Groundwater Depletion and Institutions: Exploring the Colonial Origin

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Abstract:

Groundwater depletion has become a critical challenge for many countries, and its underlying drivers extend far beyond climate pressures alone. This study examines how the institutional structures established during the colonial period continue to impact modern groundwater outcomes. Using a large dataset covering 64 countries from 2003 to 2019, we examine the role of institutional quality—measured through the Property Rights Index and the Democracy Index—in shaping groundwater levels. To address potential endogeneity in institutional measures, we employ a two-stage least squares (2SLS) framework, using colonial legacy variables as historical instruments. Our results reveal a strong and nonlinear relationship between institutional quality and groundwater levels: improvements in property rights and democratic accountability are associated with better groundwater outcomes up to a certain point, beyond which diminishing effects become apparent. Climate variables such as average temperature and precipitation play a role, but are far less influential than institutional characteristics. Overall, the study demonstrates that the groundwater crisis is not only an environmental or climatic issue, but also a long-standing institutional one, deeply rooted in colonial history.

Keywords: Groundwater Depletion, Institutions, Colonization

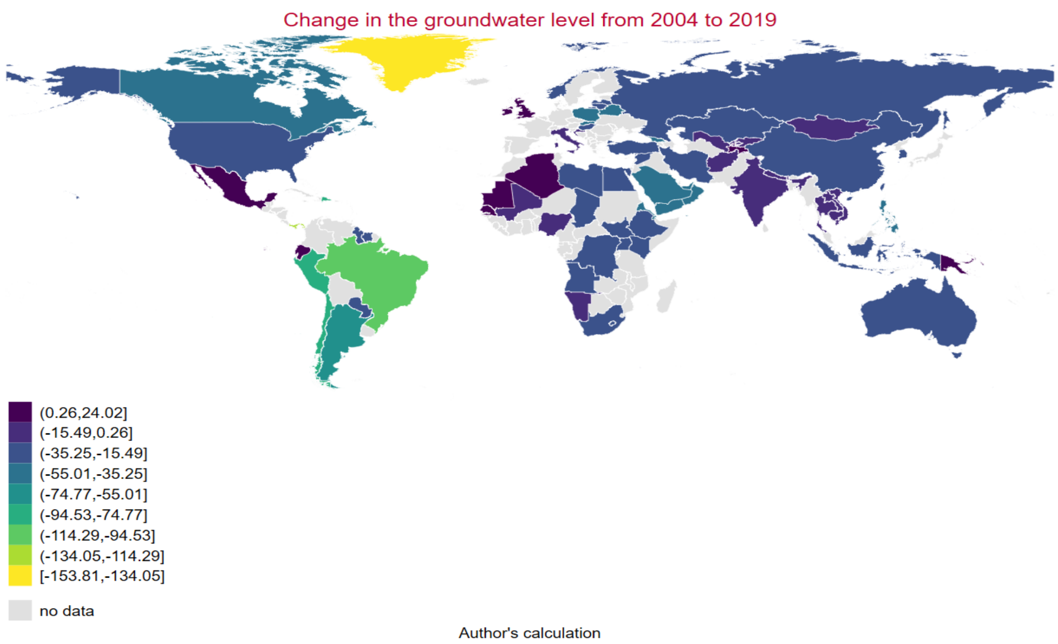
JEL Classification: K00, K11, N50, Q25, Q50

1. Introduction:

Groundwater depletion has become a major global concern, affecting drinking water, food production, and long-term environmental sustainability (Wada et al., 2010). Although climate change and agricultural pumping are widely recognized as important drivers, researchers increasingly show that institutions—the rules that govern how resources are used—play a crucial role in determining groundwater outcomes (Edella & Ostrom, 1992; Ostrom, 1990). Institutions determine who can extract water, how much can be extracted, and whether regulations are monitored and enforced, which directly influences the level of groundwater stress (Meinzen-Dick, 2007).

These institutional dynamics become more critical when viewed in conjunction with the geographical patterns of groundwater stress. Figure 1 illustrates the global groundwater depletion map, which shows that South Asia, South America, and parts of Africa exhibit higher groundwater depletion. These are the areas where monitoring and regulatory capacity are often limited, allowing extraction to exceed natural recharge (Wada et al., 2010; Rodell et al., 2018). This stark spatial variation highlights that similar climatic pressures can produce very different outcomes depending on governance strength, motivating a closer examination of how institutional quality shapes groundwater sustainability (Ostrom, 1990; Meinzen-Dick, 2007)

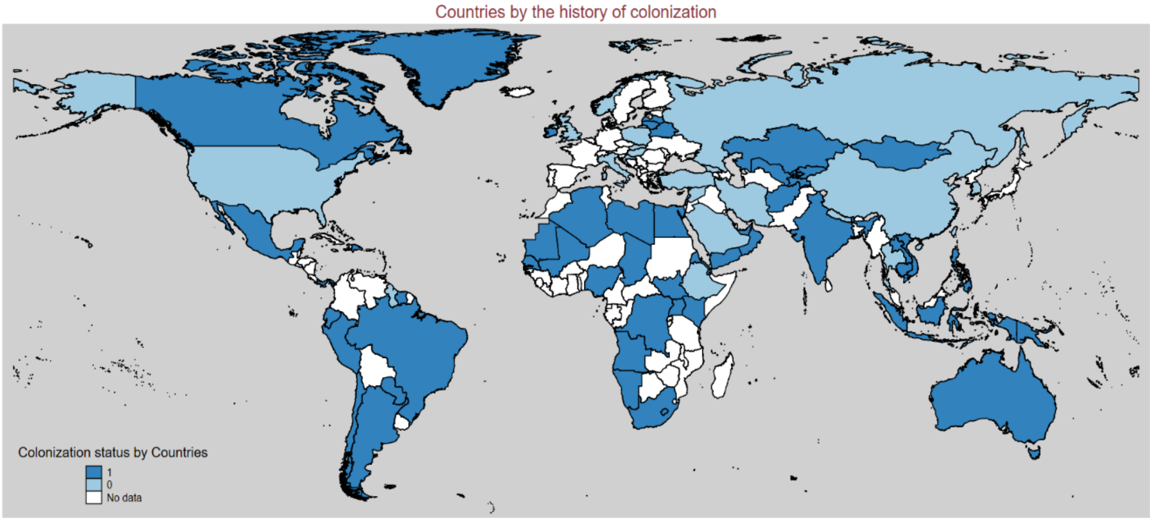
Figure 1: Change in groundwater levels from 2004 to 2019



Source: Author's calculation from GLDAS dataset

A key insight from historical and political economy research is that many of today's institutional structures in Asia, Africa, and Latin America were shaped during the colonial period, when European powers created new administrative and legal systems to manage territories and extract resources(Acemoglu, Johnson, & Robinson, 2001) . Figure 2 shows the countries in our dataset that were colonized. These systems often replaced or weakened local governance arrangements, creating long-lasting institutional paths that persisted after independence (Banerjee & Iyer, 2005; Iyer, 2010). As a result, countries inherited different types of land rules, bureaucratic structures, and political arrangements, which can influence how groundwater is governed today (Dell, 2010).

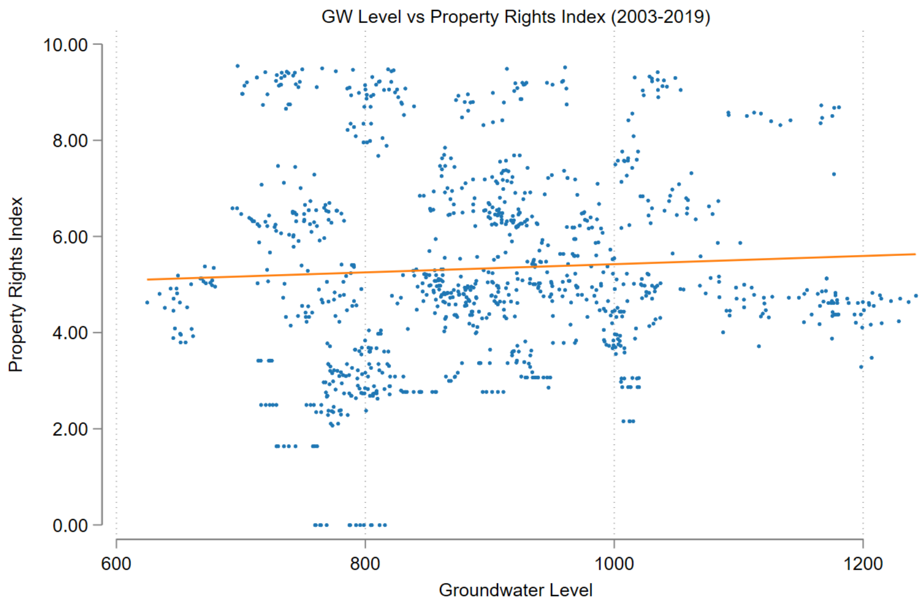
Figure 2 : Countries by the history of Colonization



Source: Various Historical Documents

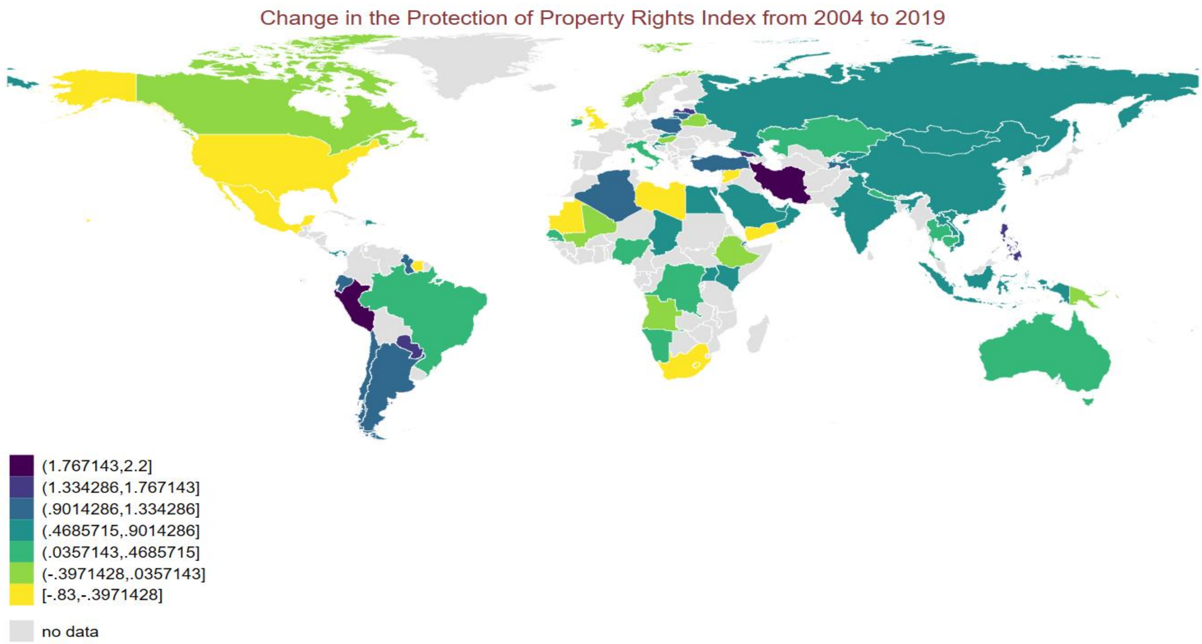
To study these institutional pathways, this paper focuses on two widely used measures of institutional quality. First, we use the Property Rights Index, which reflects how secure individuals are from expropriation and how well ownership is protected—factors that shape long-term investment and resource management(Acemoglu & Johnson, 2003). Graph 1 shows a positive relationship between groundwater levels and the property rights index. To illustrate how institutional quality has evolved over time in the countries included in our analysis, we examine trends in the Property Rights Index over the study period. Figure 2 below illustrates the changes in property rights scores between 2019 and 2004, highlighting both cross-country variation and long-term institutional shifts relevant to groundwater governance. Negative values highlight the drop in the scores from 2004.

Graph 1: Association between Groundwater levels and Property rights Index



Source: Author's Calculation

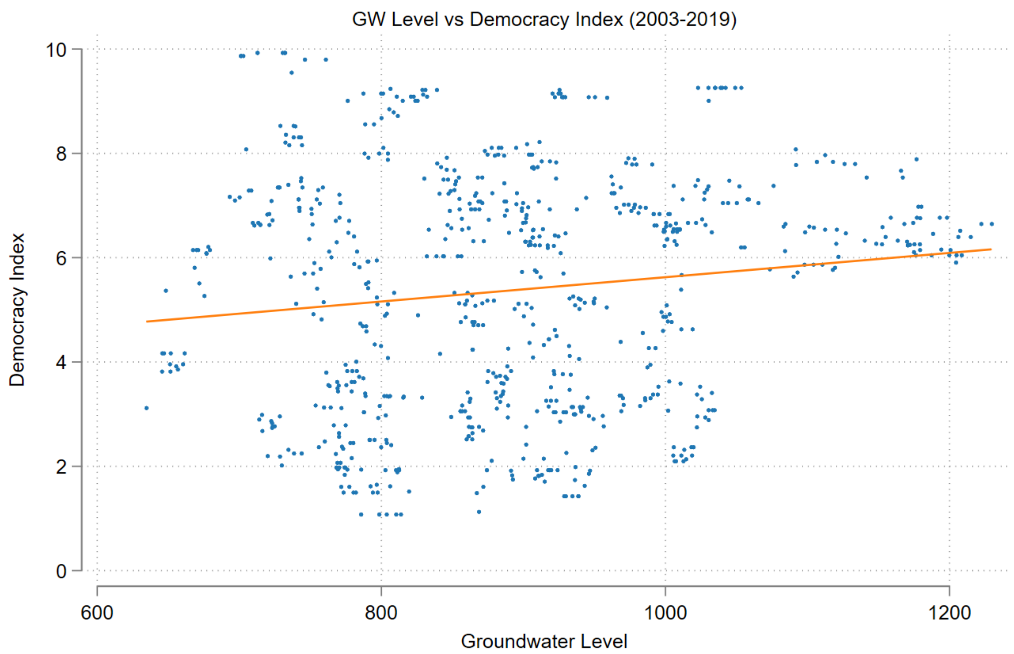
Figure 3: Change in Property Rights Index



Source: Author's calculation from the Economic Freedom Index, 2004 and 2019

Second, we use the Democracy Index, which captures the level of political participation, accountability, and government responsiveness—features that influence public regulation and environmental policy (Baum & Lake, 2003; Persson & Tabellini, 2001). We check the association between the democracy index and groundwater level in Graph 2.

Graph 2: Association between Groundwater levels and Democracy Index

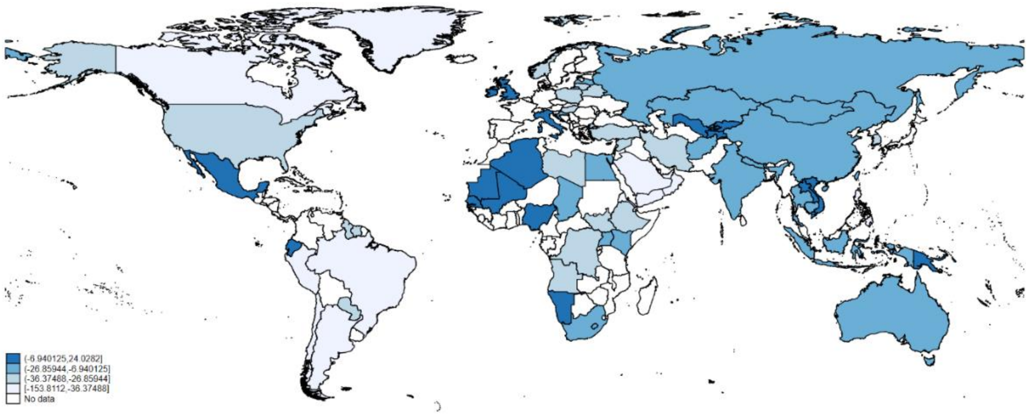


Source: Author's calculation

The graph illustrates a positive association between the democracy index and groundwater levels, underscoring the need for further investigation. To situate this measure within our period of analysis, we next examine how the Democracy Index has changed over time. The following figure presents the evolution of democratic institutions from 2004 to 2019, offering a visual baseline for subsequent discussion. The negative values for various countries in Figure 3 indicate a decline in the democracy index values from 2004 to 2019.

Using both indicators allows us to examine how economic and political institutions jointly affect groundwater governance. The main idea of this paper is that colonization influenced present-day groundwater outcomes through these institutional channels. In places where colonial rule established extractive institutions—characterized by weak property rights, centralized authority, and limited political representation—governments often struggle to manage common resources, including groundwater (Acemoglu, Robinson, & Verdier, 2017; Baland & Platteau, 1997).

Figure 4: Change in democracy index from 2004 to 2019



Source: Author’s calculation from Democracy Index values for 2003 and 2019

Thus, understanding today's groundwater crisis requires examining how colonial powers shaped the institutional foundations.

Importantly, colonization did not occur randomly. European powers were more likely to colonize regions that were easier to reach by sea or land, indicating that geographical factors, such as nautical distance and inland accessibility, played a significant role(Feyrer & Sacerdote, 2006; Sachs, 1998). Because these geographic factors long predate modern economic systems, they provide exogenous variation that we can use to identify the causal effect of institutions.

Building on this insight, this paper examines how colonial exposure, as measured by navigation distance and land distance, shaped property rights and political institutions, and how these institutions, in turn, affect groundwater levels. By connecting historical influences, institutional quality, and environmental outcomes within a single empirical framework, this paper argues that today’s groundwater crisis is not only a result of climate change or technological advancements, but also the product of institutional paths set in motion during the colonial era.

2. Literature Review:

Groundwater depletion has become one of the most pressing environmental challenges worldwide, with studies documenting rapid declines across Asia, Africa, the Middle East, and even parts of North America (Famiglietti, 2014). Research indicates that rising water demand, population pressure, and agricultural expansion have intensified groundwater extraction, often exceeding natural recharge rates (Jasechko et al., 2024; Richey et al., 2015). While climate change—through altered rainfall, rising temperatures, and changing recharge cycles—contributes to groundwater stress, hydrological studies increasingly emphasize the role of warming and precipitation variability in degrading groundwater availability (Taylor et al., 2013). However, scholars argue that climatic factors alone cannot fully explain the severity or cross-country variation in groundwater depletion, noting that similar climate conditions often produce widely divergent groundwater outcomes (Shah, 2010; Mukherji & Shah, 2005). Instead, a growing body of work suggests that institutional quality fundamentally shapes how societies respond to hydrological risk and determines whether resources such as groundwater are managed sustainably, highlighting the importance of governance, regulation, and state capacity in mediating groundwater extraction behavior (Meinzen-Dick, 2007; Ostrom, 1990).

Institutions play a crucial role in governing environmental resources, as they establish the formal and informal rules that shape how societies manage shared assets (North,1990). According to standard institutional theory, well-defined property rights, predictable legal systems, and accountable governments help align individual incentives with long-term sustainability by reducing uncertainty and discouraging opportunistic behavior (Ostrom, 1990).For common-pool resources such as groundwater, strong institutional arrangements ensure that extraction is monitored, rights to access are clearly regulated, and users face meaningful consequences for overuse—mechanisms that Ostrom (1990) identifies as essential for avoiding the "tragedy of the commons." Numerous empirical studies further show that countries with higher institutional quality—captured through indicators such as rule of law, government effectiveness, and political accountability—tend to achieve better environmental outcomes, including lower pollution levels, improved forest protection, and more effective natural resource regulation (Bhattarai & Hammig, 2001; Fredriksson & Svensson, 2003). Conversely, weak institutions often create de facto open-access conditions in which groundwater is vulnerable to rapid, uncoordinated extraction, as regulatory agencies lack the capacity or authority to enforce sustainable limits (Ostrom, 1990; Meinzen-Dick, 2007)

Within the broader institutional literature, property rights institutions receive particular attention because they shape incentives for long-term investment, cooperation, and sustainability (Besley & Ghatak, 2010; North, 1990). Secure property rights reduce uncertainty, limit opportunistic behavior, and encourage users to adopt practices that protect shared resources over time (Demsetz, 1967; Libecap, 1989). These mechanisms translate directly into groundwater governance: when access rights to water are vague, unenforced, or easily captured by politically powerful groups, extraction often becomes excessive and inefficient, creating classic common-pool resource problems (Ostrom, 1990; Meinzen-Dick, 2007).

Democratic institutions—characterized by accountability, transparency, and avenues for public participation—also play an important role in shaping environmental outcomes (Fredriksson & Neumayer, 2013; Li & Reuveny, 2006).Democracies tend to exhibit stronger regulatory enforcement, greater responsiveness to ecological concerns, and lower tolerance for corruption in natural resource management (Pellegrini,& Gerlagh,2006; Bättig,& Bernauer,2009). Evidence from cross-country studies shows that higher democratic quality is often associated with improved water management, more stringent environmental laws, and better monitoring of resource extraction (Esty & Porter, 2005; Farzin & Bond, 2006).

However, contemporary institutional structures do not arise in a vacuum. A large and influential body of research shows that colonialism played a decisive role in shaping institutions across the developing world. Seminal studies by Acemoglu, Johnson, and Robinson (2001, 2002) argue that colonial powers imposed institutional systems based on their settlement strategies. Extractive institutions emerged in regions where colonizers faced high mortality rates and low settlement incentives, whereas settler colonies developed institutions that protected property rights and limited the power of the elite(Acemoglu & Johnson, 2003). Other scholars emphasize colonial legal origins, administrative structures, and land tenure systems that persist long after independence (Banerjee & Iyer, 2005; La Porta, Lopez-De-Silanes, & Shleifer, 2008). These colonial institutional legacies influence economic development, governance quality, inequality, and legal enforcement even today.

Environmental resource governance has also been shaped by these historical legacies, as a growing body of work links colonial institutional structures to long-term governance capacity in post-colonial states (Acemoglu et al.2001). Colonial authorities frequently prioritized the extraction of minerals, forests, agricultural output, and taxation over ecological sustainability, shaping resource management practices around revenue generation rather than conservation (Humphreys & Bates, 2005). Water infrastructure systems in many colonies, including canals, wells, and irrigation networks, were designed to serve colonial administrative centers or plantation agriculture rather than sustainable hydrological management, leaving a legacy of uneven water distribution and institutional neglect (Gilmartin, 1994). In addition, colonial land policies often disrupted traditional systems of common resource management, weakening long-established community-level norms that might otherwise have prevented overuse and supported sustainable groundwater extraction (Banerjee & Iyer, 2005). Scholars increasingly document how these inherited institutions continue to limit environmental regulation capacity and distort natural resource governance in post-colonial states, including groundwater governance, where institutional weakness remains a major contributor to resource depletion (Sikor & Lund, 2009).

Despite these insights, very little research directly links colonial institutional origins to contemporary groundwater outcomes. While some studies explore the colonial foundations of land governance or forest management, groundwater—a uniquely invisible and poorly regulated resource—has received limited attention. This gap persists despite groundwater extraction occurring under conditions where institutional quality is particularly crucial: monitoring is challenging, property rights are unclear, and political incentives often favor short-term extraction. Moreover, the interaction of colonial legacies with modern political systems—such as democracy and the strength of property rights—remains underexplored in the context of groundwater. Given this substantial gap in the literature, the present study empirically investigates how colonial institutional legacies continue to shape contemporary groundwater outcomes through their influence on modern political and property-rights institutions. To achieve this, we compile a comprehensive cross-country dataset that combines information on historical colonial characteristics, measures of institutional quality, and detailed groundwater indicators. This integrated dataset enables us to examine how long-term historical forces intersect with contemporary governance structures to impact groundwater sustainability.

The remainder of the paper is organized as follows. Section 3 introduces the data, outlining the sources, measurement strategies, and descriptive patterns of both institutional and groundwater variables. Section 4 presents the OLS estimation and results. Section 5 presents an empirical strategy, including the instrumental-variables framework used to address endogeneity in institutional measures, along with the main results. These results examine both linear and nonlinear effects of democratic quality and property rights on groundwater levels, and evaluate the role of colonial origins as instruments. Section 6 discusses the findings in light of the broader literature on institutional development and environmental governance. Finally, Section 7 concludes by highlighting the implications for policy, historical legacies, and groundwater sustainability.

3. Data:

Our analysis draws on groundwater level observations collected at precise geographic coordinates across 64 countries from 2003 to 2019. The primary hydrological data source is the Global Land Data Assimilation System (GLDAS), a global land-surface modelling framework that combines satellite observations and advanced data assimilation techniques(Cooley & Landerer, 2020). We employ GLDAS-2.2 outputs, which provide spatially explicit estimates of Total Water Storage (TWS) and its components. Groundwater storage (GWS) is calculated following the standard hydrological mass balance convention as TWS minus root-zone soil moisture (to 1 meter), snow water equivalent, and canopy interception (Cooley & Landerer, 2020). This approach yields a globally harmonized measure of groundwater availability that is appropriate for cross-country temporal analysis. The gridded GLDAS rasters are extracted at 0.25-degree spatial resolution, and country-level averages are constructed using spatial overlays and annual aggregation.

To measure institutional quality, we rely on two indicators. The first is the Protection of Property Rights Index from the Fraser Institute's Economic Freedom of the World dataset, scored from 0 (weakest) to 10 (strongest) for each country-year(Economic freedom Index, 2017; Gwartney et al., 2023). This index measures the legal enforcement of property rights, judicial independence, and the risk of expropriation. The second indicator is the Democracy Index from the Economist Intelligence Unit (EIU), which evaluates electoral process, civil liberties, political participation, and functioning of government on a 0–10 scale(Hoey, 2025). The EIU Index covers 165 independent countries, and we extract yearly scores for 2003–2019 to match the groundwater dataset. These two measures provide complementary perspectives on institutional conditions: the rule of law and legal enforcement on one hand, and democratic governance and political accountability on the other.

Incorporating environmental and geographical controls, we use precipitation and temperature data from NASA's GIOVANNI Earth Data system. Daily rainfall estimates are aggregated into annual rainfall rates to capture hydrological input across countries. The annual mean air temperature (in Kelvin) is used as a standardized physical measure, which is especially important given the climatic diversity of the countries included in the sample (Cooley & Landerer, 2020). Additionally, we utilize aquifer type and geological structure information from the International Groundwater Resources Assessment Centre (IGRAC). These aquifer classifications distinguish between unconsolidated sedimentary formations, alluvial aquifers, hard-rock systems, and other geological environments that influence groundwater storage capacity and recharge potential(Margat & Gun, 2019; Puri & Aureli, 2009). To account for broad climatic conditions, we add climate zone indicators derived from the updated Köppen–Geiger climate classification system. These six major zones—tropical, dry, subtropical, continental, polar, and highland—capture long-term patterns in rainfall seasonality, evapotranspiration, temperature variation, and ecological characteristics that jointly influence groundwater dynamics(Peel, Finlayson, & McMahon, 2007).

A substantial portion of our data preparation involves spatial harmonization, merging, and deduplication. All spatial layers, including GLDAS rasters, climate variables, aquifer maps, and country boundaries, are projected into a common coordinate reference system. Using the World Bank's Global Administrative Unit boundary shapefile, we perform spatial joins to match each GLDAS grid cell to its corresponding national polygon. Where multiple grid cells fall within a country, we compute spatial averages to avoid overweighting larger or more data-rich countries. To ensure internal consistency across variables, we standardize country names and ISO codes before merging the institutional datasets, environmental variables, and hydrological indicators. Duplicate geographic coordinates are identified and collapsed within each country-year to avoid redundancy. The resulting panel dataset contains unique observations of groundwater, climate, institutions, and geography for every country-year between 2003 and 2019.

To construct our instrumental variable for institutional quality, we incorporate detailed historical data on colonial origins. Colonial history has been widely utilized in political economy as a source of exogenous variation in institutional development, motivated by the idea that colonial powers established legal and administrative systems that shaped long-run institutional trajectories independently of contemporary economic outcomes (Acemoglu et al., 2001).We build this component using the Correlates of War Colonial/Dependency Relationship dataset , the Historical Dataset (Coppedge et al., 2023), and established classifications used in prior empirical work (Nunn, 2008). For each country, we identify whether it experienced colonial rule, the colonizing power (e.g., British, French, Spanish, Portuguese, Dutch), and the year of independence. Because these colonial legacies were externally imposed and largely orthogonal to present-day groundwater patterns, they provide credible instrumental variation for the Protection of Property Rights Index and the Democracy Index. Colonial attributes are merged with the rest of the dataset using standardized ISO codes from the World Bank's shapefile. In cases where historical boundaries differ from modern borders, we assign a colonial identity based on the dominant predecessor state, following established practice (Nunn, 2008). The final dataset, therefore, contains a comprehensive profile for each country, combining contemporary hydrological, institutional, climatic, geological, and historical variables suitable for instrumental variable estimation.

4. Institutions and Groundwater Level: OLS Estimates

We are interested in investigating the impact of institutions on groundwater levels across countries. Considering the presence of non-linearities, the relationship we are interested in investigating can be written as

$$Y_{ict} = \alpha + \beta I_{ct} + \gamma I_{ct}^2 + \theta_o Z_{ct} + \epsilon_{ct} \quad (1)$$

Here Y_{ict} is the groundwater level at point i in country c at time t. I_{ct} measures the property rights index and the democracy index, respectively. We account for observed non-linearities by incorporating a squared term for democracy and the property rights index. Z_{ct} is the set of other controls and θ_o captures the effect of the control variable.

Tables 1 and 2 report the ordinary least squares (OLS) regressions of groundwater levels on the protection of property rights index and democracy rights, respectively. Section A of both tables presents the results for the entire world sample. Section B displays the results for countries in the Asian continent, and Section C describes the results for the African continent. We calculate results for the three models using the three distinct samples. The analysis employs a hierarchical modeling approach. Model 1 computes the unconditional correlation (Column 1). Model 2 introduces year and time fixed effects (Column 2), and the final specification, Model 3, incorporates both control variables and fixed effects (Column 3).

Column (1) of Table 1A shows that, for the global sample, a positive and statistically significant association exists between Property Rights Protection and groundwater levels, indicating that countries with stronger institutional protection over property tend to have higher groundwater levels. The estimated coefficient of 75.25 suggests that a one-unit increase in the Property Rights Index is associated with a 75-unit rise in groundwater level, although this effect is not significant once controls are added. Column (2), which includes country and year fixed effects, shows that this relationship strengthens substantially—the coefficient rises to 264.73 and becomes highly significant at the 1% level—suggesting that within-country improvements in property rights are strongly correlated with greater groundwater levels over time.

Table 1.A Effect of Property Rights Index on Groundwater

	(1) No controls / No FE	(2) FE only (Y+C)	(3) Controls + FE (Y+C)
Property Rights Protection	75.248	264.727***	70.723**
	(60.066)	(14.092)	(28.119)
Property Rights Protection²	-5.888	-21.575***	-5.683**
	(5.512)	(2.376)	(2.427)
Average Precipitation			-299.188**
			(116.154)
Average Temperature			2.275***
			(0.331)
Observations	4.04e+05	4.04e+05	4.04e+05
R-squared	0.002	0.792	0.792

Standard errors in parentheses. SEs clustered by country. Fixed effects (where indicated): year and country
Significance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$

However, the inclusion of the squared term (–21.57***) indicates a non-linear (inverted-U) pattern, where beyond a threshold, stronger property rights lead to more regulated and sustainable groundwater extraction. Column (3), which includes both climatic controls and fixed effects, shows that the magnitude of the coefficient falls to 70.72, with a negative squared term of –5.68, still significant, implying that while early improvements in property rights increase extraction, mature property-right regimes likely reduce unsustainable water use through better enforcement and regulation (Acemoglu & Johnson, 2005; Ostrom, 1990).

Table 1.B The Effect of Property Rights Index on Groundwater In Asia

	(1) No controls / No FE	(2) FE only (Y+C)	(3) Controls + FE (Y+C)
Property Rights Protection	22.677	366.692***	115.151*
	(61.918)	(17.847)	(64.675)
Property Rights Protection²	2.428	-34.340***	-10.979*
	(7.294)	(3.002)	(6.143)
Average Precipitation			205.569
			(466.959)
Average Temperature			2.301***
			(0.589)
Observations	4.21e+05	4.21e+05	4.21e+05
R-squared	0.007	0.684	0.684

Standard errors in parentheses. SEs clustered by country. Fixed effects (where indicated): year and countrySignificance: * p<0.10, ** p<0.05, *** p<0.01

Table 1.C : The Effect of Property Rights Index on Groundwater in Africa

	(1) No controls / No FE	(2) FE only	(3) Controls + FE (Y+C)
Property Rights Protection	116.731***	309.100***	128.531***
	(29.281)	(19.405)	(38.426)
Property Rights Protection²	-9.218***	-23.430***	-9.587***
	(2.730)	(3.285)	(3.029)
Average Precipitation			157.887
			(228.546)
Average Temperature			1.952***
			(0.429)
Observations	1.46e+06	1.46e+06	1.46e+06
R-squared	0.007	0.775	0.775

Table 2.A Global Effect Democracy Index on Groundwater Level

	(1) No controls / No FE	(2) FE only (Y+C)	(3) Controls + FE (Y+C)
Democracy Index	81.385**	403.713***	65.982***
	(31.705)	(35.019)	(23.288)
Democracy Index²	-6.510**	-40.923***	-6.585**
	(3.149)	(4.988)	(2.525)
Average Precipitation			145.122
			(238.009)
Average Temperature			2.818***
			(0.195)
Observations	1.49e+06	1.49e+06	1.49e+06
R-squared	0.007	0.773	0.774

Standard errors in parentheses SEs clustered by country. Fixed effects (where indicated): year and country.
Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.B Effect Democracy Index on Groundwater level in Asia

	(1) No controls / No FE	(2) FE only (Y+C)	(3) Controls + FE (Y+C)
Democracy Index	95.612**	280.580***	36.634***
	(38.673)	(41.510)	(11.260)
Democracy Index²	-9.635**	-27.683***	-3.558***
	(3.824)	(5.804)	(1.175)
Average Precipitation			-316.515**
			(119.694)
Average Temperature			2.685***
			(0.146)
Observations	4.27e+05	4.27e+05	4.27e+05
R-squared	0.004	0.789	0.790

Standard errors in parentheses SEs clustered by country. Fixed effects (where indicated): year and country.
Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.C Effect Democracy Index on Groundwater Level in Africa

	(1) No controls / No FE	(2) FE only (Y+C)	(3) Controls + FE (Y+C)
Democracy Index	-5.157	455.456***	39.037*
	(41.328)	(55.243)	(18.733)
Democracy Index²	3.000	-53.378***	-4.235*
	(4.310)	(13.112)	(2.160)
Average Precipitation			214.836
			(465.022)
Average Temperature			3.032***
			(0.156)
Observations	4.22e+05	4.22e+05	4.22e+05
R-squared	0.004	0.681	0.684

Standard errors in parentheses SEs clustered by country. Fixed effects (where indicated): year and country. Significance: * p<0.10, ** p<0.05, *** p<0.01.

A similar pattern is observed regionally. In Asia (Table 1B), the coefficient on Property Rights Protection remains positive and significant across specifications—128.53* in Column (3)—while the squared term (–9.59*) confirms the inverted-U shape, indicating that moderate strengthening of rights initially increases water extraction but at higher institutional levels, the effect diminishes or reverses. In Africa (Table 1C), the same pattern holds with a coefficient of 115.15* and a squared term of –10.98*, both statistically significant, suggesting that institutional maturity leads to better management and conservation practices (Besley & Ghatak, 2010; Goldstein & Udry, 2008).

Turning to Table 2, the results for the Democracy Index also show a consistent inverted-U relationship between democratic quality and groundwater levels. In the global model, the coefficient on Democracy is positive and significant (95.61), while the squared term is negative (–9.63), implying that democratization initially increases groundwater extraction, likely due to political incentives to expand irrigation and subsidies, but further democratization reverses this effect as accountability and environmental regulation strengthen (Fredriksson & Svensson, 2003). For Asia, Column (3) indicates a positive coefficient of 36.63* and a squared term of –

3.56*, supporting the notion that mature democracies enforce sustainable water policies, while Africa shows a similar pattern, with democracy increasing groundwater levels (39.04*) but the negative squared term (–4.23*) showing diminishing returns as institutions consolidate.

Tables 1 and 2 show a strong correlation between groundwater level and the property rights index and the democracy index. Although there is a distinct reason for not interpreting this relationship as causal. The type of institution and institutional quality in a particular country are endogenous, as unobserved factors such as colonization and its determinants influence the type of institutions present in that country. The exclusion of these variables in the study will create omitted variable bias, leading to biased estimates. Hence, the effect captured by OLS does not correspond to the causal effect of institutions on groundwater levels. To overcome these challenges, we employ a Two-Stage Least Squares (2SLS) estimation strategy to identify the causal relationship between institutions and groundwater levels as estimated in equation (1). In the first stage, we predict the origin of the type of institution by using instrumental variables that are correlated with the institution but exogenous to current groundwater levels. In the second stage, the predicted values from the first stage are used to estimate their effect on groundwater levels.

5. Institutions and Ground Water Levels: IV Regression

We utilize colonial history as an instrumental variable for contemporary institutional quality, drawing on the extensive literature that identifies colonization as a fundamental determinant of state capacity, governance, and economic institutions. The process of colonization profoundly shaped the institutional architecture of modern states by transplanting administrative, legal, and political structures from the metropole to the colonies (Acemoglu & Johnson, 2003). These institutions were not the product of domestic social contracts or indigenous development but rather reflected the strategic and economic objectives of the colonizing powers (Humphreys & Bates, 2005; La Porta et al., 2008).The imposition of external institutional frameworks disrupted pre-existing governance arrangements and created enduring path dependencies that have continued to shape governance and economic outcomes in postcolonial societies (Engerman & Sokoloff, 1997; Acemoglu et al., 2001).

Different colonizers exported distinct institutional blueprints based on their own governance philosophies and economic interests. For instance, British colonies often adopted common law systems emphasizing judicial independence, contract enforcement, and decentralized governance structures (La Porta et al., 2008). These features have been linked to stronger property rights protections and greater economic dynamism in the long run (North, 1990; Acemoglu & Robinson, 2012). In contrast, French, Spanish, and Portuguese colonies typically implemented civil law systems characterized by centralized administrative control and codified legal systems that prioritized state authority over individual rights (La Porta et al., 1999). This legal centralization often limited local autonomy and fostered bureaucratic rigidity, constraining institutional adaptability in the postcolonial period (Mahoney, 2010; Bertocchi & Canova, 2002). Hence, colonial rule generates cross-country variation in the type of institutions built, which persists to the present, providing a source of exogenous variation for institutional measures such as democracy and the property rights index.

However, colonization itself is not exogenous, and this non-random structure could bias the results if not addressed. Historical evidence suggests that the likelihood of colonization was significantly influenced by nautical accessibility and land connectivity to European metropoles. Regions that were closer to Europe via navigable sea routes were more easily reached and administered, whereas landlocked and inland regions were often spared intensive colonial control or colonized later in history(Ertan, Fiszbein, & Putterman, 2016). Historical cartographic and navigational evidence supports this — as early as the 16th century, European expansion routes followed prevailing winds and ocean currents, making colonization a function of nautical distance and navigability, not random territorial selection (Gallup et al., 1999; Feyrer & Sacerdote, 2009).

To isolate the exogenous component of colonization, our study modeled colonization as a function of navigation distance to Europe and land distance following Ertan et al. Navigation distance measures the maritime route between the colonizing power's principal port and the colony's main port of entry. Navigation distance was calculated utilizing travel routes that were historically accurate for the era preceding the completion of the Suez Canal and Panama Canal. In contrast, land distance quantifies the overland journey, in kilometers, from the closest maritime entry point to the country's significant urban hub. This first-stage specification generates a predicted value of colonization as an instrument for institutional quality, which is captured through the democracy and property rights index in the second stage.

This layered identification strategy, where colonization instruments for institutional quality and geographical factors serve as instruments for colonization, aligns with recent empirical approaches in institutional economics that emphasize hierarchical endogeneity correction

(Ertan et al., 2016).It allows us to capture the causal pathway: geography → colonization → institutions → groundwater governance. This is consistent with the view that "property rights institutions are the outcome of political processes, and these processes are historically contingent" (Besley & Ghatak, 2010).

Building on the above theoretical framework, we use the Two-Stage Least Squares (2SLS) estimation strategy to address the endogeneity between institutional quality and groundwater levels. This approach enables us to isolate the exogenous variation in institutional quality resulting from colonial and geographic determinants, thereby estimating the causal impact of institutional quality on groundwater outcomes (Acemoglu, Johnson, & Robinson, 2001; Rodrik, Subramanian, & Trebbi, 2004). We use the data for navigation distance and land distance provided by Ertan et al. Land distance takes the value 0 if the country is coastally accessible, like India. Land distance takes non-zero values if the countries, even if accessible through the coastline, are mainly accessed through land routes, such as Jordan(Ertan et al).

To address the endogeneity of institutional quality and satisfy the exclusion restriction, we implement a hierarchical 2SLS identification strategy in which geography predicts colonization, and colonization instruments are used for institutions.

In the first stage, we model the likelihood of a country being colonized as a function of exogenous geographic determinants. Specifically, we estimate a logistic regression in which the dependent variable Y_i represents the colonization status of country i, taking the value 1 if the country was historically colonized and 0 otherwise. The probability of colonization is expressed as:

$$Logit(\Pr(Y_i = 1)) = \alpha + \beta_1 Nautical\ Distance_i + \beta_2 Land\ Distance_i + \gamma X_i + \epsilon_i \qquad (2)$$

Where, $logit(\Pr(Y_i = 1) = \ln\left(\frac{\Pr(Y_i=1)}{1-\Pr(Y_i=1)}\right)$

$Nautical\ Distance_i$ measures the navigational distance from Europe to the country's main coastal access point, and $Land\ Distance_i$ represents the overland distance from the nearest coastline to the country's main settlement or capital. X_i is a vector of additional exogenous geographic controls that may influence colonial expansion, such as terrain ruggedness, mean elevation, or proximity to trade routes. These spatial variables proxy the cost and feasibility of European expansion and are plausibly exogenous to contemporary institutional or hydrological outcomes (Feyrer & Sacerdote, 2006). The fitted values from this first stage represent the exogenous variation in colonial exposure attributable solely to geographic accessibility. The coefficients β_1 *and* β_2 measure the effect of geographic distance on the log-odds of colonization, reflecting how increasing navigational or overland distance impacts the probability of being colonized.

Table 3: Determinants of Colonization (First-stage Logit)

	(1)
	Logit (robust SE)
colonized	
Nautical distance	-0.112***
	(0.001)
Land distance	3.972***
	(0.020)
Constant	1.789***
	(0.005)
Observations	1349656
Chi-sq	66019.099
Pseudo R2	0.088

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3 presents the results from the first-stage logistic regression, which estimates the probability of a country being colonized as a function of exogenous geographic determinants—namely, *nautical distance from Europe* and *land distance from coastal access points*. The coefficient on nautical distance (-0.112, $p < 0.01$) is negative and statistically significant, indicating that as the navigational distance from Europe increases, the likelihood of a country being colonized decreases substantially. This aligns with historical evidence that European colonial expansion was concentrated in regions with shorter and more navigable sea routes (Sachs, 1998).

Conversely, the coefficient on land distance (3.9716, $p < 0.01$) is positive and highly significant, indicating that greater overland distance from the coast increases the probability of colonization, even after accessible coastal areas are controlled for. This result is consistent with the idea that colonization spread inland from coastal footholds as maritime empires expanded their administrative reach (Feyrer & Sacerdote, 2006).

Both coefficients are precisely estimated, with extremely high z-statistics and narrow confidence intervals, confirming the robustness of these relationships. The fitted values from this model represent the exogenous variation in colonization attributable to geographic accessibility, which is used as the instrumental variable for institutional quality in the second stage of the 2SLS estimation.

In the second stage, we use these predicted colonization values as instruments for institutional quality, which is proxied by the democracy index and the property rights index, to estimate their causal effects on groundwater levels. Recognizing the potential non-linear relationship between institutions and groundwater governance, we include both the linear and squared terms of institutional variables in the structured equation.

$$Y_{ict} = \beta_o + \beta_1 PRI_{ct} + \beta_2 PRI_{ct}^2 + \gamma Controls_{ct} + \epsilon_{ct} \quad (3)$$

$$Y_{ict} = \beta_o + \beta_1 DI_{ct} + \beta_2\, DI_{ct}^2 + \gamma Controls_{ct} + \epsilon_{ct} \quad (4)$$

Where, Y_{ict} is the groundwater level at point i in country c at time t in both equation (3) and equation (4). PRI_{ct} is the Property Rights Index for country c at time t and PRI_{ct}^2 controls for non-linearity in equation 3. DI_{ct} is the democracy Index in the country c at time t in equation (4). β_1 *and* β_2 are coefficients of interest. We use predicted values of colonization from equation 2 as an instrument for both the Property Rights Index (PRI) and the Democracy Index (DI). Furthermore, we utilize squared predicted values as an instrument for squared terms in the Property Rights Index and the Democracy Index.

Table 4 presents the results from the two-stage least squares (2SLS) estimation, examining the causal impact of institutional quality, as proxied by the Democracy Index, on groundwater levels. Model (1) provides baseline estimates without controls, Model (2) incorporates country fixed effects to account for unobserved, time-invariant heterogeneity (Wooldrige, 2003), and Model (3) adds both country and time fixed effects, addressing global shocks and time-specific confounders (Angrist & Pischke, 2009).

Across all specifications, the Democracy Index coefficient is positive and highly significant, while the squared term is negative and significant at the 1% level. This combination implies a nonlinear (inverted-U) relationship between democracy and groundwater outcomes, consistent with prior findings that the benefits of democratization on governance and resource management follow a diminishing returns pattern (Besley & Persson, 2011; Acemoglu & Robinson, 2012). In the early stages of democratization, stronger accountability mechanisms and effective enforcement of property rights enhance environmental regulation and sustainable groundwater management (Li & Reuveny, 2006; Ostrom, 1990). However, as democracy deepens, the marginal benefits may decline due to policy fragmentation, populist pressures, or conflicting interest group dynamics (Keefer, 2007; Damania, 2009).

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Table 4: Impact of Democracy on Groundwater

	(1)	(2)	(3)
Democracy Index	352.739***	297.310***	296.014***
	(53.070)	(78.566)	(78.355)
DemocracyIndex^2	-28.643***	-28.204***	-28.080***
	(8.039)	(7.587)	(7.563)
Average Precipitation		310.037*	307.216*
		(183.356)	(183.900)
Average Temperature		0.166	0.229
		(0.745)	(0.740)
GDP		0.000**	0.000**
		(0.000)	(0.000)
Population		-0.000**	-0.000**
		(0.000)	(0.000)
Observations	1349656	1281060	1281060
Adj. R-sq			

Standard errors in parentheses. Standard errors are clustered at the country level.
Fixed effects (where indicated): year and country
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The negative coefficient on the squared term (around −28 across models) confirms the nonlinearity: moderate democratic consolidation improves governance and environmental management, but excessive politicization may weaken enforcement or promote short-term exploitation of common-pool resources (Bättig & Bernauer, 2009; Fredriksson & Wollscheid, 2015). The implied turning point suggests that the positive influence of democracy peaks at intermediate levels of institutional maturity, consistent with the notion of institutional saturation (Besley & Ghatak, 2010; Acemoglu & Robinson, 2012).

Among the control variables in Models (2) and (3), Average Precipitation shows a positive and weakly significant coefficient ($p < 0.10$), aligning with the hydrological literature that identifies rainfall as a key driver of groundwater recharge (Foster & Chilton, 2003; Jasechko et al., 2024).

GDP exhibits a positive and significant effect ($p < 0.05$), consistent with the notion that higher-income economies invest more in water management infrastructure (World Bank, 2022). Conversely, population has a negative and significant association ($p < 0.05$), supporting the hypothesis that greater extraction pressures in densely populated regions exacerbate groundwater depletion (Wada et al., 2010; Gleeson et al., 2012). Average temperature remains insignificant, suggesting that, conditional on precipitation and institutional factors, climatic temperature variation does not directly explain differences in groundwater trends (Rodell et al., 2018).

Table 5: Effect of Property Rights Index on Groundwater

	(1)	(2)	(3)
Property Rights Index	345.806***	470.475***	471.054***
	(32.057)	(97.847)	(98.429)
Property Rights Index^2	-28.914***	-39.391***	-39.432***
	(5.004)	(8.024)	(8.063)
Average Precipitation		186.188	182.215
		(211.018)	(211.897)
Average Temperature		-1.347	-1.264
		(1.001)	(0.995)
GDP		0.000**	0.000**
		(0.000)	(0.000)
Population		-0.000***	-0.000***
		(0.000)	(0.000)
Observations	1326820	1258224	1258224

Standard errors in parentheses. Standard errors are clustered at the country level.
Fixed effects (where indicated): year and country
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5 reveals a strong and statistically significant nonlinear relationship between property rights institutions and groundwater levels. Across all three model specifications, the coefficient on the Property Rights Index (PRI) is positive and highly significant ($p < 0.01$), while the coefficient on its squared term is negative and significant ($p < 0.01$). This pattern suggests an inverted-U-shaped relationship between institutional strength and groundwater outcomes.

In Model (1), which excludes all controls, a one-unit increase in the property rights index is associated with an estimated 345.8-unit rise in groundwater levels, indicating that stronger institutional frameworks initially promote groundwater stability and management efficiency. This result aligns with the theoretical expectation that secure property rights enhance resource governance, enforcement, and investment incentives in water management systems (North, 1990; Acemoglu & Johnson, 2005; Libecap, 2011). The mechanism likely operates through reduced open-access exploitation and the creation of clearer ownership or usage boundaries that mitigate the "tragedy of the commons" (Ostrom, 1990; Grafton et al., 2011).

In Models (2) and (3), where country fixed effects and both country and time fixed effects are successively introduced, the main coefficient on PRI remains positive and highly significant (470.5 and 471.1, respectively), though its magnitude increases. This robustness, following the inclusion of fixed effects, underscores that the relationship between property rights and groundwater outcomes is not driven by unobserved heterogeneity, such as geography or long-run institutional history (Acemoglu, Johnson, & Robinson, 2001; Rodrik, Subramanian, & Trebbi, 2004). The increase in magnitude may indicate that, after controlling for persistent country-level differences, within-country institutional improvements exert a stronger marginal effect on groundwater outcomes.

However, the negative and significant coefficient on Property Rights Index^2 (ranging from –28.9 to –39.4 across specifications) indicates that the beneficial effect of institutional strengthening diminishes at higher levels of property rights protection. Beyond a certain threshold, further tightening of property rights could lead to resource rigidity, where excessive formalization or bureaucratic control hinders adaptive local water governance (Besley & Ghatak, 2010; Bardhan, 2005). This supports the notion of nonlinear institutional returns—that moderate institutional development enhances groundwater regulation, but hyper-centralized or overly restrictive systems may stifle community-based adaptive management (Ostrom, 2010; Pande & Sukhwani, 2018).

6. Interpretation:

Our empirical results reveal that the contemporary groundwater crisis cannot be understood solely as a consequence of climatic variation; rather, it is profoundly shaped by the quality of a country's political and property-rights institutions, which themselves reflect long-run historical trajectories rooted in colonial rule. The significant and positive coefficients on the Democracy Index and the Property Rights Index indicate that countries with stronger checks on elites, greater accountability, and more secure rights over resource use exhibit substantially higher groundwater levels (Acemoglu & Johnson, 2005; Besley & Ghatak, 2010). The strong statistical significance of these institutional variables, even after controlling for precipitation, temperature, and geological characteristics, demonstrates that groundwater outcomes are deeply institutional rather than merely environmental (Ostrom, 1990; Baland & Platteau, 1996).

The negative and significant quadratic terms point to diminishing marginal returns, suggesting that the benefits of institutional strengthening are largest in countries starting from weak institutional baselines, where regulatory authority is easily captured and groundwater extraction is often unmonitored or politically manipulated (Acemoglu & Robinson, 2012; Rodrik, Subramanian & Trebbi, 2004). This pattern is consistent with the broader insight that institutional failures—rather than purely climatic pressures—explain why some societies experience severe aquifer depletion despite comparable hydrological conditions (North, 1990; Ostrom, 2009).

Crucially, the historical foundation of these institutional differences can be traced to colonial state formation, which imposed externally designed legal, administrative, and property-rights regimes that continue to shape groundwater governance capacities today (Acemoglu, Johnson & Robinson, 2001; Lange, Mahoney & vom Hau, 2006). In many regions, colonizers introduced extractive institutions that centralized authority, weakened local commons governance, and prioritized resource extraction over long-term sustainability, leaving behind states with limited regulatory effectiveness (Engerman & Sokoloff, 1997; Mahoney, 2010). Our findings reflect these historical legacies: countries inheriting institutions characterized by insecure property rights or weak political accountability display poorer groundwater outcomes even today, highlighting the path-dependent nature of resource governance (La Porta et al., 1999; Acemoglu & Robinson, 2012).

This institutional channel provides a coherent explanation for why climatically similar countries can exhibit vastly different groundwater levels. While rainfall and temperature influence recharge potential, they do not determine whether groundwater extraction is regulated, monitored, or governed collectively. Such regulatory features are inherently institutional, shaped by the incentives and constraints within the political system (Besley & Ghatak, 2010; Ostrom, 1990). In this sense, climate sets the hydrological baseline, but institutions determine the trajectory—whether aquifers are sustained or depleted.

Taken together, these findings support the view that groundwater depletion is fundamentally a governance problem rooted in both contemporary institutional quality and long-standing historical legacies (Acemoglu, Johnson & Robinson, 2001; Ostrom, 2009). They underscore the need to conceptualize groundwater sustainability not merely as a hydrological challenge but as an institutional one—shaped by political accountability, secure resource rights, and the enduring imprint of colonial rule.

7. Conclusion:

This study provides evidence that the groundwater crisis is fundamentally an institutional problem, not just a climatic one. The presence of a robust inverted-U relationship between institutional quality and groundwater outcomes underscores that institutions can simultaneously constrain and intensify extraction depending on their structure. Moderate improvements in governance help internalize externalities and promote sustainable usage, but stronger property rights—when not paired with environmental safeguards—can incentivize intensified extraction by well-capitalized actors.

These empirical patterns highlight a broader and more profound insight: the institutional foundations that shape groundwater outcomes today were forged during the colonial period, when land and resource governance systems were designed to benefit select groups. As contemporary economies continue to operate within this inherited governance architecture, the long-run effects of those institutional choices remain visible in current environmental outcomes. Addressing groundwater decline, therefore, requires more than technological or climate-oriented interventions—it requires confronting the institutional legacies and power structures that determine who extracts, how much, and under what incentives.

In sum, the findings call for a policy shift toward institutional reform that integrates property rights, environmental regulation, and equitable access, recognizing that groundwater sustainability will ultimately depend on transforming the governance systems that structure resource behavior. Only by acknowledging and reforming these deep-rooted institutional pathways can societies meaningfully address the escalating groundwater crisis.

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