GROUNDWATER RECHARGE AND FLOW

Approaches and Challenges for Monitoring and Modeling Using Remotely Sensed Data

ABSTRACT PAPERS

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

Speaker Abstract Papers

These abstract papers were submitted by the speakers and are compiled here as they were submitted with only minor formatting edits.

State of the Art and Future Prospects for Observing Groundwater from Space

Matthew Roddell, NASA/GSFC

In the United States, the USGS and state agencies make a large number of groundwater monitoring well measurement records freely and easily accessible. Well drilling logs, ground penetrating radar, and other geophysical methods and geological mapping techniques provide additional information on U.S. aquifers. Outside of the U.S., depth-to-water observations and associated metadata are rarely systematic, and even where they are the data are seldom digitized, centralized, and available to the public. From 2002 to 2017 NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission delivered gravity field observations which have been used to infer variations in total terrestrial water storage (the sum of groundwater, soil moisture, snow and ice, and surface waters) at regional to continental scales. GRACE Follow On (GRACE-FO) launched in 2018 to extend this data record. Challenges to using GRACE and GRACE-FO for groundwater monitoring include their relatively coarse spatial and temporal resolutions, their inability to differentiate the terrestrial water storage components, and 2+ month data latency. Innovative approaches have been used to help overcome these challenges and to apply GRACE and GRACE-FO, together with other observations and models, for quantifying groundwater variations and depletion. Looking forward, global groundwater monitoring may be enhanced by the ongoing development of advanced satellite gravimetry techniques, application of interferometric synthetic aperture radar (InSAR) for mapping land surface vertical motions at high resolution, constraints provided new and improved observations of other hydrological variables, and more complex numerical models aided by increases in computing power. This will be crucial as reliance on groundwater continues to increase to support a growing world population and as groundwater recharge responds to climate change.

Global Data Needs to Advance Groundwater Resources Analysis

Holly Michael, University of Delaware

Sustainability of groundwater resources is an increasingly important global challenge as pressures of population and climate intensify. Effective groundwater assessment and management is critically dependent on the hydrologic, geologic, climatic, and human data available to inform the analysis. A perpetual obstacle for hydrogeologists is obtaining data with enough spatial coverage, density, and quality control to assess systems that range from plumes on the scale of tens of meters to transboundary basins that span hundreds of kilometers. Examples of groundwater studies in transboundary aquifers of southern Asia will be given that illustrate major problems of groundwater quality and quantity. The examples represent a broad range in data availability and illustrate both the role of data in groundwater sustainability analysis and strategies to tackle difficult problems in the absence of appropriate data. Though insights can be gained from generic analysis, ultimately the quality of a management strategy hinges on the quality of its data. There is a need for a global strategy to collect, manage, and share high-quality data if we are to address the water security challenges of the coming decades.

Integrating Remote Sensing Datasets to Estimate Changes in Groundwater Storage and Quality

Ryan Smith, Missouri University of Science and Technology

The availability of clean groundwater is of critical importance for food and water security. In spite of this, estimates of the spatial distribution of available clean groundwater are inherently challenging to make and typically require significant ancillary data from densely spaced wells. These datasets are either limited or not available in many regions of the world where groundwater resources are stressed. Interferometric Synthetic Aperture Radar (InSAR) and Airborne Electromagnetics (AEM) offer remote sensing-based approaches to estimate changes in groundwater storage and the total volume of storage, respectively. InSAR can be used to estimate changes in groundwater storage, which is related to land subsidence induced by pore pressure changes in confined aquifers. AEM is used to estimate the 3D resistivity of subsurface formations, which can be used to infer the presence and quantity of freshwater available.

Recent methods have been developed by Smith (Missouri S&T) and Knight (Stanford) to improve InSAR-based estimates of changes in groundwater storage by combining them with AEM data in the Central Valley of California. These data are combined in a coupled, mechanistic model that solves for the hydrologic parameters relating the observed InSAR and AEM data to groundwater storage. The model produced from this approach has the capability to forecast future loss of groundwater storage in confined aquifers given different hydrologic scenarios. Estimates of groundwater flux produced from InSAR were also linked to the release of arsenic from clays in confined aquifers in the same region by Smith, Knight and Fendorf (Stanford). The mechanism for this release is water flux from clays, which are enriched in arsenic, during episodes of extreme groundwater pumping and subsidence. This finding demonstrates that over-pumping of confined aquifers can degrade water quality in addition to depleting storage.

While using InSAR, AEM and other remote sensing methods independently of each other is beneficial, integrating them improves knowledge of groundwater storage and has particular potential in regions of the world where little geologic or hydrologic information is available. However, implementing these methods in data-sparse regions requires robust estimates of uncertainty. Ongoing research is exploring how to integrate these datasets with varying degrees of supplemental data at the regional scale in the Central Valley. While existing research is specific to California, these methods could be implemented in other regions of the world with appreciable land subsidence due to groundwater pumping.

Estimating Mountain Front Recharge and Deep Groundwater Circulation in New Mexico using Remotely Sensed Data and Magentotellueric Surveys

Mark Person, New Mexico Institute of Mining and Technology

Groundwater recharge in the arid southwest is generally confined to mountainous terrains where orographic precipitation locally exceed evapotranspiration. Within these upland environments, diffuse infiltration occurs into relatively permeable crystalline basement rocks as well as karst and sandstone aquifers. Focused recharge occurs along arroyos and streams during runoff events.

Over the past 5-10 years the faculty (Fred Phillips, Dan Cadol, Jan Hendrickx) and students (Peter Revell, David Ketchum, Fe Xu) at NM Tech have completed an analysis of diffuse and focused recharge as part of a statewide water budget assessment using a new Python Based recharge model (PyRANA). Precipitation and temperature information across the State was obtained using PRISM data. Vegetation information was obtained using MODIS satellite data. Soil properties were obtained from the NRCS soil data as well as state geologic maps. A soil water balance model was developed on a relatively high-resolution grid (250m x 250m) using daily time steps. Recharge was calculated to be as high as 20% of precipitation in mountainous terrains. In semi-arid parts of the state, recharge did not exceed 4 % of precipitation. PyRANA recharge estimates were compared to those computed using the chloride mass balance method. Focused recharge along 2nd to 3rd order streams was calibrated by comparing simulated runoff to stream and flume discharge records.

Within the Rio Grande Valley, Person and his students (Jeff Pepin, Matt Folsom, Brad Sion) undertook a magnetotelluric field campaign to image mountain front recharge and deep (> 5 km) groundwater circulation in the vicinity of the spa Town of Truth or Consequences. Geothermal springs (up to 42 ^{o}C) discharge directly from the crystalline basement near the Rio Grande within a "hydrologic window" where sedimentary confining units are absent. Disturbed temperature profiles and changes in river indicate that groundwater discharge from the crystalline basement into the Rio Grande is about 2.1 million gallons per day. These geothermal fluids are brackish (~ 2 ppt) and contribute to the salt load of the Rio Grande. The crystalline basement discharge at Truth or Consequences represents about 10 % of the total estimated mountain front recharge from the Sierra Cuchillo and San Mateo Mountains to the West. Lateral changes in crystalline basement formation resistivity obtained from our magnetotelluric survey suggests groundwater circulation to 10 km depth. Aquifer tests and ^{14}C groundwater residence time data confirm that crystalline rocks are unusually permeable (> 10^{-12} m^{2}).

Ground deformation: a tool for characterization of aquifer systems properties and groundwater recharge and flow

Estelle Chaussard, University of Oregon

GROUND DEFORMATION (INTERFEROMETRIC SYNTHETIC APERTURE RADAR AND GPS/GNSS)

InSAR (Interferometric Synthetic Aperture Radar) provides a new remote sensing method to characterize aquifer systems properties and groundwater recharge and flow through measurement of ground deformation. The high spatial resolution (10 m) and high spatial coverage (hundreds of square kilometers) of the technique provide useful information at the water management scale, while the lack of ground access enables monitoring of remote areas. Current and future SAR satellites enable weekly measurements of most aquifers on the planet, opening the way to remote sensing support and assessment of groundwater management.

Large-scale space geodetic surveys have exposed extensive ground deformation associated with exploitation and recharge of aquifers, revealing that an increasing number of cities and agricultural areas worldwide are experiencing **land subsidence** leading to high risks of infrastructure damage, flooding, and loss of productive land (e.g. Chaussard et al. (2013a); (2014b)).

Burbey (2003) showed that storage values are far more sensitive to deformation than to hydraulic head observations, suggesting that deformation can be used to **characterize the properties** of an aquifer system and their variability in time and space. By combining ground deformation measurements with groundwater levels, Chaussard et al. (2014a) showed that aquifer systems properties can be constrained at the scale of an entire aquifer and Chaussard et al. (2017) showed that temporal changes can be used to track the "health" of an aquifer system and evaluate water management practices.

Multi-decadal InSAR time series of ground deformation combined with statistical methods such as Principal and Independent Component Analyses can be used to isolate both **inelastic and elastic components** of the deformation without any a priori knowledge on the deformation history (Chaussard et al., 2014a; 2017).

In areas where elastic deformation dominates, after a period of calibration between deformation and water levels measurements, **hydraulic head levels can be predicted** from observations of ground deformation, therefore decreasing the cost of monitoring (Chaussard et al., 2014a).

Combining InSAR-derived ground deformation in aquifer systems with precipitation or water import data can be used to **track recharge and water migration** though the system (Chaussard et al., 2017). In contrast, GPS/GNSS data, which provides local but high temporal resolution deformation (continuous instead of every week or longer for InSAR) enables millimeter scale detection of hydrological load changes signal associated with *surface water* (e.g. Amos et al. (2014); Borsa et al. (2014); Argus et al. (2017)). These surface load changes can be translated into equivalent surface water thicknesses which can be used to characterize recharge from surface water near aquifer boundaries. InSAR and GPS/GNSS data are therefore highly complementary and combining them could provide a new way of characterizing local to aquifer scale water **recharge and flow from surface to groundwater**.

Faults can be barriers to fluid flow or conduits and even reservoirs for significant quantities of groundwater and can be associated with damaging earth fissures. Beyond vertical deformation, horizontal deformation retrieved from GPS/GNSS and InSAR data (when ascending and descending data are available) can be used to infer the occurrence, location and poromechanical and hydraulic characteristics of faults and aquifer systems (Burbey, 2008; Chaussard et al., 2014a).

GRAVITY (GRACE AND GRACE FO)

GRACE provides water storage variations for the past 15 years (e.g. Thomas et al. (2017)) at regional scales (e.g. Famiglietti et al. (2011)). However, the spatial resolution of the gravity data (~200 km) is too coarse to be used by water districts for evaluation of water management practices. Recently, Castellazzi et al. (2018) showed that large scale, high resolution InSAR ground deformation data could enable **bridging the gap between the remote sensing techniques** currently used to estimate hydrological loading (GPS and GRACE). Such a systematic integration of remote sensing data is a step towards remote sensing support and assessment of groundwater management and is necessary to achieve water sustainability in the context of population growth and a changing climate.

While these various remote sensing methods improve characterization of the total volume of extracted water, recharge, and aquifer properties, a major **research frontier** remains the **characterization of the total volume of remaining water in aquifer systems** worldwide.

REFERENCES:

Amos, C. B., P. Audet, W. C. Hammond, R. Burgmann, I. A. Johanson, and G. Blewitt (2014), Uplift and seismicity driven by groundwater depletion in central California, Nature, 509(7501), 483–486, doi:10.1038/nature13275.

Argus, Donald F., Felix W. Landerer, David N. Wiese, Hilary R. Martens, Yuning Fu, James S. Famiglietti, Brian F. Thomas, Thomas G. Farr, Angelyn W. Moore, and Michael M. Watkins (2017). Sustained Water Loss in California's Mountain Ranges During Severe Drought From 2012 to 2015 Inferred From GPS. Journal of Geophysical Research: Solid Earth, 122(12).

Borsa, A. A., Agnew, D. C., & Cayan, D. R. 2014. Ongoing drought-induced uplift in the western United States. *Science*, *345*(6204), 1587-1590.

Burbey, T., 2003. Use of time-subsidence data during pumping to characterize specific storage and hydraulic conductivity of semi-confining units. Journal of Hydrology, 281(1-2): 3-22.

Burbey, T.J., 2008. The influence of geologic structures on deformation due to ground water withdrawal. Ground Water, 46(2): 202-211.

Castellazzi, P., L. Longuevergne, R. Martel, A. Rivera, C. Brouard, and E. Chaussard (2018), Remote Sensing of Environment, Remote Sensing of Environment, 205, 408–418, doi:10.1016/j.rse.2017.11.025.

Chaussard, E., Amelung, F. and Aoki, Y., 2013. Characterization of open and closed volcanic systems in Indonesia and Mexico using InSAR time series. Journal of Geophysical Research: Solid Earth, 118(8): 3957-3969.

Chaussard, E., Bürgmann, R., Shirzaei, M., Fielding, E.J. and Baker, B., 2014a. Predictability of hydraulic head changes and characterization of aquifer-system and fault properties from InSAR-derived ground deformation. Journal of Geophysical Research: Solid Earth, 119(8): 6572-6590.

Chaussard, E., Milillo, P., Bürgmann, R., Perissin, D., Fielding, E.J. and Baker, B., 2017. Remote sensing of ground deformation for monitoring groundwater management practices: application to the Santa Clara Valley during the 2012–2015 California drought. *Journal of Geophysical Research: Solid Earth*, *122*(10), pp.8566-8582.

Chaussard, E., Wdowinski, S., Cabral-Cano, E. and Amelung, F., 2014b. Land subsidence in central Mexico detected by ALOS InSAR time-series. Remote Sensing of Environment, 140: 94-106.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, Geophysical research Letters, 38(3), doi:10.1029/2010GL046442.

Thomas, B. F., Famiglietti, J. S., Landerer, F. W., Wiese, D. N., Molotch, N. P., & Argus, D. F. (2017). GRACE groundwater drought index: Evaluation of California Central Valley groundwater drought. Remote Sensing of Environment, 198, 384-392.

Characterizing Groundwater Fluzes with Derived River Discharges from the Surface Water and Ocean Topography (SWOT) Mission

Edward Beighley, Northeastern University

The Surface Water and Ocean Topography (SWOT) satellite mission is a joint effort between NASA and the French Space Agency (CNES) with participation from the Canadian and UK space agencies. Scheduled in launch in late 2021, SWOT will, for the first time, provide simultaneous high-resolution measurements of water surface elevation and extent. Focusing on the terrestrial aspects, SWOT will provide near global coverage for rivers, wider than 50-100 meters, and lakes/reservoirs, with surface areas exceeding 0.01-0.06 sq. km, at least once and as many as seven times every 21 days, with more observations at higher latitudes. In addition, the revisits within the 21-day orbit cycle are not uniformly spaced in time (e.g., one site on the Mississippi River will be observed on days 8, 19 and 20 within each 21-day orbit cycle). Based on repeat visits, changes in water surface elevation, extent and slope will be used to derive reach (about 10 km) averaged river discharge. Currently, there are numerous groups developing/refining a suite discharge algorithms and assimilation methods to produce SWOT discharges. While the derived discharges will have uncertainties larger than in-situ observations, expected discharge uncertainties are still being quantified and will likely vary based on river morphology and discharge dynamics. Using one algorithm, termed the Bayesian AMHG- Manning (BAM) algorithm, which implements a Bayesian formulation of streamflow uncertainty using a combination of Manning's equation and at- many- stations hydraulic geometry (AMHG), preliminary results show that synthetic SWOT discharges (i.e., accounting for space-time sampling and potential uncertainties) capture discharge frequency behavior throughout the Mississippi River Basin. Focusing on periods of discharge recession (i.e., largely controlled by groundwater flow), preliminary results suggest that SWOT has the potential to provide new, global insights on reach scale groundwater discharges, especially in regions with limited in-situ observations.

Connecting the dots with airborne geophysics—aquifer mapping at unprecedented scales

Burke Minsley, U.S. Geological Survey

Earth's subsurface hosts the groundwater resources that sustain life and society, is the foundation to landscapes that support diverse ecosystems, and is where much of the natural- and built-environment is vulnerable to impacts from human activity, natural hazards, and climate change. Despite its importance, our ability to characterize the subsurface geology and aquifer systems beneath us- particularly over large areas and with high spatial resolution- has been limited by a lack of cost-effective and mature technologies. Recent advances in airborne geophysics—in particular airborne electromagnetic (AEM) instruments and software tools—are changing this reality. Much as LiDAR and other remote sensing technologies have transformed the way in which we interpret the geomorphological processes that have shaped Earth's surface, AEM surveys are rapidly becoming a foundational tool for extending our view into the subsurface, mapping geological and hydrological properties from 10's to 100's of meters below ground at watershed-to-basin scales.

There is growing demand for detailed geological information in support of groundwater management decisions that, in many instances, requires new understanding of aquifer systems. Hydrological applications of AEM surveys include mapping aquifer structure and hydrologic properties, delineating shallow confining layers that may be barriers to recharge, mapping of frozen ground or ice thickness, and identifying spatial variability in groundwater salinity. AEM data uniquely fill a critical scale-gap between sparse boreholes or other ground-based data, and extensive but depth-limited remote sensing observations. I will introduce the basic concepts of AEM and other airborne geophysical sensors and will discuss how they are used in hydrologic applications, including recent examples from the largest-of-its-kind survey in the US for water resource studies in the lower Mississippi River Valley.

Characterization of Aquifers Supporting Irrigated Agriculture: The Questions Determine Our Focus

James Butler, Kansas Geological Survey, University of Kansas

For decades, the majority of annual global groundwater pumping has been in support of irrigated agriculture. As a result of this intensive use, many of the world's major aquifers are being depleted at an alarming rate. Food security, whether it is viewed from a local, regional, or global perspective, will be significantly affected if this depletion continues unabated. Our ability to forecast what the future holds for these globally important systems depends on our ability to define the components of their surface and subsurface water budgets. Determining the components of the water budget on the land surface is a challenge, but determining the components of the budget of the underlying aquifer is a much more arduous task. The first issue we should address concerning aquifer characterization is what questions are we trying to answer, as as our strategies for where to focus our characterization efforts will depend on the questions we are asking and their spatial and temporal scales. For example, in aquifers that are in a mature stage of development (i.e. have been heavily pumped for decades), common questions include what would be the aquifer's response to pumping reductions (i.e. can we significantly reduce the rate of water-level declines through practically feasible reductions) and what would be the impact of drier conditions. For the agricultural sector, the time frame is typically the near to moderate term, which could be defined as a few decades or less, and the spatial scale is local, which could be defined as several thousand square kilometers or less. In that case, we can often provide reasonable predictions for practical use by exploiting the inertia in groundwater systems if we focus on acquiring information about water-level or storage changes and pumping. Water-level or storage changes can be estimated via a variety of means, although the scale of some of the estimates may hinder their utility for practical applications. Pumping, however, has proven much more difficult to quantify. We can improve our methods for estimating pumping by refining them in basins that have been heavily metered, such as the High Plains aquifer in Kansas where over 95% of non-domestic pumping wells are metered and subject to regulatory oversight. If we can acquire reliable information on these key components of the water budget, we can make significant strides forward in assessing the near-term future of a heavily stressed aquifer and in decreasing the uncertainty involving the other components of the aquifer's water budget.

Frontiers and data gaps in regional groundwater modeling

Laura Condon, University of Arizona

In recent years there has been a notable push within the hydrologic community to improve groundwater representation in large-scale models. Global Land Surface and Earth Systems Models generally do not extend below 2-3m and they either (1) exclude groundwater below this point, (2) include a conceptual bucket for groundwater storage or (3) represent baseflow using a topographically based water table configuration(Clark et al., 2015). Global water balance models focus on watershed scale hydrologic exchanges. In the past these tools mostly treated groundwater as a storage reservoir with parameterized infiltration and discharge to surface water bodies (Scanlon et al., 2018). Increasingly though, global groundwater models are also being developed and incorporated into large scale analysis. Approaches vary from 2D transect steady state models (Fan et al., 2013; Gleeson et al., 2016) to transient gridded approaches simulating saturated groundwater flow (de Graaf et al., 2015; de Graaf et al., 2017). Integrated hydrologic models, which simulate 3D variably saturated groundwater flow are not running globally but have been implemented across the continental US (Maxwell & Condon, 2016) and Europe(Keune et al., 2016).

Large scale groundwater simulations are partially limited by computational resources, but also consistent data on hydro-stratigraphy limits our ability to develop models outside watersheds with extensive observations. There have been recent efforts to map lithological classes and their hydrologic properties (i.e. permeability and porosity) globally (Gleeson et al., 2014; Gleeson et al., 2011; Hartmann & Moosdorf, 2012). These datasets provide unprecedented global information on subsurface properties below the soil (roughly the top 100m), however they still provide depth average information and are limited in their representation of hydro-stratigraphy. Previous depth to bedrock maps focused on mapping areas of shallow bedrock (i.e <2m) (Miller & White, 1998). Recently two new global products estimate the total depth of the permeable layer (i.e. soil, intact regolith and sedimentary deposits) up to 540m (Pelletier et al., 2016; Shangguan et al., 2017). In addition to these global datasets, there are efforts such as the DigitalCrust project designed to provide a central place to stitch together existing observational datasets (Fan et al., 2015).

Observations of subsurface properties and groundwater heads are one critical piece to groundwater model construction; however, flux observations are equally important for model performance. Uncertainty in the relative importance of different historical and future groundwater recharge mechanisms (e.g. episodic, diffuse, focused, mountain or irrigation recharge) (Meixner et al., 2016) as well as uncertainty in recharge magnitudes can be significant (Scanlon et al., 2006). Similarly, observations on groundwater discharge are severely lacking outside heavily studied groundwater systems. Currently, large scale groundwater storage changes are often validated using GRACE satellite observations. While GRACE provides unprecedented insights into global storage dynamics, there are still significant uncertainties and scaling limitations in these approaches and recent comparisons have demonstrated large disagreement in the storage behavior of global models (Scanlon et al., 2018). Further work is needed to improve groundwater flux observations and to improve model evaluation and performance with respect to groundwater dynamics.

References

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., et al. (2015). Improving the representation of hydrologic processes in Earth System Models. *Water Resources Research, 51*(8), 5929-5956. http://dx.doi.org/10.1002/2015WR017096

de Graaf, I. E. M., Sutanudjaja, E. H., van Beek, L. P. H., & Bierkens, M. F. P. (2015). A high-resolution global-scale groundwater model. *Hydrol. Earth Syst. Sci., 19*(2), 823-837. http://www.hydrol-earth-syst-sci.net/19/823/2015/

de Graaf, I. E. M., van Beek, R. L. P. H., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, E. H., & Bierkens, M. F. P. (2017). A global-scale two-layer transient groundwater model: Development and application to groundwater depletion. *Advances in Water Resources, 102*, 53-67. http://www.sciencedirect.com/science/article/pii/S030917081630656X

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. *Science, 339*(6122), 940-943.

Fan, Y., Richard, S., Bristol, R. S., Peters, S. E., Ingebritsen, S. E., Moosdorf, N., et al. (2015). DigitalCrust - a 4D data system of material properties for transforming research on crustal fluid flow. *Geofluids, 15*(1-2), 372-379. http://dx.doi.org/10.1111/gfl.12114

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, B. M. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience, 9*(2), 161. http://dx.doi.org/10.1038/ngeo2590

Gleeson, T., Moosdorf, N., Hartmann, J., & Beek, L. P. H. (2014). A glimpse beneath earth's surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity. *Geophysical Research Letters, 41*(11), 3891-3898. http://dx.doi.org/10.1002/2014GL059856

Gleeson, T., Smith, L., Moosdorf, N., Hartmann, J., Durr, H. H., Manning, A. H., et al. (2011). Mapping permeability over the surface of the Earth. *Geophysical Research Letters, 38*(L02401).

Hartmann, J., & Moosdorf, N. (2012). The new global lithological map database GLiM: A representation of rock properties at the Earth surface. *Geochemistry, Geophysics, Geosystems, 13*(12). http://dx.doi.org/10.1029/2012GC004370

Keune, J., Gasper, F., Goergen, K., Hense, A., Shrestha, P., Sulis, M., & Kollet, S. (2016). Studying the influence of groundwater representations on land surface-atmosphere feedbacks during the European heat wave in 2003. *Journal of Geophysical Research: Atmospheres, 121*(22), 13,301-313,325. http://dx.doi.org/10.1002/2016JD025426

Maxwell, R. M., & Condon, L. E. (2016). Connections between groundwater flow and transpiration partitioning. *Science, 353*(6297), 377-380.

Meixner, T., Manning, A. H., Stonestrom, D. A., Allen, D. M., Ajami, H., Blasch, K. W., et al. (2016). Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology, 534*, 124-138. http://dx.doi.org/10.1016/j.jhydrol.2015.12.027

Miller, D. A., & White, R. A. (1998). A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. *Earth Interactions, 2*(2), 1-26. http://dx.doi.org/10.1175/1087-3562(1998)002<0001:ACUSMS>2.3.CO;2

Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G. Y., et al. (2016). A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling. *Journal of Advances in Modeling Earth Systems, 8*(1), 41-65. http://dx.doi.org/10.1002/2015MS000526

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, M. W., & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes, 20*(15), 3335-3370. http://dx.doi.org/10.1002/hyp.6335

Scanlon, B. R., Zhang, Z., Save, H., Sun, A. Y., Schmied, H., van Beek, L. P. H., et al. (2018). Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. *Proceedings of the National Academy of Sciences, 115*(6), 201704665. http://dx.doi.org/10.1073/pnas.1704665115

Shangguan, W., Hengl, T., de Jesus, J., Yuan, H., & Dai, Y. (2017). Mapping the global depth to bedrock for land surface modeling. *Journal of Advances in Modeling Earth Systems, 9*(1), 65-88. http://dx.doi.org/10.1002/2016MS000686

Combining land-surface models and satellite data to map uncertainty

J.T. Reager, University of California, Los Angeles

A major frontier in groundwater modeling is in model-data fusion. This includes how we construct models, not just from an empirical process representation that is uninformed by observations, but rather process representations that are constructed to package the information that we have from observations. That can manifest in the facilitation of calibration/validation of models or in data assimilation methodologies. Consideration of these topics from the beginning of model design necessitate a very explicit representation of model uncertainty, as well as observational uncertainty, across scales and processes. Models and data therefore represent an ecosystem of information, that allow us to precisely map where knowledge gaps are and where we need to direct future observational efforts. I will briefly discuss some recent work on assimilation and downscaling of GRACE satellite data using a land-surface model and the model structural changes that were required in order to validate with well observations.

Draft Answers to Guiding Questions for Panel 3: Mitigating Groundwater Model Uncertainties

Stacey Archfield, U.S. Geological Survey

1. What are the modeling frontiers for understanding regional groundwater recharge and flow?

Archfield: My expertise is primarily in surface-water statistics and modeling so my perspective derives from that. Some thoughts are: (1) There is a continued need to improve process representation and storage at spatial and temporal scales relevant to manage surface and groundwater resources and that resolve the dominant yet different time scales at which groundwater and surface water processes take place and interact. (2) Attribution of regional trends in groundwater recharge and flow remain elusive because of the lack of process understanding. For example, the relation between groundwater depletion and streamflow remains difficult particularly when overlain with observed increases in precipitation.

2. What are the key groundwater model uncertainties and the methods for mitigating them using sparse ground observations, more readily available geospatial data, and other approaches?

Archfield: (1) The need for surface water and storage information to constrain regional groundwater modeling remains a challenge, particularly in sparsely gaged areas. This could be mitigated by various techniques to transfer information from gaged to ungaged locations or this could be addressed by newer remotely-sensed data products, such as DSWE (Dynamic surface-water extent). (2) Understanding the limits of applicability for remotely-sensed data so that their contribution to uncertainty is understood and quantifiable. This requires ground-truthing and having the right ground-based to ground-truth. (3) High-quality data related to water use at the temporal scales needed by groundwater models. (4) Understanding data networks and their gaps (spatial and temporal gaps as well as the types of data collected) so that if/when funding is available, these gaps can be filled to address the highest priorities for uncertainty reduction.

3. What kinds of data would be most useful in minimizing model uncertainty, whether methods exist or not for these measurements?

Archfield: (1) High resolution, real-time water quality derived from advanced monitoring systems. (2) Coupled groundwater-surface water monitoring stations. (3) Methods to understanding the relative contributions of uncertainty to prioritize where efficiencies in uncertainty reduction can be achieved. (4) Investment in time-varying geospatial data to evaluate landscape change and better constrain model parameters. (5) Continued investment in long-term montoirong locations to understand change. (6) Water use information.

4. What approaches can be used to improve the modeling of groundwater water quality (e.g., heavy metal or biological contaminants)?

Archfield: I cannot offer much here; I do not have a geochemistry background. The USGS does have a number of publications with open-source data on the state of groundwater in our Nation's rivers (see: https://water.usgs.gov/nawqa/digmap.html). I did wonder if understanding the co-occurrence of groundwater-quality constituents could be used to identify markers of groundwater quality. This would allow models to minimize the number of constituents to be modeled, as one constituent could be a proxy for others.

Argument for assessment of microbial quality of groundwater to strengthen future development of sensors

Thanh (Helen) Nguyen, University of Illinois at Urbana-Champaign

Traditional satellite remote sensing techniques have a limited scope in assessment of microbial contamination of groundwater. With the unprecedented flooding on the southeastern and midwestern regions of the US during 2018 hurricane season, there is a growing concern of unknown interaction between surface and groundwater. Increase in groundwater table, as a result of short term flooding, has resulted in wet vadose zones that are unable to sustain crops in many parts of the Midwest region and also for maintaining a healthy condition for livestock. However, the long-term impact of the flooding and connection between flood water and groundwater is unknown, and needs better quantification. Inland flooding which happens due to extreme rainfall and sometime snowmelt could spread microbial contaminants from both human and animals that are usually kept contained over a large area. Surface-groundwater interaction could allow these microbial contaminants from the flood water to intrude the groundwater. The 2018-2019 flooded regions of the southeast and Midwest are mostly rural, where animal production is concentrated and where residents rely on septic tanks and well water. There is a clear lack of knowledge on how these extensive and sometime prolonged flooding influence groundwater quality and on how to develop new remote sensing technologies to predict the potential contamination of groundwater in susceptible regions. The answers for these questions will allow the development of management strategies that will allow in preparedness for assessment of microbes in the water system. In addition, these questions should be answered not only by monitoring but also by understanding the source of microbial contaminants, the evolution of the microbes, the animal production system, the human community living in these regions, the economy of the regions and the civil infrastructure of the regions. A new system of sensors needs to be developed which will continually monitor the water quality in shallow aquifers, especially in rural agricultural regions.

Agriculture and Groundwater

Michael Cosh, U.S. Department of Agriculture Agricultural Research Center

Approximately, 40% of agriculture productivity depends on groundwater for its operation/irrigation systems. 57.2 billion gallons of groundwater are pumped for agricultural irrigation, resulting in an economic productivity of $117billion/year. Without groundwater, agriculture would be restricted to rainfed systems. Global cropping intensity of irrigated lands are approximately 130%, so the arable land use would need to increase to compensate for restriction of irrigation. In addition, groundwater interacts with agriculture in several ways, both by deficiency and excess. Flooding causes approximately $4.3B/event, and drought is responsible for $9.7B/event, while Tropical Cyclones are the highest at $21.8 B/ event. Furthermore, at the microscale, trafficability is an issue for agriculture, preventing timely harvest and loss of crop from unstable soil. Mitigation of excess water also influences and reconfigures the hydrologic cycle via tile drainage systems. These systems have been implemented for over a century in the northern plains to remove excess water from the fields to allow for crop growth and mechanized harvesting. Tillage also interacts with groundwater recharge as conservation tillage will control erosion, but increases surface runoff, thus decreasing groundwater recharge. The common prairie potholes, which have been a source of groundwater recharge are being rerouted to surface water quickly and efficiently, depriving the recharge of the deep groundwater. Lastly, oases are controlled agricultural systems, which can be operated completely by irrigation with otherwise optimal growing systems, such as the California central valley and the American Southwest. These systems are run from groundwater and surface water systems, which are intimately tied together, but in an otherwise water poor region. This rebranding of the ecosystem has unusual and unnatural impacts, which are only being understood in the short term, due to the lack of record. Lastly, groundwater systems are complex with regards to water rights and a variety of legal precedents and basin partnerships usually come into play when negotiating water use, including ecosystem services and minimum flows.

Challenges in Understanding Continental Scale Groundwater Variability, Change and Appropriation

Sankar Arumugam, North Carolina State University

Understanding the changes in regional/continental groundwater use is essential for the sustainable use of the resource. However, sparse and discontinuous groundwater data poses challenges in estimating the groundwater appropriation. We analyze changes in long-term groundwater withdrawal for two sectors, public supply and irrigation, at continental scale over the US and China. Our analyses using the six USGS surveys over a 30-year period show that groundwater appropriation is in general on the rise over the coterminous US with the exception of few states (Public Supply: CA, TX, PA, NY, VA; Irrigation: AZ, CA, KS, CO, NE). As opposed to the USGS once-in-five-year surveys, water use data is collected every year in China. Similar analysis was conducted at the state level over China based on the annual water use data available over the period 1998-2015. Spatio-temporal analyses show that arid states in the North East China (i.e., North China Plain (NCP)) show decline in the consumption of groundwater as most states in the NCP region have reached the physical limits with the withdrawal being more than the recharge. Analyses on irrigation efficiency over China also shows water-rich provinces have lesser efficiency (Southern and Western Provinces) compared to the arid North Eastern States.

Even though the analyses on both the US and China show a large-scale pattern of changes in withdrawal over a longer period, considerable skepticism remains on the USGS water use data as the once-in-five-year data is reported voluntarily. Additional challenges also remain with the USGS water use data. For instance, details on the area irrigated under surface water and groundwater do not exist with the USGS surveys. Thus, it is hard to relate the role of irrigation technology on the increase/decrease the irrigation efficiency. Further, the reported withdrawal information is presented at the source of withdrawal rather than the place where it is delivered/consumed. Even though the source of withdrawal is not a significant source of uncertainty in the case of groundwater data, it limits our understanding in analyzing the consumption patterns between surface water and groundwater. In addition, once-in-five-year updating of water use data limits our ability to attribute the role of climate variability on groundwater and surface water withdrawal. Since groundwater appropriation is very local, it is difficult to collect quality withdrawal data. What we need is a rigorous data fusion analyses that validates the in-situ groundwater levels, remote sensing data and water use information with an integrated surface-water-groundwater model and use that information to develop a national database of groundwater availability/recharge/withdrawal. Given the uncertainty in each data source (i.e., in-situ well level, remote sensing and water use), it is first important to identify/agree on the appropriate spatio-temporal scale (e.g., HUC-4 level and annual) under which the uncertainty on groundwater storage and appropriation of the database is effectively less. Developing such a groundwater database with reduced uncertainty will be quite useful in understanding the changes/variability in groundwater availability and use and also in relating their response to policy and management strategies.