keywords: Water diversion, Hydrological simulation, Irrigation

1 INTRODUCTION

The terrestrial water cycle is being altered by human activity such as water diversion and withdrawal for agricultural use. Water diversions have often been initiated to mitigate water shortage or increasing food productions. Many major rivers are now diminished in their lower reaches due to diversions and impoundments for irrigation. For example, the Yellow River has experienced a persistent decline in observed annual runoff from 1960 to 2000 that was significantly affected by irrigation withdrawals (Tang et al., 2008).

Many studies have produced water resource assessment using global hydrological models. Wada et al., 2012 calculated net irrigation water requirements and groundwater recharge to estimate non-renewable groundwater abstraction over the period 1960–2000 (Wada et al., 2012). Hanasaki et al. (2010 estimated the irrigation water requirements from different sources for major crops and livestock products and the level of global virtual water exports using the global water resources model H08 (Hanasaki et al., 2010; Hanasaki et al., 2008) (hereafter H08). In the simulation in H08, irrigation water demand is met by four water three sources; river, medium sized reservoir and conceptual water resources. In the original H08 model, Water diversions are not modeled because these activities transport fresh water beyond grid cells. This water transported beyond grid cells is called nonlocal water resources.

In this study, geographical data of hydrological water transfers was made and amount of irrigation water supply from nonlocal water resources was estimated by enhancing an integrated global hydrological model H08. The water diverted beyond grid cells is so called nonlocal water resources.

The structure of this report is as follows. Section 2 reviews H08 and described several enhancements of H08. Then the methodology of the global hydrological simulation is described. In section 3, we discuss the results of global hydrological simulation focusing on irrigation water use.

2 METHODOLOGY

2.1 Global hydrological model H08

H08 was developed by Hanasaki et al. (2008). The model consists of six modules: land surface hydrology, river routing, crop growth, reservoir operation, environmental flow requirements estimate, and anthropogenic water withdrawal. It simulates both natural and anthropogenic water flow globally on a daily basis at a spatial resolution of $0.5° \times 0.5°$ (longitude and latitude) with water and energy balance closure. The crop growth module of H08 estimates planting and harvesting dates globally, and the land surface hydrology module calculates daily evapotranspiration from cropland during cropping periods. The water withdrawal module estimates irrigation water requirements at a daily interval during cropping periods to maintain the soil moisture of the upper 1 m at 100% of field capacity for rice and 75% for other crops in irrigated cropland. The river routing module simulates daily river discharge. The 452 largest reservoirs worldwide that have greater than 1.0×10^9 m^3 storage capacity (hereafter, large reservoirs) are individually geo-referenced to the digital river map of the H08 model, and their operations influence the river simulation. Reservoirs with storage capacities ranging from 3.0×10^6 to 1.0×10^9 m^3 (hereafter, medium-size reservoirs) and conceptual water source were added as a source of water withdrawals to the H08 model by Hanasaki et al. (2010). In this study, water diversions are modeled to estimate irrigation water supply from nonlocal water resources. However, deep groundwater, lakes, and glaciers are not modeled in the H08 model because they formed over decades and centuries and are beyond the time frame of the H08 simulation. The conceptual water source represents these waters and acts as a limitless source of water withdrawals because the capacity of each source is unknown.

2.2 Geographical data of water diversions

In H08, water availability in rivers and medium-sized reservoir are calculated and consumed in each grid. It means water transportation beyond cells cannot be calculated. In this study, transportation of irrigation water beyond cells is defined as nonlocal water withdrawal. Moreover, irrigation areas using such water are defined as nonlocal irrigation area.

Simulation of water diversions needs geographical data which shows where nonlocal water sources are and where the nonlocal water are used. The data was described in the following processes.

At first, we created digital map of irrigation canals used for nonlocal water withdrawal from satellite images. Then we specified irrigation areas using nonlocal water resources.

Finally gridded data covering major irrigated croplands using nonlocal water resources (Pakistan, India, Yellow river basin(China), California(USA) and Israel) in spatial resolution of $0.5° \times 0.5°$ were obtained. The data has the information of correspondence between source of water and nonlocal irrigation area (**Fig.1**).

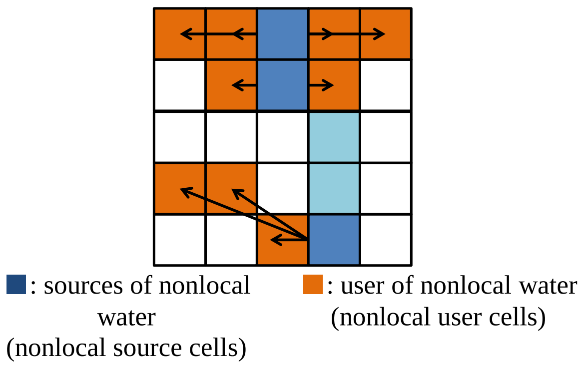

Fig.1. Geographical data of water diversions. Allows shows flow of water.

2.3 Withdrawal from nonlocal water resources

In this research, the flow of the water in a grid and the withdrawal rule of irrigation water were set up as follows.

Runoff from land surface flow into medium-sized reservoirs first. When the storage of medium-sized reservoirs exceed the storage capacities, amount of the excess flow into rivers. Withdrawal is performed when irrigation demand occurs in the irrigation farmland inside of the grid cell, or nonlocal areas. When irrigation demand arises in the irrigation farmland of two or more grid cells, withdrawal is performed sequentially from a cell with a near distance.

First of all, withdrawal is performed from rivers. In this study, it was presupposed that all the river flow rates can be taken. When river water is insufficient to meet the demand, withdrawal from nonlocal water resources is performed. When both the river water and nonlocal water resources are drained, withdrawal is performed from the storage of medium sized reservoir.

When the storage of medium-sized reservoir is drained, withdrawal is performed from the source of conceptual water.

In this study, the conceptual water source is available everywhere without limit and is not recharged. Consequently, the irrigation water requirements are met from one of four sources: river, nonlocal water resource, medium-size reservoirs, or Conceptual water source (**Fig. 2**).

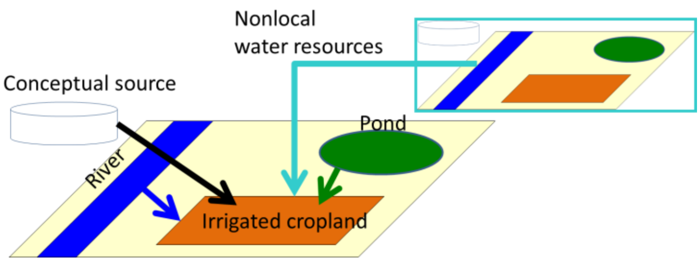

Fig.2. Schematic diagram of water withdrawal

2.4 Hydrological simulation

Two types of input data are necessary to run the H08 model: meteorological forcing and land use. We used WATCH Forcing Data (WFD) made by WATer and global Change. WFD data are near-surface meteorological data with a 6-h time step from 1960 to 2000 and a spatial resolution of 0.5° × 0.5° . Eight variables are included in the WFD dataset: air temperature, specific humidity, wind speed, air pressure, shortwave/longwave downward radiation, rainfall, and snowfall, all of which were used for the hydrological simulation.

We used land-use data compiled by Hanasaki et al., 2010, including the global distribution of major crops (Monfreda et al., 2000) and cropping intensity (Döll and Siegert, 2002). We used distribution of Irrigated areas described by Yoshikawa et al. (2013). These data were gridded for consistency with the spatial resolution and meteorological forcing land/sea mask.

3 RESULTS

Pakistan was the largest user of nonlocal water resources (23km^3) and India was the second (11km^3) (**Table 1**).

Fig. 3 shows contribution of water resources to irrigation and annual irrigation water requirement in the year 2000. Large amount of water requirement can be seen in India, east coast of China and the High plains, U.S.A. Contributions of river water are quite little in Pakistan and China. Medium size reservoirs supply more than half of total irrigation water requirement in Israel and China. In each region, nonlocal water resources have large contribution to total irrigation water requirement. Nonlocal water resources supply nearly half of total irrigation water requirement in Pakistan. Large contribution of conceptual water sources can be seen in Pakistan and California.

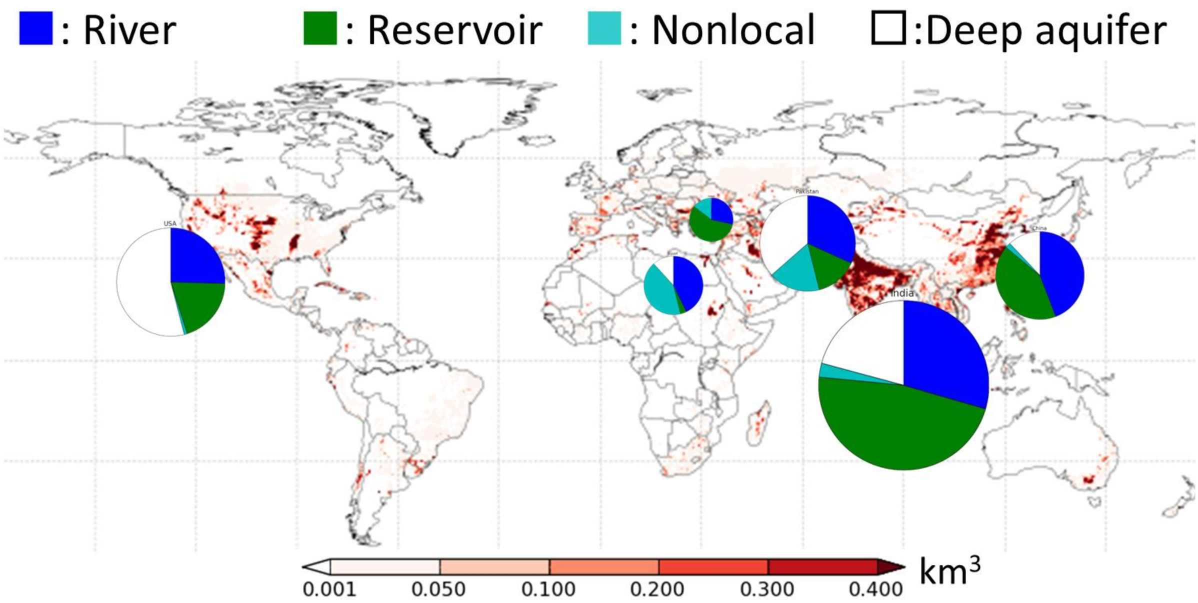

Fig. 3. Pie charts show contribution per water resources to water used for irrigation in 'nonlocal user cells'. Back ground shows total irrigation water requirement in the year 2000.

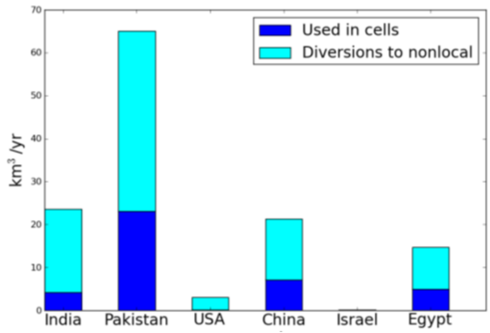

Fig. 4. Monthly irrigation water taken from rivers in 'nonlocal source cells'. 'Local' is denoted bars in the bottom. 'Nonlocal' is denoted bars in the upper.

Table 1 Annual global irrigation water requirement (km^3)

	River	Reservoir	Nonlocal	Nonrenewable	total
India	126	202	11	89	429
Pakistan	42	19	23	49	134
USA	46	35	2	97	181
China	121	114	5	32	273
Egypt	9	1	9	2	21
Israel	0	0	0	0	0

4 DISCUSSIONS

4.1 Nonlocal water resources

Nonlocal water resources have large contribution in most regions in **Fig. 3**. We can say that nonlocal water resources play an important role to sustain irrigation in ‘nonlocal user cells’. On the other hands, **Fig.4** shows that more than half of water taken from river was transferred from ‘nonlocal source cells’ to ‘nonlocal user cells’. In other words, more water was taken from river comparing original H08. That indicates diversion of river water can increase risk of water scarcity in ‘nonlocal source cells’.

4.2 Conceptual water sources

In this study, withdrawal from nonlocal water resources was estimated. Then we can regard conceptual water sources as nonrenewable water resources. Withdrawal from nonrenewable water sources was estimated at 425km^3 yr^{-1} over the world. Pokarel et al. (2008) estimated annual groundwater depletion at 454 km^3 yr^{-1} globally. Furthermore, they estimated sea-level rise assuming that 97% of unsustainable groundwater use ends up in the oceans. They also applied H08 for their study. However, water diversions were not modeled in their model. It might lead them overestimation of groundwater depletions and thus sea-level rise.

4.3 Limitations

Limitations of this study come from input data and modeling assumptions of H08. Yoshikawa et al., 2013 showed that sensitivity tests of model parameter can result in 20 % increase of irrigation water requirement at most.

In this study, we described geographical data and irrigated croplands using nonlocal water resources were specified. However, areas covered by the data are limited to major irrigated cropland.

5 CONCLUSIONS

Diversions of river water and thus withdrawal from nonlocal water resources are one of more important changes in hydrological cycle. We described geographical data of nonlocal withdrawal of irrigation water. We enhanced a global hydrological model and estimated irrigation water supply from four water sources; river, nonlocal water, medium-sized reservoir and conceptual water sources. The simulation was conducted for the year 2000 at a spatial resolution of $0.5^\circ \times 0.5^\circ$. The results show that nonlocal water resources supply almost half of total irrigation water requirement in Pakistan. Nonlocal water resources have potential to mitigate water shortage in ‘water using cells’. On the other hand, withdrawals from nonlocal water resources have large impact on the amount of water resources in ‘nonlocal source cells’. Conceptual water source can be regard as nonrenewable water resources and we can pinpoint areas where irrigation is sustained by nonrenewable water resources.

This study has some limitations mainly caused by input data and model assumptions. Nevertheless the results are meaningful because few data are available for issues mentioned above. The results of this study provided important information for water resource assessment.

ACKNOWLEDGMENTS

We gratefully acknowledge the ‘Long-term Vision for the Sustainable Use of the World's Freshwater Resources’ program through Core Research for Evolutional Science and Technology (CREST) under the Japan Science and Technology Agency for its financial support of this study.

This work was also partly supported by JSPS Core-to-Core Program, B. Asia-Africa Science Platforms.

REFERENCES

[1]. Tang, Q., Oki, T., Kanae, S., and Hu, H.(2008) Hydrological cycles change in the Yellow river basin during the last half of the 20th century: Journal of Climate, 21, pp.1790–1806

[2]. Wada, Y., van Beek, L. P. H., Bierkens, M. F. P. (2012) *Nonsustainable groundwater sustaining irrigation: A global assessment* : Water Resources Research, 48.

[3]. Hanasaki, N., Inuzuka, T., Kanae, S., and Oki, T. (2010) *An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model*: Journal of Hydrology, 384, pp. 232–244.

[4]. Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K. (2008) An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing: *Hydrology and Earth System Sciences*, 12, pp. 1007–1025.

[5]. Weedon, G. P. , Gomes, S., Viterbo, P., Österle, H., Adam, J.C. and Bellouin, N. (2011) The WATCH Forcing Data 1958-2001: A meteorological forcing dataset for land surface- and hydrological-models: *WATCH technical report No.22*.

[6]. Monfreda, C., Ramankutty, N. and Foley, J.A. (2000) Farming the planet, part 2: the geographic distribution of crop areas and yields in the year 2000: *Global Biogeochemical Cycles*, GB1022.

[7]. Döll, P. and Siebert, S. (2002) Global modeling of irrigation water requirements, *Water Resources Research 38*, pp. 1037.

[8]. Yoshikawa, S., Cho, J., Yamada, H. G., Hanasaki, N., Khajuria, A. and Kanae, S. (2013) An assessment of global net irrigation water requirement from various water supply sources to sustain irrigation: rivers and reservoirs (1960-2000 and 2050): *Hydrol. Earth Syst. Sci. Discuss.*, 10, pp. 1251-1288.

[9]. Pokhrel, Y., N., Hanasaki, N., Yeh, P., J-F., Yamada, T., J., Kanae, S. and Oki, T. (2011) Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage: *Nature Geoscience* 5, pp. 389–392.