Title: Groundwater basin depletion and international political borders

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Using data from NASA's Grace-Tellus Satellite project we study the effects of international borders on large scale groundwater basins. This is the first global socio-economic study of all major groundwater basins using these novel satellite data and connecting them to anthropogenic, political, and physical drivers of terrestrial water storage change. We find groundwater basins that intersect country borders face greater depletion than ones that do not, providing evidence of inefficiency in international water management. The source of inefficiency is driven by agricultural demand and the lack of international property rights.

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The 2006 United Nations Human Development Report (Watkins, 2006) paints a grim picture in regards to access to water, stating that "By 2025 more than 3 billion people could be living in water-stressed countries and 14 countries will slip from water stress to water scarcity". It goes on to explain that "high overuse tends to occur in regions heavily dependent on irrigated agriculture such as the Indo-Gangetic Plain in South Asia, the North China Plain, and the High Plains in North America". The overuse of groundwater basins is vital to society and is not just a local problem but a global one (Konikow and Kendy, 2005; Shah et al., 2000). This phenomenon is especially troubling because the distribution of natural resources may not coincide with geopolitical boundaries, meaning, international groundwater is at greater risk of depletion. Therefore, it is important to understand how these scarce resources are shared, used, and effectively managed in an international context.

Large scale common pool resource management is potentially the next great challenge in natural resource management (McGinnis and Ostrom 1996; Ostrom, 1999; Worm, 2009) and depends on coordination between local, regional, national, and international institutions (Ostrom, 2010). As revealed almost 50 years ago by Garrett Hardin (1968), common pool resources can fall victim to the tragedy of the commons when institutions fail to offer incentives to govern over-extraction. The economics literature has yet to empirically address free riding in international groundwater (Olmstead and Sigman, 2015), where water availability can be central to development. In this article we address one critically important question about large-scale groundwater basin management: Do international borders exacerbate the loss of large-scale groundwater basin stocks? We find evidence that they do.

The world's unfrozen freshwater resources are primarily made up of groundwater, roughly 96% (Jousma and Roelofsen, 2004), though much of this water may be inaccessible to humans. These supplies are subject to stressors from human and physical systems but only recently have global data been available to compare the profiles of groundwater basin loss on a large scale (Famiglietti et al., 2011; Rodell et al., 2009). In 2002, NASA started collecting gravity data, known as the GRACE-Tellus data, which we use to look at causal drivers of terrestrial water storage changes in the major groundwater basins of the world. Ineffective management of internationally shared basins could be caused by strategic over-extraction or could reflect additional coordination costs to managing water across multiple countries. Coordination costs could arise from increased monitoring and enforcement, the uncertainty of the information gathered, or the lack of legal institutions and recourse for the damaged party. The lack of coordination or co-management of large scale water resources is critical to society as increasing concerns grow over drought, starvation, human health, and water conflicts (Giordano, 2009; Gleick 2003; Sigman, 2002; Gleditsch et al. 2006; Dinar 2009).

Terrestrial water consumption is very influential in shaping the sustainable life of aquifers and is driven by irrigated agriculture, demand for drinking water, and manufacturing. Irrigation is the most significant source of demand, as it makes up approximately 67% of all groundwater extraction, drinking water is the second most common reason for extraction, and manufacturing falls in third place, driving about 10% of global groundwater extraction (Van der Gun, 2012). The characteristics of demand can vary based on climatic variables like precipitation and evapotranspiration, population density, the depth and cost to extract groundwater, the suitability of the soil to growing crops, available substitutes, available technologies, and restrictions on behavior through groundwater management institutions.

Much of the social science research on groundwater basin management is on small scale, such as community self-governance (Ostrom and Gardner, 1993) and state level coordination and cooperation (Schlager et al., 1994). While these studies have contributed to our understanding of local management of common pool resource management, they do not address large scale natural resources that span multiple countries. While empirical studies comparing depletion of basins is lacking in the economics literature there is important contributions to the design of optimal surface water contracts for international basins (Kilgour and Dinar, 2001), and elements of groundwater treaties and relevant politics have been studied and structures for future treaties proposed (Hayton and Utton, 1989; Zawahri et al., 2010).

1 International Agreements

Few international groundwater basin specific treaties are currently in place.[1] We list the major international groundwater basin treaties in Table 1. While there are few groundwater basin specific treaties, there are more treaties that mention water or groundwater within them, roughly 14% of water treaties mention groundwater according to Giordano et al. (2014). When groundwater treaties do exist, they can often establish information sharing, set property rights, have conflict mitigation mechanisms, or create binding limits on extraction. Groundwater basin agreements vary quite considerably in levels of governance, and there is little that individual countries can do if one partner decides to break the agreement. This basic aspect of governance, or lack of recourse, in international treaties is common to most environmental treaties and not unique to international water treaties. The lack of an international framework for groundwater

[1] This claim depends on how you classify groundwater treaties. There are very few international agreements solely focused on groundwater basins. This does not include treaties that has a surface water focus but mention groundwater usage. We do not include all water treaties that may include groundwater provisions but focus on treaties primarily focused on groundwater management. It is difficult to classify all treaties that mention groundwater and how these treaties relate to depletion concerns.

basins, which has only recently been addressed, and the complex nature of the resource, which is notoriously costly to monitor and sometimes poorly understood, greatly affects the establishment of international property rights and rules that affect depletion of groundwater. Even though few formal international groundwater treaties exist there is a push for governance; in 2009 the Law of Transboundary Aquifers, which encourages bilateral and regional groundwater agreements, was officially adopted through resolution by the UN General Assembly. Even so, the inability to enact legal recourse internationally suggests that large scale groundwater basins are potentially threatened by over-extraction driven by the lack of international property rights.

It is worth noting that there are many issues that are taken up through water treaties (Giordano, 2014), such as variability in supply, water quality concerns, hydro power, local needs and governance and that these issues speak to more than just concerns about depletion of internationally shared basins. Therefore, even if groundwater treaties are ineffective in reducing depletion, they may be successful by other metrics.

2 Model and Econometrics

A large innovation in the information of global water is the GRACE-Tellus project, which utilizes satellites to measure large scale changes in terrestrial water storage through gravity measurements. We use this data to measure depletion of large scale groundwater basins in this manuscript. The strength of this dataset resides on the independence from farmers or agencies that may have a direct conflict of interest in sharing truthful information, and on the consistency in the way large water storage changes are estimated across the globe. Although GRACE data have been used in physical science studies and is suitable to monitor large scale changes in terrestrial water storage (TWS) with relatively low spatial resolution (Famiglietti et al., 2011; Rodell et al., 2009) it has been underutilized in social science research.

Many studies on global water take a combination of empirical observations and estimates from models to understand changes in TWS. We use data from the Gravity Recovery and Climate Experiment (GRACE) project and data from the Global Land Data Assimilation System (GLDAS) model (Rodell and Beaudoing, 2007) to isolate TWS changes in our study. GLDAS incorporates satellite and observational ground data to produce land surface states and fluxes. Both methods, GRACE and GLDAS, have been used to compare large scale water storage changes (Syed, 2008). Changes in TWS, at the moment, cannot be further broken down explicitly into groundwater and surface water changes although certain components can be accounted for through models like GLDAS, such as changes in snow water equivalent (SWE) and canopy water storage (CWS). Typically, researches interested in the change of terrestrial water storage would start with a water balance equation:

(1) $$\Delta S_{it} = P_{it} - E_{it} - R_{it}$$

where ΔS_{it} represents the change in water storage for location *i* and time *t*. The change to water storage is driven by precipitation, P, evapotranspiration, E, and runoff, R. The water balance approach typically models the components of physical change and makes assumptions about human behavior, as this component is not observed. In contrast to the water balance approach, we use an econometric method to identify the causal changes to TWS. To isolate TWS change, we take annual GRACE estimates of TWS change (Swenson, 2012) and subtract the annual changes of SWE and CWS (output from GLDAS (Rodell and Beaudoing, 2007)) to constitute our dependent variable in the regression. One limitation of our study, and others that use GRACE data, is that we cannot separate out groundwater changes from surface storage changes completely. Therefore, changes in surface storage, like reservoirs, can contribute to changes in TWS which we are not able to isolate. Though we do note that other studies in specific basins have found large changes in basins to be due to groundwater changes (MacDonald et al., 2016) and a study of surface water impoundments show general increases in global and country level storage (Chao et al., 2008), up through 2007.

To test our hypothesis, the econometric approach is more advantageous than a pure modeling approach for multiple reasons: 1) it can control, rather than model, for unobservable factors such as country specific laws or institutions and their influence on TWS, 2) it relies less on important modeling assumptions of human behavior and land-use decisions but rather tests the observed depletion behavior controlling for the physical factors, and 3) components of the uncertainty in GRACE data can be directly used in estimation. The GRACE dataset is known to have large amounts of uncertainty, and some systematic errors that can be accounted for in the regression model.

To identify drivers of TWS change, we start fitting standard regression models that include variables that drive water change (e.g. evapotranspiration, precipitation) and control variables (e.g. latitude, longitude, soil constraints) that are included to validate the comparisons between domestic and international groundwater basins. The control variables serve as a modeling choice to discount the effect of spatial and temporal dependence in the conditional mean of the response variable. We estimate the function $\mathrm{f}(\mathrm{X}_{it})$ which includes the variables of interest and controls, X_{it}, measured at location i and at time t, providing the following basic regression structure:

$$\Delta\mathrm{TWS}_{it} = \mathrm{TWS}_{it} - \mathrm{TWS}_{i(t-1)} = \mathrm{f}(\mathrm{X}_{it}) + \varepsilon_{it}, \tag{2}$$

where ε_{it} is an independent gaussian error term. Our dependent variable, ΔTWS_{it}, is the annual change in terrestrial water storage (cm), defined by the GRACE Tellus dataset, for year t, which is adjusted by subtracting annual changes of SWE and CWS.

The measurement scale of GRACE data (1 arc degree longitude by 1 arc degree latitude) is arbitrarily determined by NASA. We collect all the gridded observations that are above major groundwater systems as seen in Figure 1. The data, ΔTWS and all controls variables, are combined and averaged at a ~330km X 330km spatial resolution (3 arc degree by 3 arc degree), and we call these rasters. This aggregation brings TWS to the spatial resolution that more effectively identifies changes in TWS from the filtered and spatially smoothed data from GRACE post-processing (Swenson and Wahr, 2006; Landerer and Swenson, 2012). Each i^{th} observation, or raster, provides a gravity field measurement which when differenced over time captures the change in TWS over a raster.

Our dataset has the form of a balanced spatial panel that is a cross-section of observations collected at specific geographic locations (in our case, rasters) over several time points (years). Several selections for variables of interest and controls have been considered. The spatial and time component of the model is largely accounted for with control variables, or fixed effects. We present the results with these simpler controls.[2]

GRACE data are known to be attenuated (Swenson and Wahr, 2006). Gain factors, when applied to the GRACE data, return a significant portion of the signal attenuation. These gain factors mostly return the seasonal component of the signal attenuation, and our study focuses on

[2] The spatial models are used to investigate how borders affect depletion within a basin and results are available upon request from the authors.

the long term annual changes in TWS. We therefore exclude the gain factors from our main results, but analyze the significance of using gain factors by performing a robustness analysis.

We address uncertainty in the GRACE data in three distinct ways. First, as stated, we aggregate the data to a ~330km X 330km level to match filtering and smoothing data processing; this reduces the correlation in the errors between rasters. Second, we adjust the standard errors in our analysis to be clustered at the groundwater basin level which accounts for the correlation of rasters within the same basin. Third, we use the estimated errors from GRACE as weights in the regression model. The aspects of uncertainty in GRACE data are referred to as measurement errors and leakage errors (Swenson and Wahr, 2006). They are a result of the uncertainty of measurement across grid points when compared to models and observations of TWS change, such as GLDAS. The gridded uncertainty estimates are used as weights, in equation (3) to estimate the coefficients of interest.

(3) $$Min \sum w_i[\widehat{\varepsilon_{it}}]^2 = \sum w_i[\Delta TWS_{it} - \mathrm{f}(\mathrm{X}_{it})\,]^2$$

The weighting of observations is based on the estimated errors from the GRACE data, $w_i = \frac{1}{\sqrt{ME_i^2 + LE_i^2}}$, where ME_i is the measurement error for raster *i* and LE_i is the leakage error for raster *i*. This weighted regression is the primary model specification used throughout this paper.

3 Data

Using GIS maps produced by international organizations (e.g. Food and Agricultural Organization (FAO), BGR & UNESCO, International Water Management Institute) we define the major groundwater systems used in this study, as seen in Figure 1. The boundaries of major groundwater basins in Figure 1 are defined by maps produced by World-wide Hydrogeological

Mapping and Assessment Programme (WHYMAP) (Richts et al., 2011) and Internationally Shared Aquifer Resources Management (ISARM) (Puri and Aureli, 2009).

The change in annual TWS from GRACE Tellus spans 2002-2015, providing 13 years of annual changes measured at December of each year. Explanatory variables are captured and matched to the geographic location of the GRACE gridded observations. The primary explanatory variables include spatial and temporal controls as well as annual precipitation (mm/yr), mean annual evapotranspiration (mm/yr), soil suitability (%), irrigated acreage (%), water table depth (m), presence of a major river, population density, and a control for international groundwater basin systems. We use irrigated acreage even though this measure of water demand might be potentially determined endogenously by countries; this would be true if countries encouraged (through subsidies or regulations) irrigated agriculture in shared groundwater basins. To alleviate this concern we also substitute irrigated agriculture with soil suitability as a control variable, which is an exogenous measure of the likelihood of agricultural cultivation of the land based on climatic and soil characteristics (Ramankutty et al., 2002).

Precipitation data are gathered by the Global Precipitation Climatology Centre (Schneider et al., 2008). Precipitation has two major effects on the groundwater basin stock. First, it provides recharge to the aquifer and surface storage through rain water or snowmelt. Second, rainfall reduces the demand for water, whether it be drinking water or irrigation water. If there is conjunctive use of surface water and groundwater additional precipitation may decrease the amount of groundwater pumped for consumptive use. The variation of precipitation may have nonlinear effects on groundwater, and we include a square term in the estimates to control for this effect.

Evapotranspiration refers to the quantity of water lost to the atmosphere which is unavailable for consumption or irrigation. Average annual evapotranspiration is estimated as a long term average, using information from 1950-2000, and is measured in millimeters per year (Fekete et al., 2002). The relationship between terrestrial water storage stocks and the natural process of evapotranspiration may be nonlinear, thus we control for this effect with a square term on evapotranspiration.

Irrigated agriculture, compiled by the FAO (Siebert et al., 2005), is the percentage of total equipped irrigated land. This data provides the position and extent of irrigated areas derived through multiple sources that leveraged maps, atlases, and remote sensing information to digitize an estimate of irrigation density in the scale of 5 arc minute cells.

Soil suitability is defined as the percentage area that is suitable to be used for agriculture based on the climatic and soil conditions (Ramankutty et al., 2002). This spatial index estimates the likelihood of cultivation to grow crops based on environmental conditions. In order to grow, crops need an appropriate combination of topology, water, and climate variables. Climate variables used in this index are growing degree days and the difference between precipitation and evapotranspiration. Soil properties used in this index are defined as soil carbon and soil pH, and together with climate variables are used to define the suitability for cultivation.

The water table data (Fan et al., 2013) is collected through a unique study of individual wells across the globe. The depth to the water table is measured in meters and is approximated across areas with sparse data elements when necessary, such as Northern Africa. Water table depth could capture the cost of extraction to bring groundwater to the surface: typically this is interpreted as the marginal cost of extraction in an economic context. However, the water table could also be correlated with elements of demand, as in areas where economic returns tend to be large water would be extracted more heavily and face a lower table.

Major rivers are identified by the Global Runoff Data Centre (GRDC) and include 687 major rivers across the globe (Global Runoff Data Centre (2007)). Major rivers are incorporated into the data by using the count of major rivers within a raster. Controlling for major rivers may account for available surface water as a substitute for groundwater where there are sustained flows.

Population density, the amount of people per square kilometer (NASA Socioeconomic Data and Applications Center, 2002) for the year 2000 is used as a control for municipal water demand.

Soil constraints are included to control for geological conditions that may affect agriculture water demand and the relative demand for water across different land uses. We include two types of soil constraints as controls. First, a combined measure of soil constraints in developed which includes soil depth, soil fertility, soil drainage, slope, soil texture, and chemical composition which is captured as categorical variables as defined by the authors of the source data (Fisher et al. 2002). Second, we control for excess salt as measured by Electric Conductivity (EC in dS/m) which is grouped into categorical variables defined by the authors of the source data (Fisher et al. 2008). Salt accumulation in soils can affect crops, generally through inhibiting their ability to uptake water.

We construct the dataset by aggregating the data for all variables at the 1 arc degree latitude by 1 arc degree longitude scale matched to the GRACE data, assign binary variables for the appropriate variables (e.g. International aquifer, country fixed effects), and spatially average other continuous variables (e.g. precipitation, soil suitability, population density). We then aggregate the data to the raster size used in the analysis (~330km X 330km) in order to deal with uncertainty in the GRACE data. For all binary variables this creates a quasi-continuous measure that is bounded by 0 and 1 and represents the share of the 1 by 1 arc degree data that contain that binary variable (e.g. the percentage of a raster that contains a specific country). The descriptive statistics for our sample are provided in Table 2.

4 International vs. Domestic Groundwater Systems Results

We first test the average annual effect of groundwater basins being international using domestic groundwater basins as controls. Table 3 reports the results of Eq. 3 for all major groundwater systems while controlling for the drivers of TWS change, the recharge characteristics by area, spatial controls of longitude and latitude, fixed effects by country, year, and soil constraints. We express the function, $f(X_{it})$, as the linear combination of the primary variables of interest, $International_i$, $IntAgreements_i$, and other controls of terrestrial water storage change in Eq. 4. $International_i$, is a binary variable equal to 1 if the groundwater basin is shared by more than one countries, and 0 otherwise. The coefficient on $International_i$ in Eq. 4 is the average annual effect on groundwater basin stocks for international groundwater basins. $IntAgreements_i$ is a binary that is equal to 1 if the country and basin of the groundwater system is listed in Table 1 for the years covered in an international agreement.

(4) $$f(X_{it}) = \beta X_{it} + \varphi International_i + \theta IntAgreements_i$$

We report a series of results that vary the control variables to explore our main result. Our preferred estimate is Table 3 column 3 which includes all controls. We find evidence of greater depletion in international basins compared to domestic basins. Table 2 column 4 shows that international groundwater basin systems are subject to an additional 0.614 cm annual decrease in TWS, on average.

International agreements are weakly statistically significant in this regression. In our preferred model the international agreements coefficient has the expected positive sign and is significant at the 10% level. This suggests that these International agreements may be effective at mitigating groundwater depletion at approximately 50% of the depletion realized by the International basins without agreements.

These results suggest that sharing groundwater basin systems with multiple countries causes greater depletion over the period from 2002 to 2015, controlling for physical, spatial, and economic factors. The results presented here are in terms of the change in *TWS* over rasters which are ~330km X 330km. One centimeter change in storage over this size area is significant, approximately 1,107,000,000 m^3.[3] Our estimates from Table 3 approximates to an additional annual loss of 679,698,000 m^3 of water over a raster if it is in an international groundwater basin system. This aggregation highlights the immense size of depletion across shared basins.

4.1 Degree of Sharedness

The degree to which each basin is shared by countries may also play a role in groundwater depletion. Basins which are equally shared would presumably have greater incentives to deplete the basin compared to basins in which one country controls the majority of the basin and another country is a relatively minor player. To investigate this question, we first construct the percentage of the groundwater basin which each country overlays. Then

[3] We also find similar results using a 110km X 110km rasters, these results are available upon request.

calculate the mean absolute deviation from the mean for each basin by country, which is bounded by 0 and 0.5. A value close to zero describes the case where countries in the basin equally share the basin and there is a high degree of sharedness. A value close to 0.5 describes the case where one country overlays a high percentage of the basin and other countries overlay a very small percentage of the basin. At the limit, a domestic aquifer would have a value of 0.5 since they do not share the basin with any other countries. In addition to the degree of sharedness we explore how the number of countries affects depletion as coordination costs may increase with the number of countries in a basin.

Table 4 shows results using the identical specification from Table 3 column 3 with all controls but include measures of sharedness of the basin. We find that the sharedness measure is statistically insignificant, the defining feature is the international designation of the basin rather than how much of the basin is shared by countries. The number of countries is also insignificant, and non-parametric controls for the number of countries suggests that two countries basins are similar to the basins with three or more countries whom share a basin. Regressions with fixed effects for basins with four or more countries have the problem of few basins per fixed effect, therefore we do not pursue this strategy any further. Since we cannot reject that our two country and three country or more coefficients are different from each other or that the level of sharedness is insignificant, we conclude that the international designation is the critical aspect of greater groundwater basin depletion.

5 Borders within International Groundwater Basin Systems Results

We also hypothesize that areas within an international groundwater basin system but not close to a border could experience better coordination and regulation of water extraction leading to greater relative depletion at the borders. Within international basins we compare TWS change in rasters at the border using the counterfactual of rasters not at the border. This approach isolates the effect of international borders on groundwater basin systems while reducing un-observables that would complicate the identification of our variable of interest. We deconstruct the $f(X_{it})$ function below to highlight our variables of interest in Eq. 5.

(5) $$f(X_{it}) = \beta X_{it} + \varphi Border_i + \theta Border_i \cdot Irrigation\ Acreage_i$$

Unlike our previous analysis, here we use a subset of our data to estimate the effect of rasters overlapping an international border and interact this with measures of irrigated agriculture. We use observations only in international basins and apply these data to Eq. 5, effectively comparing rasters that overlay international borders and rasters that are farther away from international borders. *Border*, the primary variable of interest, is defined as the approximate percentage of the raster that intersects with an international border. The GRACE Tellus data, at the 1 degree latitude by 1 degree longitude scale, are assigned binary variables if they intersect an international border. When the data is aggregated to the 3 degree latitude by 3 degree longitude scale *Border* is averaged to produces a measure of the 'sharedness' of the particular raster bounded by 0 and 1. We interact $Border_i$ with the spatial index $Irrigation\ acreage_i$, to capture the heterogeneous effects that agriculture can have on groundwater extraction at the border. Table 5 column 2 shows that greater extraction does occur at the border of international groundwater systems and that this effect is more dramatic when there is a greater density of irrigated acreage. This suggests that inefficiency in water extraction is driven by agricultural demand for groundwater within international aquifers.

We also use soil suitability, rather than irrigated acreage, to control for irrigation water demand as this measure is more likely to be exogenous to water use decisions. Endogeneity can be a problem in estimation because the amount of irrigated acreage may be determined jointly with how water is used in shared groundwater basins. In our research, we can use this aspect of endogeneity to look at underlying causes of greater depletion at the border, which are the extensive margin and intensive margin changes. The depletion caused by agriculture at an international border could be effected by extensive margin choices (eg. land use policies) that encourage additional irrigation or cultivation on marginal lands or intensive margin choices, i.e. using more water on similarly irrigated areas, through quantity restrictions from groundwater management of subsidizing irrigation technologies. If there are extensive margin policies that affect irrigation water demand, we expect estimates using irrigated acreage to be biased upward. In Table 5 column 4 we find that the interaction between *soil suitability* and *border* is smaller than the interaction between *irrigated acreage* and *border* but has the expected negative sign; and is not statistically significant at the 10% level. This suggests that there are two important effects occurring; 1) more water is lost at international borders than is likely economically efficient driven by agricultural demand and, 2) the decrease in TWS at the border is most likely associated with extensive margin changes. By recovering a statistically insignificant coefficient from the interaction with soil suitability we find that areas with similar conditions for agriculture may have similar depletion rates. This suggests that the type of irrigated agriculture is related to the inefficiency of groundwater use in international basins, not just the presence of irrigated agriculture.

6 Monte Carlo Analysis

One limitation in this analysis is the small number of major groundwater basins available to measure differences between basins. The nature of this data require that small aquifers be ignored since the measurement of change is on a scale much larger than small identifiable basins. One may rightfully question the result as a false positive due to the small number of basins tested. Therefore, we run a Monte Carlo analysis by randomizing the treatment of 'International' for each aquifer and run simulations to test the significance of Type I error. This test provides essential information of how likely it is that the significance of our finding is by random chance.

Using the same regression specification as in Table 3 column 3, we produce results of 3,000 simulations with random assignment of 'International' for each aquifer, and require that observations within the same aquifer are assigned the same status. Figure 2 shows the distribution of coefficients from these simulations with the random assignment of 'International'. Our preferred estimate falls outside of the range of this distribution which shows that there is a small probability of a Type I error and that our result is highly significant when comparing to the simulation results. The distribution of randomized assignment is centered on zero, as expected, and none of the estimates from the simulation are larger than the estimate from Table 3 column 3, suggesting a very small p-value for our main estimate. These results are again suggestive of a significant negative effect of International designation of a groundwater basin on terrestrial water storage leading to greater groundwater depletion which is not attributable to random chance.

We also provide a similar analysis to check the significance of depletion at borders within International basins due to irrigated agriculture, established in Table 5. We take the regression specification from Table 5 column 2, but randomize the designation of on 'Border' across the sample. We produce 3,000 simulations to retrieve a distribution of the coefficient from the interaction between $Border_i$ and the spatial index $Irrigation\ acreage_i$. We provide the distribution of this coefficient in Figure 3 which shows that our main estimate is highly significant, only one simulation out of 3,000 produced a coefficient of equal of larger size than our result in Table 5 column 2. This again suggests that the result that observations with greater irrigated acreage is not due to random chance but rather is due to the assignment of closeness to International borders within a basin.

7 Robustness

As robustness checks to the main results in Table 3 and Table 5, we pursue various specifications that apply gain factors, drop the weighting scheme, or use subsets of our data reported in Table 6, Table 7, and Table 8. These robustness checks suggest that our main specification and controls reported are robust to these econometric specifications. The application of gain factors, which returns the attenuated signal that filtering of the data produced, does little to our estimate. We also restrict the data to prior to 2014 because GRACE data lacked an estimate of TWS for December 2014. Therefore, in the main specification we average the observations across November 2014 and January 2015. In Table 7 column 5 and Table 8 column 5 we decrease the sample to only include rasters within 400 miles from a border, calculated at the nearest edge of the raster to an international border within the shared basin. This is meant to improve the comparison of the unobserved differences between border rasters and off border rasters. We find stronger evidence of intensive margin changes within international groundwater basin systems with the restricted sample. This taken with our earlier results suggests that both the internal and external margins may be important to large scale groundwater basin depletion.

8 Conclusions

We offer the first empirical global study of political boundaries and water use inefficiencies, which suggests a new hypothesis: international groundwater basin inefficiencies exist and are likely driven by agricultural water use and ineffective water management. Similar to recent work that combines GRACE data with more localized data (MacDonald et al., 2016), future research should look to micro level evidence to confirm this new hypothesis. The challenges to obtaining micro level data are considerable, requiring detailed groundwater use data across multiple countries, but these will be needed in the future to more fully understand the behavior within internationally shared groundwater basins.

Our study finds evidence that political borders play an important role in the inefficiency of international groundwater basin management. We estimate that approximately 0.6 cm of equivalent water thickness of terrestrial water storage is depleted due to coordination failures and water management inefficiency in international groundwater basins. The size of this inefficiency is large. In unconfined aquifers, the water table would decrease by 24 cm more in International basins than domestic basins over a 10-year period, presuming a specific yield of 0.25. Over-time this could lead to significant cumulative costs in extraction, loss of access to groundwater, or to a host of other societal costs. International agreements appear statistically weak in our results but may mitigate reduction of this depletion to an economically significant degree. We hold reservations about this result due to the statistical weakness and the minimal number of large basins with agreements in place.

We find evidence of greater water depletion close to international borders within international basins, driven by agricultural water demand (e.g. irrigated agriculture). This enforces the conclusion that internationally shared basins suffer greater depletion caused by the political borders and agricultural water demand. There is weaker evidence that the inefficiency found includes intensive margin changes.

The inefficiency in the large scale groundwater commons could be driven by the lack of legal frameworks in international basins. Property rights in domestic basins allow for legal recourse by states or communities. For instance, in the United States, Kansas and Colorado successfully won a case over Nebraska in the Republican River Basin in 2014 that changed the allocation of water use between states and regulated irrigation behavior. Our results suggest the lack of similar legal recourse and property rights at an international level may lead to inefficiency in water use on a large scale.

In this analysis we do not assume that domestic basins are exempt from the tragedy of the commons, only that international basins are subject to a greater relative depletion and furthermore that international basins experience greater depletion of water storage at the border. Agricultural demand for groundwater is important to international groundwater management as it is such a strong source of demand and a driver of inefficiencies in international basins. This result coupled with the lack of international groundwater governance suggests improvements to the sustainable use of international groundwater basins are needed and are sensitive to the types of groundwater use.

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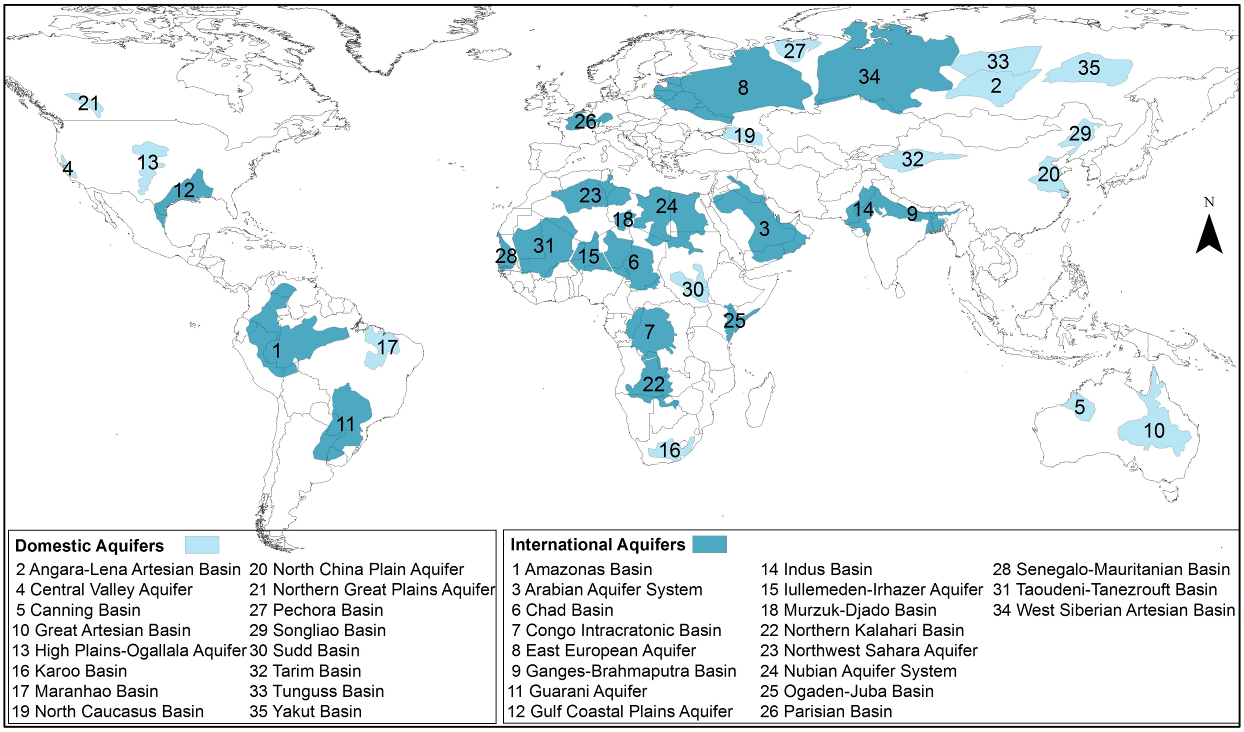

Fig. 1. Major groundwater systems.

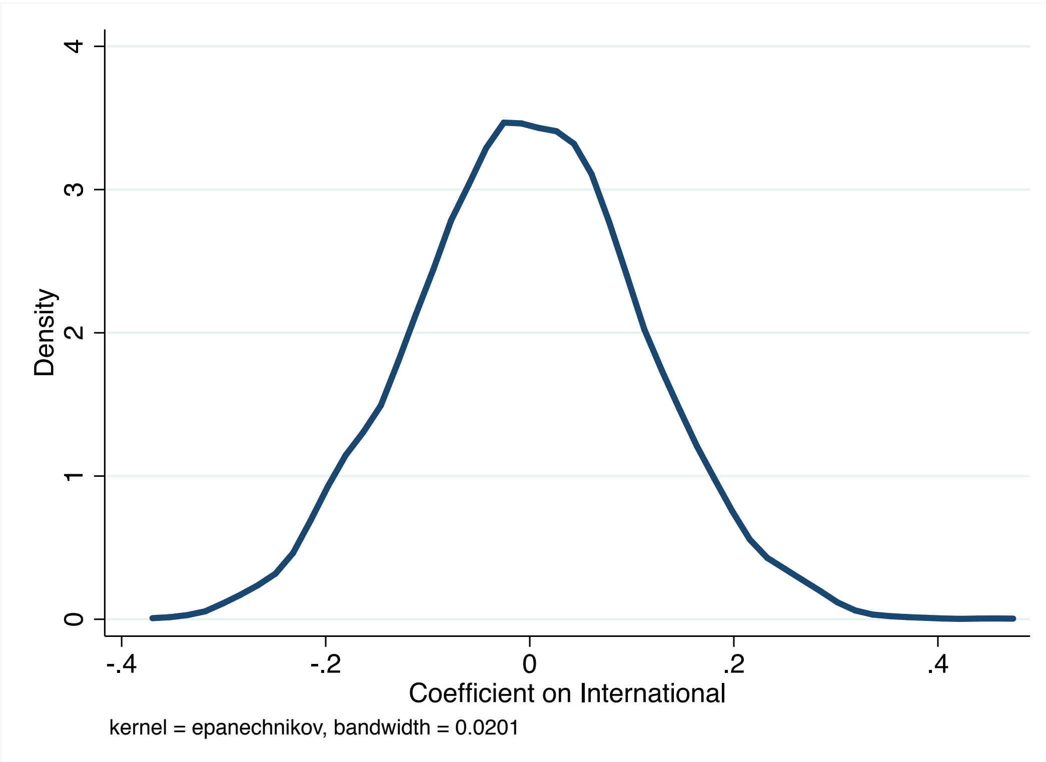

Figure 2. Monte Carlo Simulation Results for International Basins. The simulation results used the WLS regression specification from Table 3 column 3. 3,000 runs of the simulation were run to provide the distribution of coefficients on 'International' designations using randomized assignment for each aquifer.

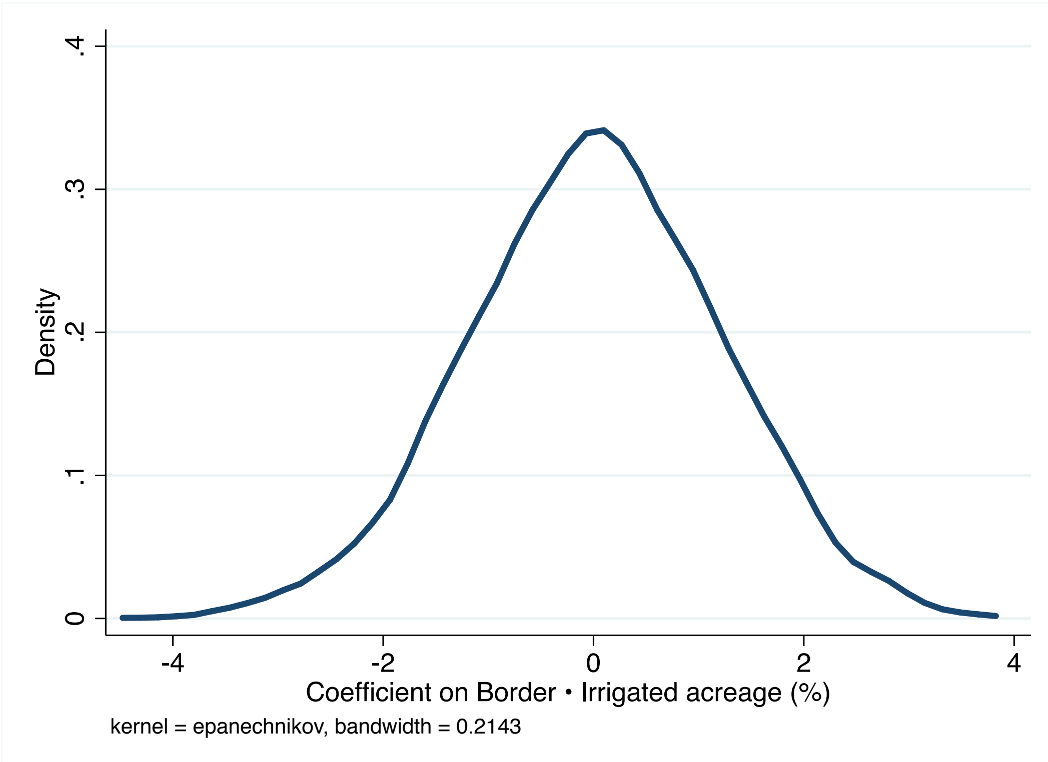

Figure 3. Monte Carlo Simulation Results for Borders. The simulation results used the WLS regression specification from Table 5 column 2. 3,000 runs of the simulation were run to provide the distribution of coefficients on 'Border • Irrigated acreage (%)' using randomized assignment for Border across International basin observations.

	Countries	Treaty/Agreement name	Date
1	Algeria; Benin; Mali; Niger; Nigeria; Burkina Faso; Mauritania	Memorandum of Understanding for the establishment of a Consultation Mechanism for the Integrated Management of the Water Resources of the Iullemeden, Taoudeni/Tanezrouft Aquifer Systems (ITAS).	28-Mar-14
2	Russian Federation; Kazakhstan	Agreement between the Government of the Russian Federation and the Government of the Republic of Kazakhstan on joint management of transboundary waterbodies.	7-Sep-10
3	Argentina, Brazil,Paraguay Uruguay	Guarani Aquifer Agreement	2-Aug-10
4	Paraguay; Brazil	Cooperation agreement between the Government of the Republic of Paraguay and the Government of the Federative Republic of Brazil for the sustainable development and integrated management of the watershed basin of the Río Apa.	11-Sep-06
5	Russian Federation; Belarus	Agreement between the Government of the Russian Federation and the Government of Belarus on cooperation in the sphere of protection and rational use of transboundary waterbodies.	24-May-02
6	Algeria, Libya, Tunisia	Establishment of a Consultation Mechanism for the Northwestern Sahara Aquifer System (SASS)	24-Jun-05
7	Ukraine; Belarus	Agreement between the Cabinet of Ministers of Ukraine and the Government of Belarus on joint management and protection of transboundary waterbodies.	16-Oct-01
8	Sudan; Libya; Egypt; Chad	Agreement 1 between Chad, Egypt, Libya and Sudan concerning the monitoring and exchange of information related to the groundwater of the Nubian Sandstone Aquifer System.	5-Oct-00
9	Sudan; Libya; Egypt; Chad	Agreement No. 2 between Chad, Egypt, Libya and Sudan for Monitoring and Sharing Data for the sustainable development and proper management of the Nubian Sandstone Aquifer System.	5-Oct-00
10	Angola; Botswana; Congo, Dem. Rep. of Congo; Lesotho; Malawi; Mauritius; Mozambique; Namibia; South Africa; Seychelles; Swaziland; Un. Rep. of Tanzania; Zambia; Zimbabwe	Revised Protocol on Shared Watercourse Systems in the Southern African Development Community (SADC).	7-Aug-00
11	Ukraine; Republic of Moldova	Agreement between the Government of Ukraine and the Government of Moldova on joint boundary waters management and protection.	23-Nov-94
12	Ukraine; Russian Federation	Agreement between the Government of Ukraine and the Government of the Russian Federation on joint transboundary waterbodies management and protection.	19-Oct-92
13	Egypt; Libya	Bilateral Cooperation Agreement Minutes between Egypt and Libya on the establishment of the Joint Authority for the Study and Development of Groundwater of the Nubian Sandstone Aquifer System.	8-Jul-91

Table 1. International groundwater agreements. Source: FAO legal database of international agreements (faolex.fao.org) and http://www.internationalwaterlaw.org.

	Domestic Basins		International Basins	
	Mean	Std. Deviation	Mean	Std. Deviation
Δ TWS	0.065	4.552	-0.002	5.340
Precipitation (mm)	1,001.640	849.402	1,336.449	1.454.935
Precipitation squared	1,743,016	3,865,502	3,968,489	8,842,397
Evapotranspiration (mm)	412.520	213.564	424.064	326.408
Evapotranspiration squared	216,723	202,659	288,985.9	340,641.4
Population density (km^2)	53.290	160.422	48.187	150.506
Irrigated acreage (%)	0.049	0.111	0.029	0.106
Water table (m)	4.731	4.547	5.068	5.567
Major river	0.505	0.423	0.455	0.477
International agreement	-	-	0.547	0.497
Year	2009	3.742	2009	3.742
Number of rasters	194		428	

Table 2. Descriptive Statistics.

	Dependent Var: Δ TWS		
	(1)	(2)	(3)
Precipitation (mm)	0.002**	0.003***	0.003***
	(0.001)	(0.001)	(0.001)
Precipitation squared	-1.55e-07**	-2.68e-07***	-2.92e-07***
	(7.41e-08)	(9.57e-08)	(8.92e-08)
Evapotranspiration (mm)	-0.002	-0.003	-0.003**
	(0.001)	(0.002)	(0.001)
Evapotranspiration squared	-1.01e-06	-1.57e-06	-5.46e-07
	(1.27e-06)	(1.46e-06)	(1.36e-06)
Population density (km^2)	-0.001	-0.001**	-0.001
	(0.001)	(0.001)	(0.001)
Irrigated acreage (%)	0.069	-0.150	0.525
	(0.886)	(0.741)	(0.890)
Water table (m)	0.007	0.005	0.016**
	(0.005)	(0.007)	(0.007)
Major river	-0.207	-0.114	-0.110
	(0.167)	(0.118)	(0.109)
International basin	-0.100	-0.464**	-0.614***
	(0.168)	(0.201)	(0.174)
International Agreement	0.002	0.239	0.294*
	(0.140)	(0.166)	(0.165)
Year FE	N	Y	Y
Recharge area FE	N	N	Y
Soil Constraints FE	N	N	Y
Excess Salt FE	N	N	Y
Spatial Controls	N	Y	Y
Observations	8,099	8,099	8,099
R^2	0.011	0.0522	0.0591

Table 3. International aquifers and international agreements. Spatial controls are defined as longitude, latitude, and latitude squared. Recharge areas are designated through Whymap.org as deep and shallow aquifers by low, moderate, and high recharge rates. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively. Standard errors are clustered at the aquifer level to control for correlation of the errors by basin. For brevity we do not report the entire estimation results for the control variables, and instead we indicate with Y or N the inclusion or exclusion of the listed fixed effects.

	Dependent Var: Δ TWS		
	(1)	(2)	(3)
International basin	-0.630**	-0.666***	-
	(0.271)	(0.228)	-
Sharedness	-0.034	-	-
	(0.803)	-	-
# of Countries	-	0.010	-
	-	(0.031)	-
Two Countries	-	-	-0.662***
	-	-	(0.186)
Three or more Countries	-	-	-0.567***
	-	-	(0.200)
Observations	8,099	8,099	8,099
R^2	0.0591	0.0591	0.0591

Table 4. Sharedness of Groundwater Basins. Standard errors are reported below the coefficients in parentheses and are clustered at the aquifer basin level to control for correlation of the errors by basin. The other controls are the same as in Table 3 column 3 and are not reported. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively.

	Dependent Var: Δ TWS			
	(1)	(2)	(3)	(4)
Precipitation (mm)	0.004***	0.004***	0.003***	0.003***
	(0.001)	(0.001)	(0.001)	(0.001)
Precipitation squared	-2.60E-07**	-2.62E-07**	-2.59E-07**	-2.59E-07**
	(9.21E-08)	(9.22E-08)	(9.23E-08)	(9.24E-08)
Evapotranspiration (mm)	-0.004**	-0.005**	-0.004**	-0.004**
	(0.002)	(0.002)	(0.002)	(0.002)
Evapotranspiration squared	7.54E-07	7.27E-07	8.63E-07	8.68E-07
	(1.42E-06)	(1.41E-06)	(1.38E-06)	(1.39E-06)
Population density (km^2)	0.001	-0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Irrigated acreage (%)	-0.768	-0.246	-	-
	(1.123)	(1.305)	-	-
Soil suitability (%)	-	-	-0.533	-0.420
	-	-	(0.525)	(0.524)
Water table (m)	0.020**	0.021**	0.019**	0.020**
	(0.008)	(0.008)	(0.008)	(0.008)
Major river	-0.191*	-0.187*	-0.178	-0.170
	(0.109)	(0.108)	(0.110)	(0.106)
Border	-0.041	0.017	-0.021	0.052
	(0.063)	(0.053)	(0.064)	(0.065)
Border • Irrigated acreage (%)	-	-3.953***	-	-
	-	(1.019)	-	-
Border • Soil suitability	-	-	-	-0.517
	-	-	-	(0.458)
Basin FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Country FE	Y	Y	Y	Y
Recharge area FE	Y	Y	Y	Y
Soil Constraints FE	Y	Y	Y	Y
Excess Salt FE	Y	Y	Y	Y
Spatial Controls	Y	Y	Y	Y
Observations	5,551	5,551	5,551	5,551
R^2	0.0681	0.0683	0.0682	0.0682

Table 5. International borders and agricultural water demand. Basins are defined as in Figure 1 that correspond to major groundwater systems. Spatial controls are longitude, latitude, and latitude squared. Recharge areas are designated through Whymap.org as deep and shallow aquifers by low, moderate, and high recharge rates. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively. Standard errors are reported below the Coefficients

in parentheses and are clustered at the aquifer basin level to control for correlation of the errors by basin. For brevity we do not report the entire estimation results for the control variables, and instead we indicate with Y or N the inclusion or exclusion of the listed fixed effects.

	Dependent Var: Δ TWS			
	(1) Main Specification	(2) Gain factors applied	(3) Without weighting by errors	(4) Prior to 2014
International basin	-0.614***	-0.480***	-0.727***	-0.685***
	(0.174)	(0.156)	(0.220)	(0.190)
Observations	8,099	8,099	8,099	6,853
R^2	0.0591	0.0497	0.0737	0.0688

Table 6. International borders robustness results. Standard error are reported below the coefficients in parentheses and are clustered at the aquifer basin level to control for correlation of the errors by basin. The other controls are the same as in Table 3 column 3 and are not reported. Column 1 repeats the main results from Table 3. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively.

	Dependent Var: Δ TWS				
	(1) Main Specification	(2) Gain factors applied	(3) Without weighting by errors	(4) Prior to 2014	(5) Trimmed within 400 miles of border
Border	0.052	0.026	0.171	0.065	0.054
	(0.065)	(0.076)	(0.139)	(0.112)	(0.064)
Border • Soil suitability	-0.517	-0.635	-1.062*	-0.584	-0.652*
	(0.458)	(0.526)	(0.592)	(0.511)	(0.357)
Observations	5,551	5,551	5,551	4,697	4,017
R^2	0.0682	0.0521	0.0956	0.0632	0.1428

Table 7. International borders and soil suitability robustness results. Standard errors are reported below the coefficients in parentheses and are clustered at the aquifer basin level to control for correlation of the errors by basin. The other controls are the same as in Table 5 column 4 and are not reported. Column 1 repeats the main results from Table 5. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively.

	Dependent Var: Δ TWS				
	(1) Main Specification	(2) Gain factors applied	(3) Without weighting by errors	(4) Prior to 2014	(5) Trimmed within 400 miles of border
Border	0.016	-0.009	0.015	0.012	0.015
	(0.052)	(0.059)	(0.098)	(0.087)	(0.054)
Border • Irrigated acreage (%)	-3.953***	-4.255**	-3.629***	-3.616***	-3.328***
	(1.019)	(1.499)	(0.871)	(0.792)	(1.277)
Observations	5,551	5,551	5,551	4,697	4,017
R^2	0.0683	0.0522	0.0957	0.0632	0.1418

Table 8. International borders and irrigated agriculture robustness results. Standard errors are reported below the coefficients in parentheses and are clustered at the aquifer basin level to control for correlation of the errors by basin. The other controls are the same as in Table 5 column 2 and are not reported. Column 1 repeats the main results from Table 5. Asterisks (***,**,*) denote variables significant at 1%, 5%, and 10% respectively.