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Sustainable Groundwater Management: The Path Forward

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Speaker Abstracts

Tuesday, October 9

Groundwater: Making Invisible Visible 3
Neno Kukuric
Opportunities and Challenges in Groundwater Policy and Governance 5
Andrea Gerlak
USGS Global Engagement in Groundwater Resources – The Science, Resource Management, and Policy Nexus ... 7
Ingrid Verstraeten
The Hidden Hazard of Deep Groundwater Arsenic 9
Steven Gorelick
Land Subsidence Hazards Challenge Groundwater Sustainability in Many Inland and Coastal Aquifer Systems .. 10
Devin Galloway
Groundwater Depletion and Its Implications for Sustainable Groundwater Management 11
Lenny Konikow
Geophysical Imaging of Groundwater Systems 12
Rosemary Knight
California Climate, Groundwater, and Their Interrelated Future 14
Claudia Faunt

Wednesday, October 10

India: Groundwater Management through Electricity Reforms: Case Studies From Three States in India 15
Aditi Mukherji
China: Safe and Sustainable Groundwater Supply in China 17
Yanxin Wang
Food Self-Sufficiency or Groundwater Bankruptcy? 19
Kaveh Madani
Regulating Groundwater Uses in Spain: A Long-distance Race 21
Lucia De Stefano

Will We Get to “Safe Yield?” Embracing and Dodging Groundwater Sustainability in Arizona 24

Paul Hirt

Mexico: Groundwater Management Paradigm Shift in Mexico: Urban Areas Growing vs Land Subsidence......... 26

Dora Carreón-Freyre

Groundwater Wells and Withdrawal Management in the Western USA 29

Debra Perrone

Groundwater Recharge Using the Agricultural Landscape 30

Helen Dahlke

Groundwater Governance, Policy and Regulation in the Arab World: A Reviewed Paradigm 33

Alvar Closas

Groundwater: Making Invisible Visible

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Water scarcity already affects about 2.7 billion people around the world for at least one month per year and by 2025 this will worsen to severe water shortages if consumption continues at current rates. As surface water availability decreases in the face of climate change and increasing consumption, reliance on groundwater is growing and is likely to grow even faster.

Groundwater already provides almost half of all drinking water worldwide, about 40% of water for irrigated agriculture and about 1/3 of water required for industry. It sustains ecosystems, maintains the baseflow of rivers and prevents land subsidence and seawater intrusion. Groundwater is an important part of the climate change adaptation process and is often a solution for people without access to safe water. Despite these impressive facts and figures, invisible groundwater is out of sight and out of mind for most people.

Human activities (including growth of population and wealth) and climate variability are increasing the pressure on groundwater resources; serious pollution and depletion problems are reported for many parts of the world. Nevertheless (and despite the high importance and evident threats), we still do not know sufficient about the state and trends of groundwater resources globally and we do not manage aquifers well enough.

What could we do more to improve state and visibility of groundwater resources? Obviously a better/more extensive monitoring and assessment leads to better understanding of groundwater issues, which is prerequisite for informed management and governance. However, the level of investments for monitoring/assessment of groundwater resources tends to be very much related to visibility, clarity and priority of a problem. Since groundwater is invisible to many, it is an additional challenge to provide sufficient evidence, convince decisionmakers about priority issues and secure investments. Therefore, building a case for invisible groundwater (through improving information sharing, awareness, education, lobbying, etc.) deserves more attention.

It is simple: the more we know (monitoring & assessment), the more we can tell; by telling more (visibility) we increase possibilities to do/learn more again. Below are some suggestions (points for discussion) about where and how to step up our efforts:

- Improve the knowledge on groundwater resources, especially their **status/change** through **monitoring**: “You can't manage, what you don't measure.” In 2007 IGRAC initiated the Global Groundwater Monitoring Network (GGMN) programme to improve quality and accessibility of groundwater monitoring information. There is a concern about reduction of monitoring networks and overvaluation of proxy/derived information from remote sensing and regional/global models (also as consequence of lack of sufficient monitoring datasets).
- Improve **information and knowledge sharing**. In order to engage in groundwater management and take responsibility, stakeholders need access to reliable data and information on groundwater. This requires processes and systems for sharing of data, information and knowledge at all levels.
- Climate change and human impact on groundwater resources do not stop at administrative borders. The majority of large aquifers in the World are **transboundary**. Political, institutional, socio-economic, cultural and other differences among countries make the assessment and management of internationally shared aquifers challenging. Significant progress has been made in assessing transboundary aquifers, but less so in management/governance.

- Develop and promote use of contemporary, interactive **information management systems** as an enabling environment for **international cooperation**. A breath-taking development of web-based ITC already provides a unique support for sharing (and joint gathering, processing and dissemination) of data and information. *(Technology is in place, it's about people where most additional effort is required.)*

- Raise awareness on **multiple value** of groundwater using **customised approaches and tools** (social media, serious gaming, water footprint, educational material, etc.) for various target groups. *How to effectively convey a message that invisible character of groundwater does not easily lend itself to inform policy and therefore needs constant increased attention?*

- Go beyond the groundwater sector: raise attention to groundwater **in a context of relevant societal/environmental issues** (e.g. managed aquifer recharge as an effective climate adaptation measure) and **in an integrated manner** (i.e. groundwater as a part of the problem/solution, cross-sectoral integration).

- Involve **investor risk** analysts and assets managers: **why groundwater matters**? Groundwater resources are extensively used in production processes by companies all over the world, including large multinationals. The knowledge about these resources needs a substantial improvement for the benefit of all: the investors, society and environment. What are **business incentives** for action and how to distinct genuine efforts in water stewardship from "greenwashing"?

- Think positively, think **in terms of solutions**: advantages (and limitations) of solar pumping, smart crops, and water-saving irrigation technology. Is silent revolution over? Regulations (e.g. metering), legislation and other measures on **demand side**.

- Provide a fresh view on the role of **UN agencies** and international groundwater (related) organisations. Explore the ways to develop joint UN inter-agency projects/activities on groundwater (e.g. World Groundwater Day), to link groundwater stronger to SDGs and to add groundwater on agenda of high level panels and national cooperation agencies.

- Strengthen **people networks** and trust building process: it is all about people/stakeholders and connecting/involving them. Human dimension of decision-making in water sector is often larger barrier than engineering or even financial restrictions, also due to number/diversity of stakeholders and a **non-market value** of water. The latter (common resource pool) makes groundwater additionally vulnerable to "tragedy of commons" and only good groundwater governance at the local level can prevent it.

Practically all the above-mentioned issues have already been addressed by various organisations, at various levels, all over the world. Yet, apparently not sufficiently or effectively enough: although there are still no completely reliable figures about the magnitude of groundwater stress globally, there is no doubt that we are **increasingly depleting and polluting** our groundwaters. **Strengthening cooperation and information & knowledge sharing** (at all levels!) is crucial for all groundwater issues listed above, whether it is monitoring, assessment or good governance. Only by working together (with dedication and passion of someone who has a dream) we can substantially increase visibility and improve management of groundwater resources globally. Is there any other option?

Opportunities and Challenges in Groundwater Policy and Governance

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Groundwater as an intractable problem.

- Invisibility obscures
- Boundaries that cross borders
- Politics dominated by users
- Uneven access
- Crisis-driven action

I. Growing attention to groundwater governance

A. What do we mean by governance?

a. The overarching framework of groundwater-use laws, regulations, & customs, as well as processes of engaging the public sector, private sector, and civil society.

i. Governance is the way we manage our common affairs

ii. More than just government

iii. Governance implies a process by which societies govern

B. Evidence of growing attention to groundwater governance:

a. Variety of reports and projects

b. Regional and international initiatives

c. National legislation

C. A changing paradigm in water governance

a. Not just the exclusive domain of hydrogeologists and engineers

b. Attention from economists, sociologists, ecologists, climatologists, lawyers, institutional experts, communication specialists and others

II. What do we know (and are learning…) about groundwater governance?

A. Diversity of actors and scales

B. Key elements of governance

a. Role of institutions

b. Role of science and information

c. Role of civil society

d. Role of economic and regulatory frameworks

C. Informal groundwater governance

a. In absence of quantified groundwater rights and without central regulatory power

b. Can support self-regulation, either as a complement or alternative to central regulation

D. Transboundary groundwater governance

a. Problems may be magnified or exacerbated by the borders above the waters

b. Attention to the mechanisms and the enablers that trigger some cooperation

E. Groundwater and the food-energy-water nexus

a. Poor sectoral coordination and institutional fragmentation have triggered an unsustainable use of resources and threatened the long-term sustainability of food, water, and energy security

b. The nexus approach can enhance understanding of the interconnectedness of the sectors and strengthen coordination among them

III. How do we improve groundwater governance?

A. How can we build institutions and processes for groundwater governance?

a. Best available science

i. Asymmetries in data availability

ii. Metrics to inform decision-making

iii. Science may be politicized

b. Inclusive, participatory processes

i. Exclusion from decision-making

ii. Lack of capacity or time to be involved, and inadequate access to information

iii. Participatory approaches may reflect existing inequalities

c. Produce fair and equitable outcomes

i. Issues of poor infrastructure, access and good quality

ii. Drawdown disproportionately harms the poor

iii. Growing threats to drinking water security

USGS Global Engagement in Groundwater Resources – The Science, Resource Management, and Policy Nexus

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The U.S. Geological Survey (USGS) is the science agency in the US Department of Interior focused on natural resources and natural hazards. At the Department of Interior, we strongly believe that natural resource managers should make decisions based on objective, authoritative science. The USGS provides reliable information that improves the understanding and description of our earth and minimizes loss of life and property from natural disasters. We provide data and information to improve the management of natural resources and aim at protecting our quality of life. Within our water resources mission area, we focus on ice, surface water, groundwater and water quality data collection and investigations.

While USGS is focused on domestic issues, it also has an international mission as we are responsible for selected global resource assessments, global land-imaging, and engagement in natural hazards worldwide. Our international engagement however is limited to the mission of USGS and aims to contribute to US Foreign Assistance objectives including promotion of peace and security, just and democratic government, investment in people to achieve improvements in well-being and productivity, generation of economic growth, and indirectly providing humanitarian assistance to protect lives and reduce suffering.

Moreover, USGS contributes annually to the development of the US Global Water Strategy as part of the US Interagency Water Working Group. This US Global Water Strategy aims to increase access to water, improve water management, strengthen water governance, and promote cross-border cooperation. The USGS engages in the implementation of US Global Water Strategy by providing technical assistance, strengthening of institutions, reconstruction efforts, mitigation of disasters, promotion of the application of science, technology, and sound, objective information, open data policy, and gender equality through science diplomacy in partnership with other US entities, foreign governments, international institutions such as the United Nations, educational institutions, and non-government organizations. These USGS engagements globally are widely reflected in projects ranging from space-based endeavors to detailed on-the-ground investigations.

For example, USGS engages with Mexico as well as Canada in a transboundary aquifer assessment program in order to improve the management of shared groundwater resources. Another great example of USGS science is the USGS groundwater project in Cabo Verde in order to strengthen the local groundwater management due to the sparse groundwater availability affected by saltwater intrusion. In the United Arab Emirates (UAE), USGS scientists have worked in close cooperation with the Abu Dhabi National Drilling Company (NDC) and more recently with the Environment Agency – Abu Dhabi (EAD) for more than 28 years. Here we served as advisors while helping to create capacity to manage the ground water resource while engaging in scientific endeavors including estimation of recharge, determination of water use, evaluating perchlorate contamination in groundwater, and looking into subsidence issues. On the other hand, our USGS efforts in collaboration with our Malagash counterparts in the Anosy Region of Madagascar were focused on an integrated resource assessment in order to promote economic development in the region without affecting its biodiversity negatively and to promote sustainable development of this very poor, drought-stricken region.

Moreover, to further US science and technology cooperation in many countries, USGS implemented several projects in Pakistan, through capacity building and technical assistance with the Pakistan Council for Research in Water Resources of the Ministry of Science and Education, in order to aid Pakistan in providing clean water to the people of Pakistan. This was accomplished through hands-on training, workshops, review of papers and publications, laboratory review, exchange of scientists, and more.

In Afghanistan, USGS has engaged continuously for more than 13 years in natural resources assessments which included focus on groundwater availability, assistance to UNHCR regarding drinking water availability at refugee camps, and assistance in the USGS efforts focused on Afghanistan's groundwater in an attempt to ensure safe, adequate, and sustainable water resources. We focused our efforts on the Kabul Basin with the study of groundwater level declines and effects of climate change and possible increased agricultural production on groundwater availability. We also have focused on groundwater availability in areas of extensive mineralization to instill economic growth through sustainable mining and decrease the Afghanistan's dependency on income from illegal drugs. In cooperation with the US African Command AFRICOM Environment program, and USAID-funded initiatives in Kenia and Ethiopia, USGS performs capacity building in the application of remote sensing focused on groundwater security and coastal security in Africa.

Finally, USGS is engaged in bilateral and multilateral endeavors to instill cooperation through science diplomacy bringing people together that usually do not have the ability to discuss common topics and interests. Through these bilateral and multilateral engagements cooperation is enhanced, improved groundwater resources management is promoted, and improved policies are created. USGS, recently also has engaged in the empowerment of women in sustainable management of water resources in Central Asia including groundwater resources. We conduct these efforts in close coordination with the country governments, local governments, educational institutions, and local NGOs.

In summary, USGS has a science mission globally, engages in science diplomacy, and furthers US policy overseas in part through improving the sustainable management of groundwater resources, an issue that has not received sufficient attention in the US and globally.

The Hidden Hazard of Deep Groundwater Arsenic

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“Deep aquifers in South and Southeast Asia are increasingly exploited as presumed sources of pathogen- and arsenic-free water, although little is known of the processes that may compromise their long-term viability. We analyze a large area (**>**1,000 sq km) of the Mekong Delta, Vietnam, in which arsenic is found pervasively in deep, Pliocene Miocene-age aquifers, where nearly 900 wells at depths of 200**–**500 m are contaminated. There, intensive groundwater extraction is causing land subsidence of up to 3 cm/y as measured using satellite-based radar images from 2007 to 2010 and consistent with transient 3D aquifer simulations showing similar subsidence rates and total subsidence of up to 27 cm since 1988. We propose a previously unrecognized mechanism in which deep groundwater extraction is causing interbedded clays to compact and expel water containing dissolved arsenic or arsenic-mobilizing solutes (e.g., dissolved organic carbon and competing ions) to deep aquifers over decades. The implication for the broader Mekong Delta region, and potentially others like it across Asia, is that deep, untreated groundwater will not necessarily remain a safe source of drinking water.”*

“Groundwater exploitation is a major cause of land subsidence, which in coastal areas poses a flood inundation hazard that is compounded by the threat of sea-level rise (SLR). In the lower Mekong Delta, most of which lies <2 m above sea level, over-exploitation is inducing widespread hydraulic head (i.e., groundwater level) declines. The average rate of head decline is ∼0.3 m yr−1, based on time-series data from 79 nested monitoring wells at 18 locations. The consequent compaction of sedimentary layers at these locations is calculated to be causing land subsidence at an average rate of 1.6 cm yr−1. We further measure recent subsidence rates (annual average, 2006–10) throughout the Delta, by analysis of interferometric synthetic aperture radar (InSAR), using 78 ALOS PALSAR interferograms. InSAR-based subsidence rates are 1) consistent with compaction-based rates calculated at monitoring wells, and 2) ∼1–4 cmyr−1 over large (1000s of km^2) regions. Ours are the first mapped estimates of Delta-wide land subsidence due to groundwater pumping. If pumping continues at present rates, ∼0.88 m (0.35–1.4 m) of land subsidence is expected by 2050. Anticipated SLR of ∼0.10 m (0.07–0.14 m) by 2050 will compound flood inundation potential. Our results suggest that by mid-century portions of the Mekong Delta will likely experience ∼1 m (0.42–1.54 m) of additional inundation hazard.”**

*Erban, L., S. M. Gorelick, H. A. Zebker, and S. Fendorf. 2013. Release of arsenic to deep groundwater in the Mekong Delta, Vietnam, linked to pumping-induced land subsidence, *Proc. National Academy of Sciences* doi/10.1073/pnas1300503110.

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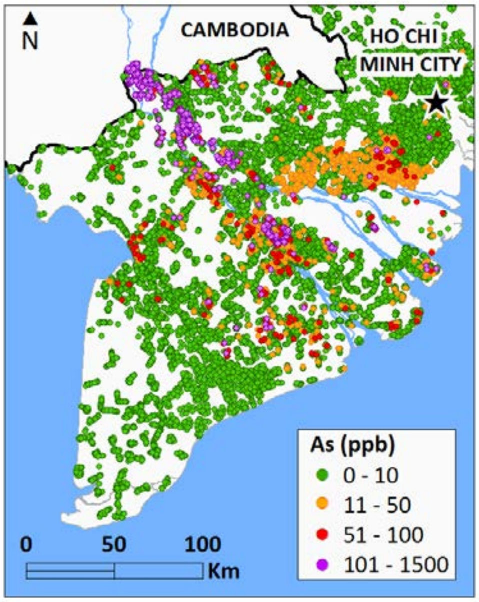

Land Subsidence Hazards Challenge Groundwater Sustainability in Many Inland and Coastal Aquifer Systems

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Land subsidence accompanying the development of water and land resources is increasing globally in both inland and coastal areas. In many coastal areas anthropogenic subsidence caused by increasing groundwater withdrawals from unconsolidated alluvial aquifer systems and the drainage of organic soils principally for agricultural development is a significant, if not the dominant component of ground motion contributing to relative sea-level rise. This presentation focuses on groundwater sustainability issues complicated by the compaction of susceptible aquifer systems and resulting land subsidence hazards that frequently accompany groundwater withdrawals. These hazards include riverine and coastal flooding, structural damages to built infrastructure (including buildings, roadways, pipelines, canals and aqueducts) principally related to differential subsidence, and ecosystem degradation chiefly related to changing inundation and erosion processes.

Generally, sustainable groundwater use has been defined in the context of acceptable environmental, economic, or social consequences that result from the development and use of groundwater for an indefinite period. As such, determinations of sustainable groundwater use are largely subjective, and ideally based on stakeholder input, forecasting of future potential damages, and risk/benefit analysis. Traditional measures of the safe yield of a groundwater resource — the long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge, fail to adequately address the sustainable use of groundwater resources owing to the unaccounted effects of captured recharge and discharge, and changes in groundwater storage accrued in arriving at the safe yield. The compaction of susceptible aquifer systems and land subsidence related to groundwater exploitation largely results from permanent changes in the aquifer storage capacity of the groundwater system that can lag the imposed stresses by decades or centuries. Thus, depletion of groundwater storage capacity, along with the hazards accompanying this type of subsidence further complicate determinations of groundwater sustainability.

Successful groundwater-resource management strategies to mitigate hazards caused by aquifer-system compaction and land subsidence typically are based on maintaining aquifer-system heads above critical preconsolidation stress thresholds to avoid permanent compaction. The identification of these threshold stresses, requires knowledge of the aquifer-system hydromechanical dynamics, hydrogeologic and geodetic data, monitoring (groundwater levels, compaction/subsidence, groundwater withdrawals), analysis, and process modeling. Other elements of successful mitigation strategies generally include:

1. An authority to regulate groundwater pumping;
2. A means to artificially recharge the aquifer system;
3. Alternate sources of water supply, and conjunctive use practices; and
4. Adaptive management.

Ideally, when the combination of these strategies can be optimized in a management system that incorporates near real-time monitoring, analysis/modeling and decision-making, optimal benefits of the available water resources can be achieved while reducing risks associated with their use.

Groundwater Depletion and Its Implications for Sustainable Groundwater Management

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Development of global groundwater resources for agricultural, industrial, and municipal purposes greatly expanded in the last century, and economic gains from groundwater use have been dramatic. In many places, however, groundwater reserves have been depleted to the extent that water levels have declined tens to hundreds of meters, well yields have decreased, pumping costs have increased, and detrimental environmental impacts have become evident. These impacts increase the cost and reduce the sustainability of groundwater development. Estimates of depletion in individual aquifer systems based primarily on direct volumetric approaches indicate that from 1900-2008 cumulative groundwater storage depletion in the U.S. is about 1,000 km3 during 1900-2008 and the cumulative global groundwater depletion totals about 4,500 km^3. This large volume represents a substantial net transfer of water mass from continents to oceans, thereby contributing to sea-level rise (equivalent to a sea-level rise of 12.6 mm—approximately 6 percent of the observed total rise). The rate of annual depletion has increased markedly since about 1950, with maximum rates occurring during 2000-2008, when they averaged about 145 km^3/yr (equivalent to 0.40 mm/yr of sea-level rise, or 13 percent of the reported rate of 3.1 mm/yr during this time). For the U.S. as a whole during 1950-2005, about 15 percent of total pumpage was derived from a reduction of storage of groundwater—a depletion fraction of 0.15. But depletion fractions vary widely within the U.S. and even within any given large aquifer system. Because most long-term pumpage is balanced by capture in real systems, capture must be recognized as a critical factor in assessing water budgets, groundwater depletion, and sustainability of groundwater development. During 2000-2008 the Central Valley of California had the largest depletion intensity (a measure that accounts for areal extent of aquifer) of any major aquifer system in the U.S. at an average rate of 0.075 m/yr. Trends in the annual number of days of zero streamflow and 7-day-minimum streamflow values were evaluated in several areas of known groundwater depletion. Results clearly show that in some cases streamflow depletion is related to (and probably caused by) groundwater depletion. Groundwater depletion must be confronted on local and regional scales, where water managers will necessarily have to take actions to reduce demand (primarily in irrigated agriculture) and/or increase supply through managed aquifer recharge, desalination, and/or developing alternative sources.

Geophysical Imaging of Groundwater Systems

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Ensuring the long-term sustainability of our groundwater resources requires that we develop improved ways to acquire the data we need to evaluate, model, monitor and manage groundwater systems. Geophysical methods, deployed using ground-based, airborne or satellite platforms, provide a way of remotely probing the subsurface. The acquired data are processed and interpreted to obtain high-resolution images that can complement well data, filling in the data gaps between and below the wells. There are a number of geophysical methods available that vary in terms of the property measured, the derived information and the spatial resolution and extent of the resulting images. Over the past eight years, we have explored the use of three different methods to image groundwater systems in California.

Detailed deformation maps of the ground surface can be derived from interferometric synthetic aperture radar (InSAR) data, acquired using satellites since 1992. Analysis of InSAR data has revealed dramatic subsidence of the ground surface due to groundwater withdrawal in many parts of the western United States. In our work, we have used InSAR data to obtain quantitative estimates of the monthly to seasonal variation in head levels in a confined aquifer system. Our methodology was developed working in the agricultural San Luis Valley in Colorado (Reeves et al., 2011; Chen et al., 2015, 2016). Using data from three satellites and calibration with well data, we were able to use InSAR-derived deformation measurements to estimate the variation in head over a 20 year time period throughout the San Luis Valley, filling in temporal and spatial gaps in the well data (Chen et al., 2018). The InSAR-derived head estimates show good agreement with measurements made in 22 wells.

Our work in the Central Valley of California has illustrated the important role that InSAR data can play in monitoring groundwater systems. Our analysis of InSAR and hydrogeologic data led us to conclude that between 54% (lower estimate) and 98% (best estimate) of the subsidence that occurred during the 2007-2012 drought was due to the permanent compaction of the aquifer. The 98% estimate corresponds to the permanent loss of 7 x 108 m^3 of storage, equivalent to 9% of the volume of groundwater used from 2007 to 2012.

The InSAR-derived deformation is an integrated measurement over the package of subsurface materials experiencing changes in head levels. In order to understand the controls on the subsidence, and accurately predict the susceptibility of a region to continued subsidence, more information is required about the hydrostratigraphy of the subsurface. We are in the process of conducting a series of pilot studies in the Central Valley to develop and demonstrate the use of the airborne electromagnetic (AEM) method. The AEM method is deployed using a helicopter that moves geophysical instruments 30 meters above the land surface at a speed of about 80 km per hour, imaging to a depth of approximately 100 m to 500 m, with the depth of imaging dependent on the electrical resistivity of the subsurface. The result, after data processing and analysis, is a set of 2D slices displaying the detailed variation in the electrical resistivity of the subsurface. Through calibration with well data and geologic interpretation, this can be transformed to map out the distribution of sediment textures, defining the large-scale architecture of the groundwater system. During the first pilot study in the San Joaquin Valley (Knight et al., 2018), we were able to obtain very high quality data, imaging to a depth of ~500 m, along the 100 line kilometers of acquired data. The derived images displays the four principal units previously recognized in the area: an upper aquifer, the Corcoran Clay, a lower aquifer, and a permeable unit at depth. The spatial resolution and depth of imaging far exceeds what was available with the existing well data, revealing the lateral variability in the units and previously unmapped units at depth. The AEM method can provide the data required to develop a hydrogeologic conceptual model for an area; an essential step for sustainable groundwater management.

In the Monterey Bay area, along the coast of California, the excessive pumping of groundwater for agriculture has led to saltwater intrusion at numerous depths and in numerous locations. Local water agencies are committed to undertaking actions to prevent further intrusion, but need an improved understanding of the current location of the saltwater-freshwater interface to inform their modeling efforts. We have used two geophysical methods to image the distribution of saltwater and fresh water along the coastline. Data were first acquired along a 40 km stretch of beach using electrical resistivity tomography (Goebel et al., 2017). Electrodes were spaced every 22.5 m, with a total of 81 electrodes along a 1.8 km active cable length. Current was injected at two electrodes, and potential measured between all other electrode pairs; this was repeated for all combinations of electrodes. Cable segments were rolled over in 450 m increments to ensure continuous overlap in data acquisition. The full dataset was inverted to obtain models of electrical resistivity. The data quality was outstanding, imaging to a depth of ~300 m. Seen in the resistivity image is a complex pattern of saltwater intrusion which reveals the control that the hydrogeology and the patterns of pumping have on intrusion.

Along a southern section of the coast, we extended the study inland using the AEM method (Gottschalk et al., 2018). The presence of saltwater limited the imaging depth in areas to ~100 m, increasing to ~400 m in other areas. We acquired 650 line kilometers of data with outstanding results. The 3D resistivity image displays the classic wedge-shaped geometry of saltwater intrusion, captures the complexity of the distribution of the saltwater and freshwater, and reveals connectivity between the upper and lower aquifer that moves saltwater into the underlying region.

The passage of the Sustainable Groundwater Management Act in 2014 in California has provided a framework for addressing concerns about water quantity and quality. Geophysical methods can play an important role by providing much-needed data.

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California Climate, Groundwater, and Their Interrelated Future

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Management to ensure the sustainability of California’s water resources is critical. Groundwater is a crucial buffer against land-use change effects, water restrictions, drought, and the impacts of climate change, including the depletion of mountain snowpack that is relied on for part of California's water supply. Despite its essential role, the state’s groundwater system is under considerable strain and until recently has been largely unregulated. California’s Sustainable Groundwater Management Act of 2014 (SGMA) provides a framework to comprehensively measure and manage groundwater and empowers local agencies to assess hydrologic issues that may cause “undesirable results.” California’s Central Valley has many basins with “undesirable results,” and most of these are considered “critically overdrafted basins.” The Central Valley covers about 20,000 mi^2 and is one of the most productive agricultural regions in the world. Because the valley is semi-arid, surface-water availability varies substantially. Agricultural demand for irrigation is heavily reliant on surface water and groundwater, and in parts of the valley, groundwater pumping has caused severe groundwater-level declines, resulting in land subsidence of up to 30 feet. Starting in the 1950s, state and federal water distribution systems eased reliance on groundwater as dependence shifted to diverted surface water. As a result, groundwater levels recovered, and subsidence virtually ceased for a few decades. In the last 20 years, however, land-use changes and limitations to surface-water availability—including drought and environmental flows—have increased pumping, causing groundwater-level and groundwater-storage declines, renewed subsidence, decreased stream flows, and changes to ecosystems. As these recent trends continue, monitoring and modelling are critical to understanding the dynamics of groundwater use and developing management strategies. Modeling tools, such as the USGS’s Central Valley Hydrologic Model, enable: (1) Groundwater Sustainability Agencies (GSAs) to have a head start in meeting requirements for key elements of their Groundwater Sustainability Plans, including a hydrogeologic conceptual model, water budgets (past & projected), development of measurable objectives and minimum thresholds, and monitoring network design; and (2) GSAs and state agencies to develop management strategies to mitigate adverse impacts while also optimizing water availability. Such capabilities are critical for successful implementation of SGMA.

India: Groundwater Management through Electricity Reforms: Case Studies From Three States in India

Aditi Mukherji
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Agriculture, groundwater and electricity sectors in much of India are bound in an invidious nexus of mutual dependence where the growth in agriculture sector is being supported by unsustainable trends in groundwater and electricity sectors. Such mutual interdependence among the three sectors where policies and practices in one affects outcomes in all three sectors is referred to as water-energy-food nexus (WEF). In this talk, I argue that India's WEF nexus is unique when compared to other countries who use groundwater for irrigation and trace the reasons for the same. Since, water, energy and food are all on state or concurrent list, I will also show that there are wide state specific variations in the way this nexus has played out over the years. I will also demonstrate that even similar policies in these three sectors across various states has given rise to different outcomes either because of differences in physical realities of groundwater endowments and rainfall-recharge ratios, or because those policies have been implemented differently due to political exigency and state of governance.

What is water-energy-food (WEF) nexus and why is India's WEF nexus so unique?

Groundwater is the main source of irrigation and irrigates over 60% of India's net irrigated area today. This wasn't always so. Till the late 1970s, surface water (canals and tanks) accounted for the largest share of irrigated land. This started changing from 1980s onwards. This was the time of Green Revolution. What happened; what triggered this change and what made us as dependent on groundwater irrigation as we are today? To understand this, we need to take ourselves out from the water sector for a little while and understand what happened in two other sectors – agriculture (food) and energy around that time.

First, let's talk about agriculture and food. In the 1960s and the 1970s, the imperative for growing more food drove our policies simply because India was at risk of becoming a basket case of hunger and starvation. Green Revolution seemed like the best solution available at that time. High Yielding Varieties (HYV) of seeds, application of high doses of fertilizers and assured irrigation were the three components of Green Revolution. Initially, canal water provided the needed irrigation, but canal systems designed during the British period and later in the 1950s were not meant for the kind of intensive cropping that Green Revolution brought about. Those systems were designed for 75% cropping intensity and the intent was to spread water as thinly as possible across a large command area. Every farmer got irrigation in turn – a system called *warabandi*. However, increased cropping intensity – now it was possible to grow 2-3 crops a year, provided you fertilised and watered them – meant that canals were no longer enough for the needs of a post Green Revolution India. Around this time, costs of pumps and drilling also came down drastically due to improvement of technology. All of a sudden, constructing a well (a shallow tube well to begin with), attaching a motorised or diesel pump to it and extracting groundwater for irrigation became technologically, financially and economically feasible. Agriculture as an enterprise became profitable due to assured input subsidies on the one hand and assured procurement price for food grains on the other hand. Both these – input subsidies and guaranteed procurement prices – were in response to the twin imperative of growing enough food to feed a burgeoning population and ensuring that food prices were kept cheap and affordable for growing urban population.

Second, and even more importantly, this period saw one significant change in electricity tariff structure. Electricity for agricultural pumping was de-metered and a flat rate was introduced. This change had much wider repercussions than were envisaged at that time. Till the end of 1970s, there was not much emphasis on electrification of agricultural tube wells. But it started changing around the 1980s when state electricity boards were given targets or rural electrification. Till then, electric tubewells were relatively few and far between, all of them were metered and farmers had to pay their electricity bills in accordance to usage. By the early 1980s, when rural electrification and electrification of agricultural tubewells was made a policy priority, many argued that costs of metering and billing scattered rural customers was way too expensive compared to the total revenue generated. Political populism coupled with pragmatism (at least it seemed so, then) led to a policy decision to de-meter electric tubewells in most (but not all) states in India. This meant no body measured the energy intensity of groundwater pumping any longer. Soon, electricity was made free in most states and this further tied the two sectors in an invidious nexus that eventually led to the kind of downward spiral in both electricity and groundwater sectors that we are witnessing today. I argue that it was the act of de-metering, rather than free electricity alone, that makes today's groundwater-irrigation nexus problem so hard to crack.

Managing W-E-F nexus in India: Examples from three states of West Bengal, Punjab and Karnataka

In this talk, I will describe three specific examples of states which have managed the W-E-F nexus quite differently with different outcomes. West Bengal has taken the classical textbook approach of introducing metering of agricultural pumps, while Punjab and Karnataka have taken the second-best option of segregating agricultural feeders and rationing power supply to agriculture. While Punjab implemented this measure with a modicum of success, Karnataka designed its rural feeder segregation in a way that was designed to fail. The difference in outcomes among the three states, I argue, is related to good governance and political will to enforce unpopular decisions. This underpins the need to adopt a political ecology approach to groundwater issues in India.

China: Safe and Sustainable Groundwater Supply in China

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Groundwater resources are critical for economic development and potable water supply, and groundwater supply accounts for 17.5% of the total water supply in China. Groundwater resources are unevenly distributed in China: 67.7% in southern China, and 32.3% in northern China where the extent of groundwater exploitation has been much more intensive. According to the 2011-2020 National Groundwater Pollution and Control Plan of China, 65% of domestic water consumption, 50% of industrial water consumption and 33% of agricultural water consumption in northern China depend on groundwater. Groundwater extraction has increased by approximately 2.5 billion cubic meters per year to meet agricultural, industrial and domestic needs over the past few decades. Consequently, groundwater levels have dropped greatly in many areas. As a result, 240 depression cones have formed which occupy an area of 7×104 km^2 in the eastern part of the North China Plain (NCP). Water scarcity has become an increasingly serious problem for most cities in China. In particular, the successive decrease in the groundwater level in many areas has led to groundwater resource depletion at an alarming rate in the northern and northwestern regions of China.

Groundwater containing high concentrations of geogenic arsenic, fluoride, iodine, and salinity is widely distributed across China, which has negatively affected safe supply of water for drinking and other purposes. Anthropogenic contamination of groundwater is most serious in developed regions at NCP, Yangtze River delta and Pearl River delta regions. The interaction between surface water and groundwater, including seawater intrusion, is another important factor for deterioration of groundwater quality. The ecosystem and geo-environment have been severely affected by the depletion of groundwater resources. Land subsidence due to excessive groundwater withdrawal has been observed in more than 50 cities in China, with a maximum accumulated subsidence of 2–3 m. Groundwater-dependent ecosystems are being degraded due to changes in the water table or poor groundwater quality.

Large scale irrigation has changed both recharge and discharge processes of groundwater systems. Improving irrigation efficiency and reducing groundwater pumping for irrigation may have no effect on water table declines due to reduced seepage.

The implementation of inter/intra-basin water diversion projects increases the frequency and complexity of surface water and groundwater interactions. The positive effect of the central route of the South to North Water Transfer (SNWT) project on groundwater has been obvious in retarding the trend of groundwater level decline and reducing the area of groundwater overexploitation in NCP by approximately 20%. By contrast, the water diversion projects in the endorheic river basins of northwestern China have led to more intensive groundwater use in the middle reaches but less groundwater replenishment due to decreased river leakage in the lower reaches.

Other human activities, such as intensive coal mining above Cambrian-Ordovician carbonate aquifers in northern China, have substantially changed groundwater recharge and discharge conditions. Water/wastewater drainage by coal mines has caused depletion of karst water resource and degradation of water quality.

Land-use change and climate change are also important factors affecting spatial and temporal changes in groundwater flow regimes, both directly (through replenishment by recharge) and indirectly (through changes in groundwater use).

The effects of rapid economic growth on groundwater systems should be monitored, understood and predicted for safe and sustainable groundwater supply. Although almost 30 thousand groundwater monitoring stations had been established by the Ministry of Water Resources by 2016, high-precision, high-resolution, and high-frequency depth-specific monitoring and field experiments are urgently needed for observing the behavior of groundwater flow and contaminant transport. In addition to traditional monitoring methods, interpretation of remote sensing and satellites data useful for monitoring regional changes in groundwater systems should be included in groundwater monitoring systems. Coupled groundwater and surface water models, which can simulate changes in both water quality and quantity caused by different impacts, should be developed for large basins and catchments to simulate and predict the evolution of groundwater systems. Such models should take into account the effects of water conservancy projects on groundwater systems. Optimization models should be developed and tested to optimize groundwater use, and guide water-saving practices and joint utilization of surface water and groundwater resource. More cost-effective and user-friendly remediation technologies to clean up contaminated aquifers need to be invented, tested and applied, which is especially important for distant and poor regions where there are no alternative sources for water supply. Geo-environmental engineering that aims to cost-effectively in situ remove or fix geogenic and/or anthropogenic contaminants in contaminated aquifers will become an increasing important new discipline linking hydrogeology and environmental engineering. Studies of complex problems such as the nexus of water-food-energy that will allow us to better understand the synergies and trade-offs between groundwater use and energy and food production involve multiple disciplines, such as hydrogeology, ecology, economy, management, law, and climate change. Thus, hydrogeological studies should be incorporated with these disciplines to resolve groundwater-associated problems and better manage groundwater resources.

Food Self-Sufficiency or Groundwater Bankruptcy?

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There is no doubt that the ancient Persians have proven their determination to survive and thrive by developing innovative methods for regulating, withdrawing, transferring, redirecting, and distributing water in an arid area of the world where water availability is limited. The Persians are still proud of their significant contributions to hydraulic engineering by inventing qanat—a series of well-like vertical shafts, connected by hand-dug underground tunnels—for sustainable groundwater withdrawal and transfer centuries before the Romans built their aqueducts; they developed one of the oldest water regulation, monitoring, and market systems in the history; and they constructed the tallest historic arch dam of the world, large gravity dams, flood control infrastructure, weirs, water transfer and delivery channels, as well as water mills long before most other nations.

In the modern times, however, rapid socioeconomic development has created a serious water bankruptcy problem for this proud nation. Drying lakes and rivers, declining groundwater resources, land subsidence, sinkholes, water contamination, water supply rationing and disruptions, forced migration, agricultural losses, desertification, salt and sand storms, and ecosystem damages are the modern water-related issues of a nation which was once recognized as the pioneer of sustainable groundwater management for thousands of years.

Iran has always suffered from a seriously inefficient agriculture that heavily relies on irrigation and consumes most of the country’s limited water resources. While only 15% of the country’s area is cultivated, this sector is responsible for 92% of the water consumption in Iran (compared to the 7% domestic water use and 1% industrial water use). Since the 1979 Revolution, the government has tried to be supportive of this sector in order to achieve food security and increase the non-oil production revenues. This policy was of particular importance and turned to be helpful during the Iran-Iraq war. Nevertheless, the economic efficiency of this sector has decreased significantly over time. Currently, this sector only provides about 20% of the jobs, and its contribution to GDP has decreased from over 30% to about 10%, while Iran has also lost its leading position at the international level in export of some high-value agricultural products like pistachio.

To support this sector, the government has heavily subsidized agricultural water and energy use. The significantly cheap prices have not provided any motivation for increasing the production efficiency in this sector. The average irrigation efficiency is less than 35%, and only 5% of the farmed area is under pressured irrigation. The rainfed agriculture is also unproductive, mainly due to the rainfall patterns. While the area under rainfed and irrigated agriculture are almost equal, the share of rainfed agriculture from the total yield is only about 10% (compared to the global food production shares of the rainfed and irrigated agriculture, which are 60 and 40 %, respectively). The crop pattern does not match the regional water availability and land suitability conditions and has remained more responsive to the traditional crop choices and farming practices as well as market price signals and the guaranteed crop purchase prices set by the government.

Groundwater is used as a supplementary source of water when surface water is insufficient. Groundwater pumping increases when surface water becomes scarcer as a result of droughts or allocation of surface water to other uses and users. Hence, the increase in water demand and use over the years has resulted in increased groundwater pumping. Given the low price of energy, the costs of energy for pumping have not been a limiting factor. As wells run dry due to lower groundwater levels, farmers dig deeper wells and buy pumps with higher lifting capacities. The collective effect of such behavior has been drastic.

The agricultural sector that pursues food self-sufficiency and security policies consumes a lot of groundwater, which currently satisfies close to 60% of the total water demand in Iran. The agricultural sector is responsible for more than 90% of the groundwater consumption (compared to the 8% domestic groundwater use and 2%

industrial groundwater use). The excess groundwater withdrawal is hard to estimate, but the dramatic drop of groundwater table reflects the extent of the consumption of the non-renewable portion of groundwater. As a result, almost half of the 609 plains in the country are in a critical condition and the declining groundwater table has caused groundwater quality degradation, significant land subsidence in many plains throughout the country, and formation of sinkholes in parts of the country.

The popularity of deep wells in Iran increased after the introduction of pumping technologies and the land reforms in the 1960s. The increased interest in deep wells and adoption of modern (Western) water harvesting technologies made traditional water harvesting techniques less attractive. Many qanats dried up and cooperative management institutions were replaced with fragmented, non-cooperative management systems that promoted competitive pumping, creating a tragedy of the commons.

In theory, wells need to have permits, although in practice, unpermitted wells are ubiquitous. Thus, illegal pumping is another important issue that the decision makers need to deal with. This problem has no easy solution as illegal wells are generally hard to detect and monitor. The government has put some effort into installing smart energy water meters for better monitoring of groundwater withdrawal and the associated energy use. Nevertheless, this has not yet resulted in a major shift in the behavior of well owners in most parts of the country. The government claims to be vigorously pursuing its national groundwater restoration and balancing plan, which intends to stop and reverse the current trend in groundwater use.

The presentation discusses how the thirst for independence and development together with overlooking the important trade-off between food self-sufficiency and water sustainability has resulted in groundwater bankruptcy and human security problems in Iran. It is argued why the problem cannot be resolved without a radical reform of the current water governance structure and policy solutions are proposed to address Iran’s groundwater bankruptcy problems that would be applicable to most other countries in Middle East and the developing world with similar socio-economic conditions.

Regulating Groundwater Uses in Spain: A Long-distance Race

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In Spain aquifers stretch across about 70% of Spain's territory and store over 300,000 hm^3 of water. Currently, estimated overall groundwater abstraction is about 7000 hm^3/y corresponding to 22% of Spain's total water demand for consumptive uses. Aquifers supply water to about 13 million inhabitants (28% of Spain's population) and are used to irrigate over one-fourth of the country's irrigated land. They also provide for almost one-fourth of the industrial demand and are key for hydrological functioning of rivers and wetlands.

Groundwater is a key resource for irrigating high value crops in several regions of Spain and for domestic supply in the vast majority of medium to small municipalities. Throughout Spain, it is a strategic resource during droughts, when it is used to complement declining surface water reserves in order to supply all sectors, including large cities that usually are supplied mostly with surface water. About 40% of Spain's groundwater bodies - units of groundwater management according to the European Union legislation that often correspond to aquifers - are classified to be in "poor status" either for water overdraft or for water pollution, or both.

Groundwater use started in the 1970s and experienced a spectacular increase during the 1980s and 1990s, when it enabled socioeconomic development in many rural regions. Declining water levels, together with the need for a legal framework to manage all waters led to approval of the Spanish Water Act in 1985. The Water Act established that from January 1st 1986 onwards all waters should be considered as public good, but pre-dating groundwater users could opt to maintain ownership over the resource. The 1985 Water Act also established specific measures in case of groundwater overexploitation, including moratorium on well drilling, restrictions to withdrawals and the mandatory creation of groundwater users associations.

After 32 years since the approval of the Water Act, it is possible to draw some lessons from the experience gained so far:

- In 1985 existing water institutions were designed to manage surface water. They were not ready to groundwater, which has very different characteristics and management challenges. This hampered the effective implementation of groundwater regulation and soon it became clear that it was necessary to build specific institutional capacity in order to manage groundwater.

- The set up and maintenance of a comprehensive inventory of groundwater rights proved to be extremely challenging because of its legal and technical complexity. The competent water authorities were not prepared to fulfil the role the Act assigned them.

- Insufficient human and technical resources, combined with local petty local corruption and a severe drought in the early 1990s, led to the registration of many *paper water rights* and over allocation of some aquifers.

- After three decades, the Spanish Water Act has failed to transform all groundwater rights into public water use permits (the law was designed to encourage that transition). The coexistence of private and public groundwater complicates the management of the resource.

- In several aquifers unauthorized wells have been a shortcut for accessing the resource, causing environmental and social problems.

- In many areas, mostly close to the Mediterranean coast, many small aquifers will never recover, because of seawater intrusion or groundwater mining.

- Water users associations have rarely emerged spontaneously and where they exist, they often have been for lobbying against governmental actions rather than for better managing the resource. Yet, there are some examples of water users associations (e.g. La Mancha Oriental; Llobregat) that are succeeding in improving the sustainability of groundwater use in their aquifer.
- Some of the strategies used to ensure water supply even when water table levels decline:
  - Look for external (subsidized) surface water (substitution of groundwater for surface water at times imported from other river basins; aquifer recharge);
  - Complement groundwater withdrawals with desalinated water for domestic supply and high value crops;
  - (Subsidized) improved water use efficiency;
  - Lobbying for public acquisition of irrigated land and groundwater rights
- Groundwater users traditionally have developed and managed their activity individually and still resist to external governmental interventions and limits on pumping.
- Groundwater users accept to cooperate and contain groundwater abstraction growth when they ‘hit the ceiling’ of water withdrawal (i.e. water quality degradation and/or too high pumping costs); or where there is a very strong social/legal pressure against environmental degradation and illegal pumping.
- Incentives for water users to act within the legal framework and make groundwater withdrawal compatible with environmental conservation need to be the right mix of legal, economic and social ingredients.

Key messages

a) Strategies implemented by the authorities and/or users to address groundwater overdraft have achieved the **gradual stabilization of groundwater levels rather than the recovery of the water table** and of ecosystems depending on groundwater.

b) **Groundwater users accept regulation and/or self-regulation only when they see their business jeopardize** e.g. because they are concerned for declining water quality, rocketing pumping costs or for reputational risks in the produce export market.

c) To achieve real change **it is necessary have all the parties committed to sustainable groundwater governance**: authorities at all administrative levels; users; consumers; NGOs; scientists, etc.

d) Groundwater use management requires a **change of mindset** in users, the authorities and the society at large, as well as the development of a solid governance ‘infrastructure’. This **cannot be achieved overnight**, only in the long run.

Some emerging issues related to groundwater use that will require higher attention in the future are:

- High concentrations of nitrates from agriculture in groundwater are an increasingly more severe problem for domestic supply in medium to small towns, where groundwater is the only resource available. Water degradation is causing interruptions in water supply, higher operation costs and the construction of infrastructure to bring surface water to substitute groundwater.

- Solar panels are increasingly being used to produce energy to operate groundwater pumps. While this can be positively valued from an energy production perspective, the availability of “cheap” energy is having a negative effect on pumping rates.

Will We Get to “Safe Yield?” Embracing and Dodging Groundwater Sustainability in Arizona

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Arizona has serious groundwater depletion and water supply sustainability problems to solve. But the state’s record so far in meeting this challenge has been disappointing. Arizona’s water elites have obfuscated the seriousness of Arizona’s water supply challenges by exaggerating progress toward sustainability, emphasizing short-term mitigations, and asserting that everything is under control and the future looks bright. While ample tools exist to put the state on a more sustainable path, regulators and politicians often undermine or fail to utilize those tools. Progress often comes at too slow a pace to avert crises, and crisis management is a deeply flawed approach to long-term resilience in water supply/demand management. As Jared Diamond argued in his provocative book, *Collapse*, societies choose whether to succeed or fail. Water leaders in Arizona have chosen a crooked and compromised path that will not assure the bright future they promise the public.

Groundwater depletion in central and southern Arizona’s main urban/agricultural regions became alarmingly noticeable by the 1940s. In the 1950s the Arizona legislature made its first timid effort to address it—to no effect. As water consumption and aquifer depletion accelerated in the 1960s the state’s water elite sought simply to augment the supply by importing more water to Phoenix and Tucson. Conversations about conservation and demand-management existed, but the real effort, money and political capital went to support a massive federally funded water importation scheme called the Central Arizona Project (CAP), a giant concrete canal designed to bring a large portion of Arizona’s Colorado River water entitlement 300 miles and a thousand feet uphill from the river to farmers and cities in central and southern Arizona. The promise of imported water reduced pressure on policy makers to get serious about demand reduction. As a result, aquifer depletion continued to worsen in the 1970s as the state eagerly looked forward to a flush of new water from the CAP.

During President Carter’s administration in the late 1970s a funding crisis stimulated the state’s first substantive success in establishing effective groundwater management policies. President Carter and his Interior Department administrators threatened to withhold funding for the CAP if Arizona did not adopt strong policies to curb groundwater overdraft. A new Arizona governor was elected in 1978, Democrat Bruce Babbitt, and he immediately went to work convening a group of power brokers from agriculture, industry, and the cities to draft a law that would satisfy the feds that Arizona was serious about water sustainability and thus “save” CAP funding. The 1980 Arizona Groundwater Management Act (AGMA) resulted.

At the time it was passed, the AGMA was considered to be one of the most forward-thinking and innovative groundwater laws in the United States. It designated several “Active Management Areas” (AMAs) in the state where groundwater depletion was particularly severe, mandated the AMAs achieve a “Safe Yield” of groundwater by 2025, required new housing developments in AMAs prove they had at least a 100-year “Assured Water Supply” (AWS), and created a state Department of Water Resources (ADWR) to implement the law and centralize water planning and regulation.

Unfortunately, the laudable goals of the AGMA have not been effectively or consistently realized. In the first two decades of implementation (1980s-1990s) ADWR developed unambitious conservation targets for cities and farmers and adopted a policy of voluntary compliance. Minimal measurable progress in reducing per capita water consumption occurred in those decades. Moreover, after the CAP Canal was completed to greater Phoenix in 1986, ADWR became even less willing to enforce conservation and more willing to tolerate noncompliance.

By 1993 the canal had been completed all the way to the state's second main urban center: Tucson. That same year the state legislature created a new agency cleverly designed to undermine the 100-year assured water supply regulation. It created the Central Arizona Groundwater Replenishment District (CAGRD), which would take over the responsibility of finding a water supply in the future for developments that could not demonstrate reliable access to 100 years of water. Developers would pay an enrollment fee and then homeowners would later have to pay whatever it would cost to acquire needed water resources. CAGRD has no guaranteed water supplies of its own other than a modest amount of temporary "excess" CAP water it bought and stored underground in the 1990s and 2000s. It has no guaranteed means for getting this water to the developments that will need it. One thing CAGRD was very successful at was facilitating uninterrupted housing development in the AMAs.

Arizona is now only seven years from the 2025 deadline to reach Safe Yield of groundwater and no credible analyst thinks the goal will be achieved. Arizona has made meaningful progress toward reducing per capita consumption in cities, substituting CAP water for groundwater, and halting the decline in some portions of the aquifers in the AMAs. But this progress is substantially based on temporary gains from converting agriculture to urban land uses and from the short-term availability of excess CAP water placed in underground storage. Continued progress in reducing groundwater overdraft in the Phoenix and Tucson AMAs is dependent on the continued availability of 1.4 million acre feet of CAP water. Climate change has already made a mockery of that hope as the Colorado River Basin states are today on the cusp of a water shortage declaration that would result in the CAP losing at least 300,000 acre-feet of water by 2020, with deeper cuts likely in the next five years.

The most common response of water managers and policy makers facing drought and shortages is to ramp up groundwater pumping and consume the water banked underground in recent decades. The total amount of water banked over the last twenty years in Arizona is around 8 MAF. That's equal to one year's total consumption in the state of Arizona and less than six years of water supplied by CAP. This does not inspire confidence that the gains in reducing groundwater overdraft will be sustained for long, unless new strategies are quickly adopted.

Exacerbating these challenges is the fact that most of the state lies outside Active Management Areas and therefore lacks effective groundwater monitoring and regulation. ADWR has the authority to extend active management to other parts of the state but has so far declined to do so. As a result, unresolved "water wars" are cropping up in the rural parts of the state (e.g., Willcox, San Pedro River valley, and Tusayan).

Arizona has a long way to go to get to sustainable, just, and resilient water management, and it now has less time and fewer resources to do so because of persistent drought and climate change. Policy makers in 1980 thought 45 years was a generous amount of time to get the state to groundwater sustainability but the goal keeps receding. The prevailing libertarian political culture in Arizona seems ill-prepared and maladapted to problem-solving on this scale. The thought-leaders who should be preparing the state for transformational change in consumption patterns are instead engaged in denialism (the drought is surely temporary and reservoirs will fill again), unwarranted boasting about progress, misplaced technological optimism (desalination will save us), and an intentional facade of optimism designed to reduce public concern and political interventions. Sadly, it seems likely that crises will continue to drive reforms in fits and starts, rather than measured, thoughtful long-term problem-solving guided by science, democracy, and well-designed institutions.

Mexico: Groundwater Management Paradigm Shift in Mexico: Urban Areas Growing vs Land Subsidence

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Land subsidence has become a generalized problem in metropolitan areas of Mexico. Differential compaction of sediments related to the increasing urbanization over compressible materials and strong groundwater withdrawals have caused the associated phenomena of subsidence and fracturing in the most populated cities of the country. All these cities had a rapid development in the last twenty years and many of them rely on subsurface resources for more than the 70% of water supply. This represents a great challenge that needs to be faced for the natural resources management, such as the use of land and groundwater. An accurate evaluation of the physical vulnerability of each study case requires the implementation of an interdisciplinary methodology including a review of water management, especially regarding groundwater supply in urban areas, so as studies of detailed geological, hydrogeological and morphological characterization accompanied with the surveying of groundwater piezometric evolution, land subsidence and, ground differential displacements. In order to face with the decrease in water availability in urban areas for the next years, it is urgent a paradigm shift within the Mexican water management agencies in order to increase the volumes of treated water and pluvial water collection, to increase the availability and quality of water for public use, and the efficiency in the water distribution systems in the cities.

Keywords: groundwater withdrawal, urban development, physical vulnerability, land subsidence, fracturing, Mexico

Groundwater management and growing of urban areas in Mexico: In Mexico, a population of 122.27 million inhabitants was estimated until 2016 and it is projected to be 137.5 by 2030. From 1950 to 2015, the population of the country quadrupled and went from being mostly rural (from 14.8 to 27.5 million inhabitants) to predominantly urban (from 11 to 92 million inhabitants). The process of concentration of inhabitants in urban localities has accelerated their growth, which implies strong pressure on the environment due to the increase in the demand for services, such as the availability of water. Until 2015, the 56.97% of the population in Mexico was concentrated in Metropolitan Areas (MA) (INEGI, 2015). According to estimates of the National Population Council (CONAPO, 2015), 32 MA have more than 500 thousand inhabitants, which represents a total of 62.08 million people and 50.77% of the national population, and by 2030, approximately 75% of the population will be in urban locations. Until 2016, the 15 MA with more than one million inhabitants, and that concentrates the 40.14% of the total population (49.09 millions inhabitants), are: (1) Valley of Mexico, (2) Toluca, (3) Guadalajara, (4) Monterrey, (5) Queretaro, (6) San Luis Potosi (7) Celaya-Salamanca (8) León, (9) Aguascalientes, (10) Morelia, (11) La Laguna, (12) Xalapa, (13) Puebla-Tlaxcala, (14) Mexicali, (15) Tijuana.

In Mexico two thirds of the territory (1,964 MKm^2) are arid or semi-arid zones (<500 mm/year of rain). There are 653 aquifers that contribute 39% of the volume for consumptive uses (76% agricultural, 15% Public, 4% industrial). By 2015, 105 of the aquifers were considered overexploited, 32 with saline and brackish water and 18 with saline intrusion (Conagua, 2017). Until 2016 the total volume of concessioned groundwater is 85,664.6 hm3: Agriculture 68.23%; Public-urban 14.52% and Industrial 7.4%. In the public use, the predominant source is groundwater with 58.7% of the volume. The use of superficial water coming from neighboring basins has increased, with the associated ecological issues. There are more than 3 thousand kilometers of aqueducts in Mexico that carry water to various cities and rural communities in the country. The main systems are: Lerma, Cutzamala, Acueducto II Querétaro, Realito SLP, Chalapa-Guadalajara, Linares-Monterrey (Conagua, 2017).

Geological and hydrogeological context: The most of the cities affected by land subsidence are located over former lakes in valleys bounded by faults and/or volcanic edifices of ages ranging from the Miocene to the

Quaternary that belong to a geological province named the Transmexican Volcanic Belt (TMVB) (Carreón-Freyre, 2010). The near surface stratigraphy below the cities is highly heterogeneous consisting of fluvial and/or lacustrine sediments with particle sizes varying from gravel, sand, and silt to clays, with interbedded layers of pyroclastic rocks and lava flows. Additionally, in extended lacustrine environments, such as in Mexico Basin, silt and clay size particles have a complex mechanical behavior. Compaction of sediments related to groundwater withdrawal has caused land subsidence in areas with rapidly increasing population (i.e. Mexico City, Toluca, Puebla, Queretaro, Celaya, Leon, Abasolo, Salamanca Morelia, San Luis Potosi, Aguascalientes, and Guadalajara, among others) (Carreón-Freyre, 2010). Thus, the study of the shallow stratigraphy and structural discontinuities of soil sequences in areas affected by subsidence and fracturing is necessary for the planning of urban infrastructure. Furthermore, the analysis of these phenomena requires an interdisciplinary approach for a better understating of the triggering mechanisms of differential settlements, generation and propagation of ground fracturing (Ochoa-González et al., 2018).

The Mexico Valley Basin is special study case, during the last centuries, as a consequence of the descending water level, the main valley was divided in several clay bearing fluvio-lacustrine sub-basins, which include Mexico City, Chalco, Texcoco. Xochimilco, and Zumpango basins (Carreón-Freyre et al., 2006). Over-exploitation of the aquifer has caused piezometric water level decline of about 50 m and near to 13 m of land subsidence in the central part of Mexico City. The subsidence related with the water decline was documented since the 1940´s (Carrillo, 1947). Ground fracturing in Mexico City has been reported since 1925 by Gayol and was analyzed by Carrillo (1947); Marsal & Mazari (1959) and Zeeavert (1953). Since then, the intensity of fracturing has increased and caused numerous problems to urban infrastructure. Hydrogeology studies in the basin of Mexico show that piezometric levels continuously decline in the aquifer, and that subsidence and fracturing continue to increase because of transient response of the overlying aquitard (Rivera & Ledoux, 1991). Estimations of infrastructure damage are in the order of several thousands of millions of dollars. Furthermore, the metropolitan area of Mexico City is the one in which more water is wasted, mainly due to leaks in the hydraulic network that, according to the Conagua, reach 38% (Conagua, 2017). It is important to note that the leaks can be due to a lack of maintenance but also to ground deformations and the eventual ruptures of pipes can be related to ground fracturing.

Final remarks: In order to face with the increase of population in urban areas and the decrease in water availability for the next years, it is urgent a paradigm shift within the Mexican water management agencies in order to diminish the extraction of groundwater and increase the volumes of treated water and pluvial water collection, which would increase the availability and quality of water for public use. It is also of the most importance to increase the efficiency in the water distribution systems in the cities and to take action to reduce its demand by the increase in the separation and reuse of wastewater. On the other hand, in order to continue guaranteeing social development, it will be necessary to continue increasing coverage in rural areas, especially in arid areas, and to improve agriculture irrigation systems. These trends should be considered considering climate change, whose effects will impact the global water cycle in a non-uniform manner.

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Groundwater Wells and Withdrawal Management in the Western USA

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Groundwater supplies 146 million Americans with drinking water, sustains more than 40% of USA irrigated agriculture, and enables economic productivity summing in the tens-of-billions of dollars. High demands for groundwater combined with limited long-term management and changing water supplies has led to declining water levels in many regions, especially in the western USA. Groundwater is a critical resource for the western 17 states, suggesting that future groundwater management and policy may need to go beyond the status quo. Here I present two continental-scale analyses that advance the way we think about (1) vulnerabilities and responses to declining groundwater levels and (2) our understanding of legal provisions for managing groundwater demands.

Three-dimensional, continental-scale maps of the risks to groundwater wells of varying depths imposed by groundwater level declines are not available. This lack of information about groundwater infrastructure can be problematic: without data showing where and why wells are constructed, it is difficult to identify wells and well owners at risk to groundwater issues. The first part of this presentation addresses this gap by coupling groundwater-level data and groundwater well information to identify which wells are likely dry due to groundwater level declines. Special attention is given to how existing three-dimensional, continental-scale groundwater data can be synthesized, analyzed, and visualized to advance the scientific understanding of local groundwater well vulnerability. The long-term goal of this research is to create the first-ever continent-wide maps showing where groundwater is being used so that groundwater resources can be managed better.

Water rights are regulated by state or local governments, resulting in a patchwork of legal powers over aquifers within the western USA. Nevertheless, there has yet to be a comprehensive and continental-scale characterization of legal controls on new groundwater withdrawals, nor an integration of big groundwater data from the hydrological sciences and law through quantitative spatial analyses. The second part of my presentation shows that regulatory controls have increased in space and time, covering a significant number of groundwater wells, but vast differences in regulatory frameworks may be undercutting sustainable water use. The long-term goal of this research is to create the first-ever continent-wide maps of legal provisions controlling groundwater withdrawals to expose inconsistencies in management or illuminate risks that warrant legal reform.

Groundwater Recharge Using the Agricultural Landscape

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In an average year, irrigated agriculture in the State of California uses up to 80% of the state's developed water supply allowing it to become one of the world's most productive agricultural regions. California generates 13% of the United States' agricultural farm output and 35% of the US table food on only about 1.2% of the total US farmland. California's massive agricultural production is made possible by its Mediterranean climate. However, because California's climate is characterized by the largest precipitation and streamflow variability observed within the conterminous US (Dettinger et al. 2011), it is susceptible to recurring droughts and floods that not only affect agriculture, but adversely affect the environment, urban users, industry and threaten the quality and quantity of the state's groundwater reserves. Across urban, environmental, and agricultural sectors, groundwater accounts for 38% of the California's water supply during a normal year, reaching upwards of 48% during a dry year (DWR 2015). The constant use of groundwater over the past century has led to groundwater overdraft of over 150 million acre-feet (ac-ft) throughout the Central Valley (1921-2017) (Faunt 2009, DWR 2018). During the recent 2012-2016 severe drought, groundwater depletion has averaged 8.1 million ac-ft per year alone (Xiao et al 2017).

With the passage of the Sustainable Groundwater Management Act in 2014 (SGMA 2014), state legislation now requires the implementation of groundwater sustainability plans by 2040 to ensure that all groundwater basins are managed sustainably (SWRCB 2014). One increasingly considered approach to achieve groundwater sustainability is managed aquifer recharge (MAR), which intentionally places more water in groundwater aquifers than would otherwise occur naturally (Bouwer 2002; Dillon 2005; Scanlon et al 2016; Kocis and Dahlke 2017). Efforts to recharge groundwater encompass several different approaches and sources of water. Some of the most common methods used in California are (i) conjunctive use – the joint management of surface water and groundwater to reduce overdraft, (ii) in-lieu recharge – the supply of surface water to users who otherwise rely on groundwater, and (iii) MAR methods such as infiltration basins, injection wells, and on-farm recharge (Dillon 2005, Russo et al. 2015; Dahlke et al. 2018). These MAR methods use a variety of water sources including surface water from rain and snowmelt, treated wastewater, desalinated water, and "produced water" obtained during oil-drilling to intentionally replenish underlying aquifers.

Agricultural groundwater banking (on-farm recharge, ag-MAR), a form of MAR where farmland is flooded with excess surface water in winter to intentionally recharge groundwater, has received increasing attention by policy makers and researchers in California (Bachand et al. 2014; Kocis and Dahlke 2017, Dahlke et al. 2018). The method is favored because it is capable of capturing large volumes of water when surplus surface water becomes available (e.g. during California's atmospheric river events), which can be transferred to farm fields via gravitational flow using the existing irrigation infrastructure in California.

Fig. 1. Winter flooding of an almond orchard to replenish groundwater.

This talk will present research that has been conducted over the past five years to improve understanding of the feasibility, limitations and concerns about adoption of ag-MAR in California. As illustrated in Figure 2, the talk will cover various factors of ag-MAR including the availability of excess streamflow for recharge, the suitability of alfalfa and almond cropping systems for winter flooding for recharge, concerns about groundwater quality impairments with nitrate, large-scale numerical model simulations of the effect of ag-MAR on groundwater storage and streamflow, and available decision support tools that can guide stakeholders and decision makers in water resources management.

Statistical analysis of USGS streamflow data within the Central Valley indicate that in an average year approximately 2.85 million acre feet of high-magnitude flow (10% highest flows on record) is exported from the entire Central Valley to the Sacramento-San Joaquin Delta between November and April often at times when demand quantities and water quality requirements of the Delta are fulfilled. High-magnitude flow occurs, on average, during 7 and 4.7 out of 10 years in the Sacramento River and the San Joaquin Tulare Basin, respectively, from just a few storm events lasting for 25-30 days between November and April (Kocis & Dahlke 2017).

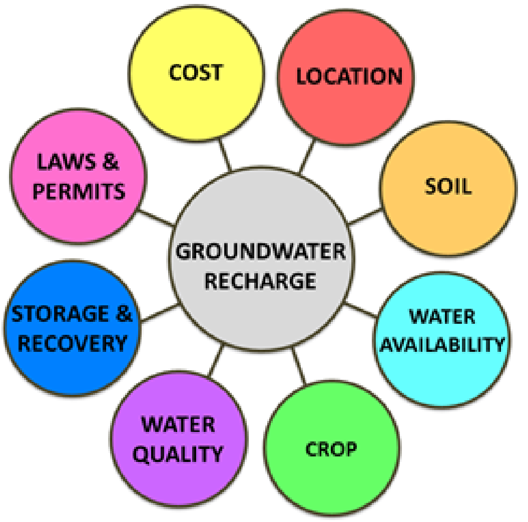

Fig. 2: Factors influencing the feasibility, risks and benefits of Ag-MAR.

Wintertime on-farm recharge experiments were conducted on old (>5-year) alfalfa stands in Davis and the Scott Valley (Siskiyou County), where variable amounts of winter water (4-28ft for alfalfa) and different water application timings were tested. At the 15-acre Scott Valley site a total of 135 AF and 107 AF of water were recharged during the winters of 2015 and 2016, respectively (Dahlke et al. 2018). Alfalfa yield data collected indicates that pulsed application of winter water on dormant alfalfa did not conclusively result in a significant decline in yield suggesting that the effect of winter flooding on dormant alfalfa is potentially small. Depending on antecedent moisture conditions and the water storage capacity of the soil more than 90% of the applied winter water percolated past the root zone and was moving towards the groundwater table. Plots where recharge water was applied later in the winter season showed clearly a higher plant available water content at the onset of the growing season (1-2 inches) than the control plots.

Using the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) we examined different hypothetical ag-MAR scenarios for a groundwater sub-basin within the Central Valley. The simulations tested the effect of (i) two different diversion locations, (ii) four different spatial distributions of recharge locations, (iii) five different temporal recharge patterns, and (iv) eight different recharge amounts on regional, long-term groundwater storage, changes in streamflow and baseflow, and changes in groundwater levels. The results show that the overall availability of stream water for recharge is critical for ag-MAR systems, while longer recharge periods at lower rates are more efficient than short recharge periods at higher rates. Recharge contributes to both, groundwater storage and stream baseflow. During the first decades of ag-MAR operation (e.g. 1930s and 1940s) the diverted water contributed mainly to groundwater storage. After several decades, about 60-70 percent of the diverted water contributed to stream baseflow. Groundwater levels rise is shown to vary with the spatial and temporal arrangement of ag-MAR, but overall ag-MAR provided long-term benefits on water availability. In addition we highlight the possible shortcomings of our current modeling approach and suggest several improvements.

Together these results highlight the opportunity and potential benefits for growers and water districts to implement ag-MAR as part of their sustainable groundwater management.

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Groundwater Governance, Policy and Regulation in the Arab World: A Reviewed Paradigm

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Faced with decreasing aquifer levels, groundwater pollution, inequitable access and generally poor management outcomes, groundwater governance has been put forward as a solution to address these challenges. Conventional efforts focus on improved legal frameworks, monitoring and control of access and abstractions through permits or formal rights, decentralised water management, and enforcement of regulations as cornerstone components of groundwater governance systems. These approaches however fail to reconcile the fundamental dynamics and properties of groundwater as a natural resource and of governance as a social and political phenomenon, thus remaining a-political and overlooking power dynamics and inequalities of access. Additionally, as the conventional definition of groundwater governance is limited, solutions put forward are also partial and do not encompass the wider challenges affecting groundwater governance. This presentation takes a particular look at agricultural groundwater use in the Arab World to constructively redefine the paradigm of groundwater governance and put forward a new approach that will support the effective development of governance-based solutions to achieve sustainable, resilient and equitable resource use. The challenging quest for such an updated groundwater governance approach starts by incorporating: 1) a proper conceptualisation of sustainable yields; 2) the appropriate consideration of ecosystem services derived from groundwater; 3) a realistic implementation of decentralised management; 4) integrated monitoring and rule enforcement; 5) enhanced incorporation of groundwater quality aspects; 6) an appropriate use of supply-side solutions and; 7) the critical and constant check on power and inequality aspects in access and allocation. The presentation emphasises why groundwater governance in its proposed new form is relevant as it enables us to streamline and expand the terminology, dialogue and frameworks necessary to fully address the multi-layered and multi-faceted complexities of groundwater governance, and improve the effectiveness of future solutions.