Interdisciplinary studies on groundwater for global sustainability

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Interdisciplinary groundwater issues related to global environmental changes are, subsurface warming due to global warming and urbanization, global groundwater depression due to rapid increase in groundwater demand, submarine groundwater discharge which is one of the water cycle component but not globally evaluated yet, and groundwater footprint which is related to global sustainability. These issues have been studied not only in the area of groundwater hydrology but also in the multi -disciplines such as coastal oceanography for submarine groundwater discharge, geothermic for subsurface warming, and geodesy for global groundwater depression which was revealed by satellite GRACE. In this paper, interdisciplinary studies on groundwater and subsurface environmental changes for global sustainability have been reviewed with conjunction of oceanography, geothermic and geodesy.

Keywords: groundwater, global sustainability, interdisciplinary

The Global Groundwater Crisis and Management Implications for Food and Water Security

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Groundwater depletion in the world’ s major aquifer systems poses a major threat to global food and water security. Many of these aquifers are trans-boundary, both within and between nations. However, very few formal trans-boundary groundwater agreements exist, at least internationally. In this presentation we review the 15-year lifetime of GRACE data (2002-2017) and our estimates of changing freshwater availability, including groundwater storage changes at the regional and aquifer scales. A roadmap for ensuring sound international groundwater management is discussed, as are implications for global food security.

Keywords: groundwater depletion, food security, water security

The contrasting impacts of climate change on groundwater hydrology in the world’ s major aquifers

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Groundwater is the source for approximately 40% of all global freshwater demand, and is thus critical for water supplies and associated food production in arid and semi-arid regions, especially during dry seasons. The increasing demand for water and food (due to population growth) and variability in water resources (due to climate change) have led to long-term groundwater depletion, compromising the sustainability of human water use in several regions of the world. Here, we utilized fully coupled climate model simulations from the Community Earth System Model Large Ensemble Project to investigate groundwater storage changes in the world’ s major aquifers (Guarani, Southern Plains, Northwestern India, Middle East, Canning, North China Plain, and Central Valley) under future climate changes. The projections show that climate change contributes to changes in groundwater storage not only via changes in precipitation, but also through changes in plant transpiration under CO2 fertilization effects, reductions in snowmelt, and enhancement of surface evaporation, which collectively lead to contrasting effects between increased precipitation and increased evapotranspiration.

Keywords: CESM-LE, groundwater

Large-scale modelling of groundwater resources: insight from the comparison of models and in-situ observations in Sub-Saharan Africa

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Fundamental challenges remain in the large-scale modelling of groundwater resources using either Global Hydrological Models (GHMs) or Land-Surface Models (LSMs). These challenges include the representation of groundwater recharge processes and geological controls on groundwater occurrence. Current large-scale models, with one notable exception, disregard indirect (*i.e.* focused) recharge that occurs via leakage from surface waters and is often the dominant recharge pathway in semi-arid environments. Further, models do not represent the preferential pathways which can control the timing and magnitude of recharge. Additional challenges include the representation of human withdrawals of groundwater, particularly in areas of intensive irrigation, that are generally disregarded (*e.g.* LSMs) and largely untested. Indeed, because groundwater-level monitoring networks are so limited globally, current assessments of groundwater resources commonly rely upon output from GCMs and LSMs as well as GRACE satellite observations in which groundwater storage changes are resolved using large-scale model data. Such models are furthermore the primary source of information on projected climate change impacts on groundwater resources. There remains a paucity of studies examining the robustness of terrestrial water balances including estimates of groundwater recharge and storage simulated by LSMs and GHMs using in situ observations. On behalf of *The Chronicles Consortium*, I report preliminary analyses comparing groundwater recharge estimated by both LSMs and GHMs to long-term observations of groundwater levels and stable-isotope ratios. Such comparisons require careful consideration as in situ observations may not represent grid-scale averaging. Nevertheless, given the non-linearities in model parameterisations that can occur during the shift to higher grid resolutions (*e.g.* 0.5° to 5 km), it will become increasingly important to reconcile revised model structures with *in situ* observations. Preliminary results derive from the analysis of the relationship between monthly precipitation and subsurface runoff (*i.e.* proxy for groundwater recharge) from 4 LSMs (CLM2.0/CLM4.5, NOAH, MOSAIC, VIC) and 3 GHMs (PCR-GLOBWB, WaterGAP, MATSIRO) at 1°x1° and both multi-decadal records of groundwater levels from 8 countries (Benin, Burkina Faso, Ghana, Niger, South Africa, Tanzania, Uganda, Zimbabwe) and stable-isotope ratios collated from long-term IAEA stations and published sources in 7 countries (Burkina Faso, Chad, Ethiopia, Namibia, South Africa, Tanzania, Zimbabwe). Analyses reveal substantial spatial variability among the GLDAS LSMs in subsurface runoff across Africa. Precipitation and subsurface runoff in LSMs show non-linear (*i.e.* reflecting bias to heavy rainfall), linear, or no bivariate associations in contrast to consistently non-linear relationships noted from the comparison of stable-isotope ratios in rainfall and groundwater. GHMs also demonstrate substantial variability in computed potential recharge though greater consistency is observed in their dependence of groundwater recharge on monthly or seasonal rainfall exceeding a monthly or seasonal threshold, consistent with some piezometric records. A key outcome from the analysis of multi-decadal groundwater-level data is the importance of indirect recharge processes (*e.g.* Niger, South Africa, Tanzania, Zimbabwe) despite their current exclusion from all but one large-scale model. On-going initiatives (*e.g.* GEWEX-GHP/GLASS, *The Chronicles Consortium*) seeking to bring large-scale modelling and GRACE communities together with those analysing *in situ* observations are urgently required to address fundamental and substantial limitations that persist in the modelled representation of groundwater in the terrestrial water balance, particularly in the tropics.

Keywords: groundwater, piezometry, models, stable-isotope ratios

Global, Regional, and Local-scale Assessment of the Impacts of Irrigation and Reservoir Operation on Land Hydrology and Climate

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In this study, we use two different land surface hydrological models to assess the global, regional, and local-scale impacts of human land-water management practices on land surface hydrology and climate system. The first model is a global land surface model called the HiGW-MAT that simulates the flows and storages of water globally at 1-degree grids, taking into account various human activities such as irrigation, reservoir operation, and groundwater pumping. The second model is the regional hydrological model called the LEAF-Hydro-Flood, which simulates surface and sub-surface hydrological processes including river-floodplain dynamics at 2 to 5km grids; the model has recently been enhanced to simulate anthropogenic water flows by incorporating the schemes to represent the aforementioned human activities. A series of numerical experiments are carried out by turning the human impact schemes on and off in each of the two models. We present four sets of analysis by using the results from the two models. First, results from the global model are used to examine the human-induced changes in global and regional water balance, with an emphasis on the widely debated issue of the desiccation of the Aral Sea in central Asia and the groundwater depletion in northwest India and Pakistan. In this analysis, we make an integrated use of model results and the data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. Second, we examine the global and regional climate impacts of human activities, particularly irrigation, again by using the results of the global model coupled with its parent climate model MIROC. Third, we compare the results from the two models over the selected river basins to examine the role of increased spatial resolution in the regional model to better simulate certain hydrologic fluxes and stores, essential to capture the human footprint. Finally, we use the results from the regional model to highlight the importance of and challenges in using the high-resolution model to simulate reservoir operation over regional to local scales.

Keywords: Hydrological modeling, Irrigation, Reservoir Operation

Contribution of groundwater pumping to global sea level rise: regional pattern and temporal evolution

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This study examines the impacts of groundwater pumping on terrestrial and atmospheric water balances and quantify its contribution to global sea level rise (SLR) using a global climate modelling approach. This is a follow-up of the pioneering study by Wada et al. (2016). In contrast to Wada et al (2016) in which the analysis was limited to the global-integrated long-term averages, the present study extends to analyse spatial and temporal patterns in the water balance at global, continental and aquifer levels, and quantify the contributions from terrestrial water storage (TWS) changes and anthropogenic pumping to SLR on the continental and aquifer scales. This research is divided into: 1. Global analysis, 2. Continental (Africa, Asia, Europe, North America, Oceania, and South America) analysis, and 3. Aquifer-based analysis (contribution from TWS changes to SLR will be analysed based on 37 global major aquifers).

Keywords: Groundwater pumping, sea level rise, terrestrial water storage

Who is eating up the world's aquifers? Groundwater depletion embedded in international food trade.

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Recent hydrological modelling and Earth observations have located and quantified alarming rates of groundwater depletion over the world. This is primarily due to water withdrawals for irrigation, but the connections with their main driver, global food consumption, have not yet been explored. Here we show that approximately eleven percent of non-renewable groundwater use for irrigation is embedded in food trade, of which two thirds are exported by Pakistan, the United States and India alone. We provide the first quantification of depleting groundwater embedded in the world’s food trade by combining unique global, crop-specific estimates of non-renewable groundwater abstraction with international food trade data. A vast majority of the world’s population lives in countries sourcing nearly all their staple crop imports from partners who deplete groundwater to produce these crops, highlighting risks for global food and water security. Groups of countries are found particularly exposed to these risks as they both produce and import food irrigated from rapidly depleting aquifers, such as the USA, Mexico, Iran and China. These results can help improve the sustainability of global food production and groundwater resources management by identifying priority regions and agricultural products at risk as well as the end-consumers of these products.

Keywords: Food trade, Groundwater depletion, Embedded water resources (virtual water)

Drought impacts to water footprints and virtual water transfers of the Central Valley of California

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The Central Valley of California is one of the most productive agricultural locations in the world, made possible by a complex and vast irrigation system. Beginning in 2012, California endured one of the worst droughts in its history. Local impacts of the drought have been evaluated, but it is not yet well understood how the drought reverberated through the global food system. Here, we quantify drought impacts to the water footprint (WF) of agricultural production and virtual water transfers (VWT) of the Central Valley of California. To do this, we utilize high spatial, temporal, and water source resolution datasets and a crop model from pre-drought conditions (2011) through three years of exceptional drought (2012--2014). Despite a 6.5% reduction in crop production over the course of the drought, the WF of agricultural production in the Central Valley increased by 1.3%. This was due to greater crop water requirements from higher temperatures and a shift to more water-intensive orchard and vine crops. The groundwater WF increased from 5.93 km3 in 2011 to 11.64 km3 in 2014, predominantly in the Tulare Basin. During the drought, transfers of food commodities declined by 1.3%. However, total VWT increased by 4.2% (0.57 km3), driven by an increase in groundwater VWT (3.31 km3), offsetting declines in green and surface VWT. During the drought, local and global consumers doubled their reliance on the already overexploited Central Valley Aquifer. These results indicate that drought may strengthen the telecoupling between unsustainable groundwater withdrawals and distant consumers of groundwater-intensive agricultural commodities.

Keywords: Water footprint, Drought, Virtual water trade, Groundwater, California

Human impact on hydrological drought in the 20th and 21st century

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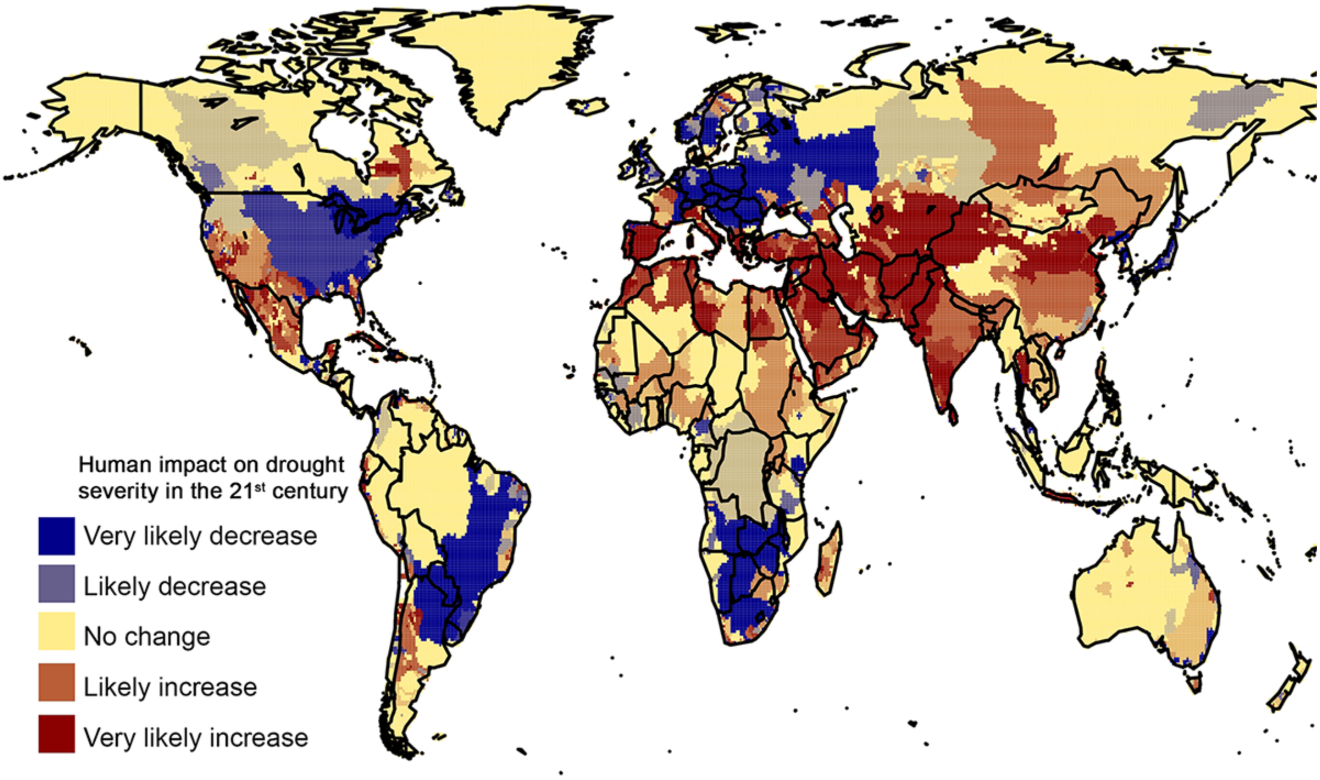
Human actions impact current drought conditions and, in combination with climate change, will very likely impact future hydrological drought characteristics across the world. Here, I quantify the impact of human water use, groundwater pumping, reservoir regulation and climate change on historical and future low flows
on a global scale. I use the global hydrological and water resources model PCR-GLOBWB to simulate daily discharge for the period 1950–2100.
First, I will show a historical analysis for the period 1950-2015, where we focus on the recent drought in the state of California and the alterations in drought characteristics that have occurred due to human water management. Next, I use the latest CMIP5 climate projections taken from five General Circulation Models (GCMs) and four emission scenarios (RCPs), under the framework of the Inter-Sectoral Impact Model Intercomparison Project to project human impact on drought for 2000-2100. A natural or pristine scenario was used to calculate the impact of the climate on hydrological drought and was compared to a scenario with human influences.
The results show that drought is severely affected by human actions, mainly by groundwater pumping and reservoir operations, respectively worsening and alleviating drought severity. For the case study in the state of California, we see the severe impact of human actions on drought in the increase in drought duration compared to the pristine conditions. The impact is most evident in groundwater and discharge, because most of the human impact is caused by groundwater pumping and surface water abstraction.
For the 21st century, we see a significant impact of climate change and human water use in large parts of Asia, Middle East and the Mediterranean, where the relative contribution of humans on the changed drought severity can be close to 100 percent. The differences between RCPs are small indicating that human water use is proportional to the changes in the climate. Reservoirs tend to reduce the impact of drought by water retention in the wet season, which in turn will lead to increased water availability in the dry season, especially for large regions in Europe and North America. The impact of climate change varies throughout the season for parts of Europe and North America, while in other regions (e.g. North Africa, Middle East and Mediterranean) the impact is not influenced by seasonal changes.
This study illustrates that the impact of groundwater pumping and reservoirs is non-trivial and can vary substantially per region and per season. Considering their large impact on changing drought conditions, human influences should be included in projections of future drought characteristics.

Keywords: Human impact, Drought, Climate change, Groundwater, Reservoirs, PCR-GLOBWB


Human impact on drought severity in the 21st century
Very likely decrease
Likely decrease
No change
Likely increase
Very likely increase

New approaches for estimating groundwater drought in near real-time in the absence of observed groundwater level data: the 2015 European drought case

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In 2015 central and eastern Europe were affected by severe drought. Impacts of the drought were felt across many sectors, incl. agriculture, drinking water supply, electricity production, navigation, fisheries, and recreation. This drought event has recently been studied from meteorological and streamflow perspective, but no analysis of the groundwater drought has been performed. This is not surprising because real-time groundwater level observations often are not available. In this study we use previously established spatially-explicit relationships between meteorological drought and groundwater drought to quantify the 2015 groundwater drought over two regions in southern Germany and eastern Netherlands. We also tested the applicability of the Gravity Recovery Climate Experiment (GRACE) Terrestrial Water Storage (TWS) and GRACE-based groundwater anomalies to capture the spatial variability of the 2003 and 2015 drought events.

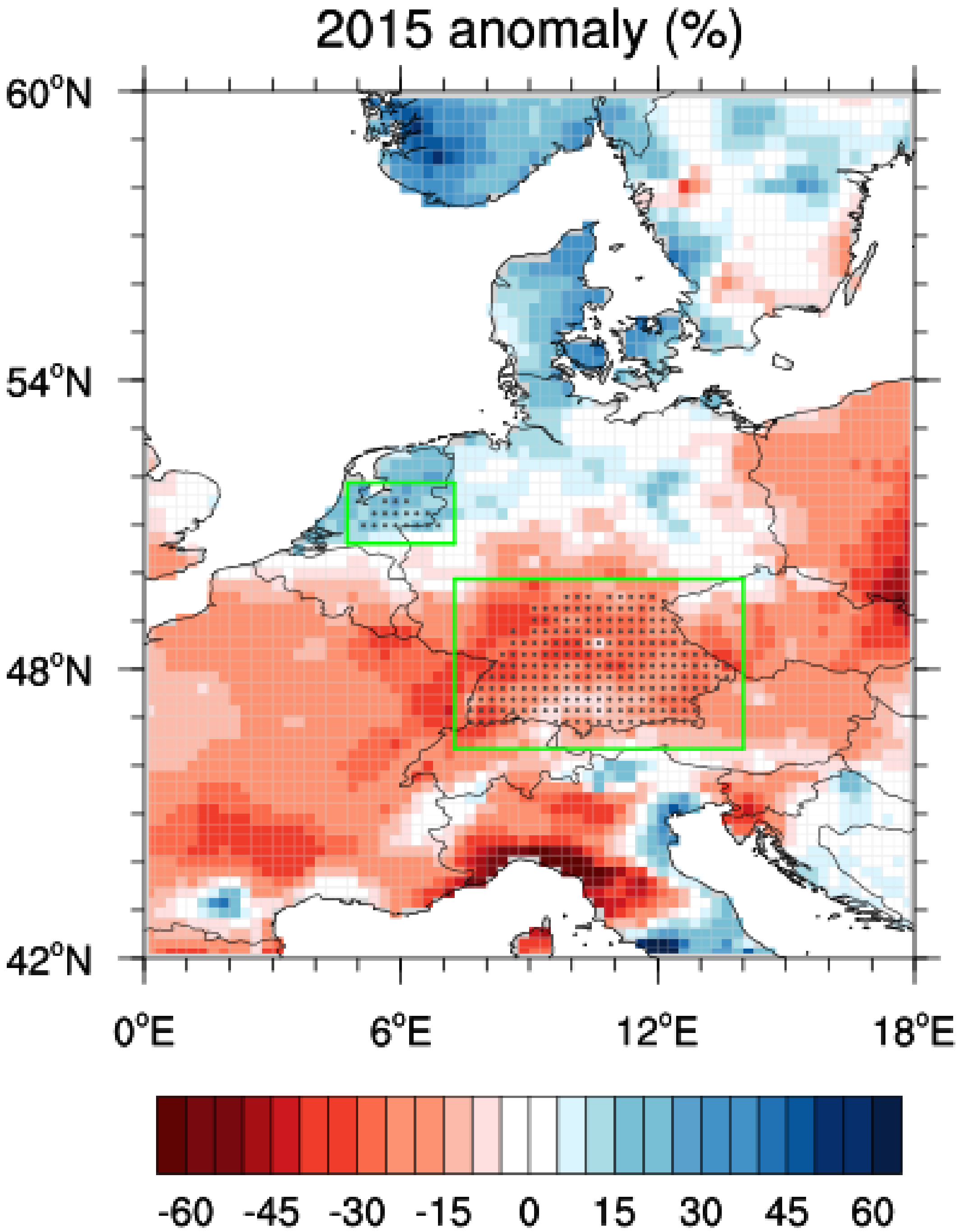
We use the monthly groundwater observations from 2040 wells to establish the spatially varying optimal accumulation period between the Standardized Groundwater Index (SGI) and the Standardized Precipitation Evapotranspiration Index (SPEI) at a 0.25^0 gridded scale. The resulting optimal accumulation periods range between 1 and more than 24 months, indicating strong spatial differences in groundwater response time to meteorological input over the region.

Based on these optimal accumulation periods, we found that in Germany a uniform severe groundwater drought persisted for several months (i.e. SGI below the drought threshold of 20th percentile for almost all grid cells in August, September and October 2015), whereas the Netherlands appeared to have relatively high groundwater levels (never below the drought threshold of 20th percentile). The differences between this event and the European 2003 benchmark drought are striking. The 2003 groundwater drought was less uniformly pronounced, both in the Netherlands and Germany, with the regional averaged SGI above the 50th percentile. This is because slowly responding wells still were above average from the wet year of 2002-2003, which experienced severe flooding in central Europe.

GRACE-TWS does show that both 2003 and 2015 were relatively dry, but the difference between Germany and the Netherlands in 2015 and the spatially-variable groundwater drought pattern in 2003 were not captured. This could be associated to the coarse spatial scale of GRACE. The simulated groundwater anomalies based on GRACE-TWS deviated considerably from the GRACE-TWS signal and from observed groundwater anomalies. These are therefore not suitable for use in real-time groundwater drought monitoring in our case study regions.

Our study shows that the relationship between meteorological drought and groundwater drought can be used to quantify groundwater drought and that the 2015 groundwater drought in southern Germany was more severe than the 2003 drought, because of preconditions in slowly responding groundwater wells. For sustainable groundwater drought management strategies the use of groundwater level monitoring is needed to study the spatial variability of local groundwater drought, which mostly coincides with drought impacts.

Keywords: groundwater drought, limited data, new techniques, standardised indices, GRACE, 2015 drought Europe



Impact of the South to North Water Diversion Project on Groundwater Resources of the Beijing Metropolitan Area: Implications for Sustainable Groundwater Use

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As China’s Capital, Beijing currently has a population of 22 million people with per capital water resources of less than 100 m^3, one twentieth of the national average and one eightieth of the global. Groundwater withdrawals (2.3 billion m^3/year) account for approximately two thirds of total water use (3.5 billion m^3/year) in Beijing, resulting in significant groundwater depletion and associated environmental issues, such as land subsidence. Ever-growing population and economy will add further pressure on Beijing’s groundwater resources. Unsustainable groundwater use threatens societal and economic development of Beijing and poses a large uncertainty in future water supply. To partly alleviate the water shortage issue in the more arid and industrialized North China, the Chinese government has launched the largest water diversion project in the world, i.e., the South to North Water Diversion Project (SNWD), which is a multi-decadal mega-infrastructure project, with the aim to transfer 44.8 billion m^3 of fresh water annually from the Yangtze River in the more humid south through three canal and pipeline systems (east, central, and west routes). Its central route flows from the upper reaches of the Han River, a tributary of the Yangtze River to Beijing, Tianjin and other major cities in Hebei and Henan Provinces. Since Dec 2014 when the water transferred by the central route reached Beijing to Feb 2017, totally 2 billion m^3 of water has been transferred. This has profoundly altered the structure of water supply in Beijing. This study quantifies how the SNWD project impacts groundwater storage of Beijing using modeling, and ground and satellite observations, and projects how groundwater storage changes in the future under different climate and, social and economic scenarios.

Keywords: Groundwater, South to North Water Diversion Project in China, Beijing

Economic costs of reducing unsustainable groundwater use: Application of IIASA global hydro-economic modeling framework

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Global water withdrawals for beneficial purposes have been increasing substantially in the last century, driven by the growth in population, food production, and income. The ensuing damages have been building up rapidly during recent years, with many basins around the world undergoing pervasive water scarcity conditions and progressive depletion of groundwater. Moreover, impacts of future climatic and socio-economic changes are projected to further exacerbate supply deficit in those basins. Therefore, the development of adaptation strategies to address growing water scarcity is needed. Groundwater resources are expected to play an important role and groundwater pumping will likely increase in the future to offset the declines in surface water availability and to provide a buffer against extreme drought events. However, groundwater resources are vulnerable to human activities and climatic conditions. For instance, aquifer systems in numerous regions around the world have been suffering considerable pressures during recent years, with extraction rates well above recharge. Intensive extractions have been brought about mainly by the adoption of low-cost pumping technologies and the supply of subsidized energy.

The damages from groundwater depletion on water and food security and ecosystem wellbeing could be substantial and irreversible, which call for the design of sustainable groundwater management policies. The design of policies requires quantitative tools for planning and policy evaluation that integrate biophysical, institutional, environmental, and economic metrics, reflecting decision-making objectives and processes. This study presents a global hydro-economic modeling framework developed at IIASA that represents water resource systems, infrastructure, management options and associated economic values in an integrated manner. The model is able to interact with existing global integrated assessment tools or global hydrological models. The model includes an economic-hydrologic optimization procedure that aims to balance water demand and supply at the level of large-scale river basins worldwide. The objective of the optimization is to minimize total costs of meeting water demands from agricultural, industrial and domestic sectors, subject to various technical and resource constraints. The optimization includes capacity expansion and is solved over a multi-decadal horizon. Sub-annual variability is incorporated at a monthly time-scale. The model can be used to simulate a variety of basin management decisions including resource extractions, inter-basin transfers, reservoir operation regimes, and water infrastructure investment. The model uses information on water demand and availability provided by existing global integrated assessment models and global hydrological models.

In this study, the model is used to evaluate the effects of different groundwater management policies (unlimited pumping vs. sustainable pumping) under future socio-economic and climatic scenarios (combinations of Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs)). The model is applied to basins in the Middle East and North Africa (MENA) region which provides a challenging case study. However, the modeling framework is designed to be adaptable for any basin elsewhere. Model results show the economic and environmental tradeoffs among the different policy choices and the hurdles facing policies aimed at reducing unsustainable groundwater use. Specifically, our results suggest that addressing the redoubled challenge of adaptation to growing water scarcity and sustainable use of groundwater resources in the MENA region will require major investments in more efficient water use technologies and unconventional freshwater supply options, such as wastewater

recycling and desalination, with potential consequences on water supply costs, energy use and carbon emissions.

Keywords: Hydro-economic modeling, Water scarcity, Groundwater resources, Sustainable management, Policy tradeoffs