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Increasing Water Use Will Escalate Disputes

By Sam Flewelling, Ph.D.

Population growth and improved standards of living have driven the dramatic rise of water use worldwide – setting the stage for water resource disputes on the horizon.

We use water for a wide range of purposes – drinking, washing, flushing, watering lawns and crops, among others. When talking about water use, there are two key concepts to consider – water supply (also called demand or withdrawals) and water consumption. Water supply is the total amount of water extracted for a given use. Water consumption is the amount of water that is transported out of a watershed (*e.g.*, in products exported to another watershed, waters piped elsewhere for municipal or industrial purposes) or evaporated, meaning that the water is effectively lost and cannot return to the stream, river, or groundwater body from whence it came. Some water uses allow for substantial portions of the supplied water to return to the environment (*e.g.,* water from sinks that returns through sewers), whereas other uses lead to near complete consumption (*e.g.,* irrigation water that almost completely evaporates).

…where will the water come from to meet the growing demand?

Over time, water use has increased globally, but at different rates in different regions (see figure). The changes for individual regions are largely driven by growth in population and standard of living. Both of these factors are expected to trend upward in the future, with concomitant increases in water use.

The population effect on water use is straightforward. If one person demands 100 gallons of water per day, adding another person increases demand proportionally.

The effect of standard of living is more complicated. For developing countries, it can mean a household upgrading from a communal water supply, such as a neighborhood kiosk or standpipe, to indoor plumbing at the home. For developed

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I N S I D E

Letter from the Editors

May 2017

Dear Colleague,

In this issue of *Trends*, we focus on water rights. Largely stemming from population growth and standard of living increases, the demand for water has been growing, creating severe pressure on water supplies in many areas around the world. Meeting this demand will entail creative and critical thinking to expand, pump, re-route, and create useable water from limited and interconnected resources. Efforts are underway to quantify water's value, anticipate effects of interventions, and define what is considered fair.

The first *Trends* article explores the increasing trend in global water consumption, how and where water is sourced and consumed, and how these issues contribute to water resource disputes. The second article addresses the question of "Who owns the rain?" The link between aquifers and streams as a single, connected resource and how one evaluates groundwater pumping impacts on surface water is the topic of the third article.

Gradient contributors to this issue include Dr. Samuel Flewelling; Matthew Tymchak, M.S., and Dr. Mason Stahl; and Drs. David Langseth and Ali Boroumand. Joining us with a guest editorial on economic analysis of water resources is Dr. Gina Waterfield from the Brattle Group.

We hope that this issue of *Trends* provides you with insights on water rights.

Yours truly,

Chris Long

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countries such as the U.S. where indoor plumbing is ubiquitous, per capita water demand is generally around 100 gallons per day, with less than half typically consumed. Increased standard of living is also associated with diets higher in calories and protein, both of which require water to produce. When you take a bite of an apple or take a sip of coffee, you are consuming products that are made from many gallons of water beyond those that you directly consume in your home; this water that is used to produce both food and non-food products is known as virtual water.

As a hypothetical example, take the case of the amount of virtual water associated with a moderate-sized piece (about 0.15 kilogram [kg]) of chicken breast that is a daily staple in many developed countries. To start, studies have demonstrated that between 1,060 and 3,960 gallons of water are required per kilogram of meat (Scanlon *et al.*, 2007). Most of this water is needed to sustain plant growth for the production of the grain fed to the chicken. Assuming that a quarter of that water came from irrigation (with the balance from rain), you could be consuming the equivalent of about 40-150 gallons of irrigation water every time you eat a chicken breast. As a result, the virtual water needed to produce a single meat portion could exceed the amount of water you consume for household purposes in a day. Thus, when increased standard of living leads to new dietary choices, water use can increase sharply.

So, where will the water come from to meet the growing demand? There are only a few options, such as expanding the capacity of existing reservoirs or building new ones, increasing groundwater pumping, building desalination plants that convert saltwater to freshwater, or piping water from one watershed into another. When considering these prospects, it is not hard to imagine that increasing water supply will be contentious to some groups. Reservoir construction is associated with land inundation (*e.g.,* over one million people displaced for the Three

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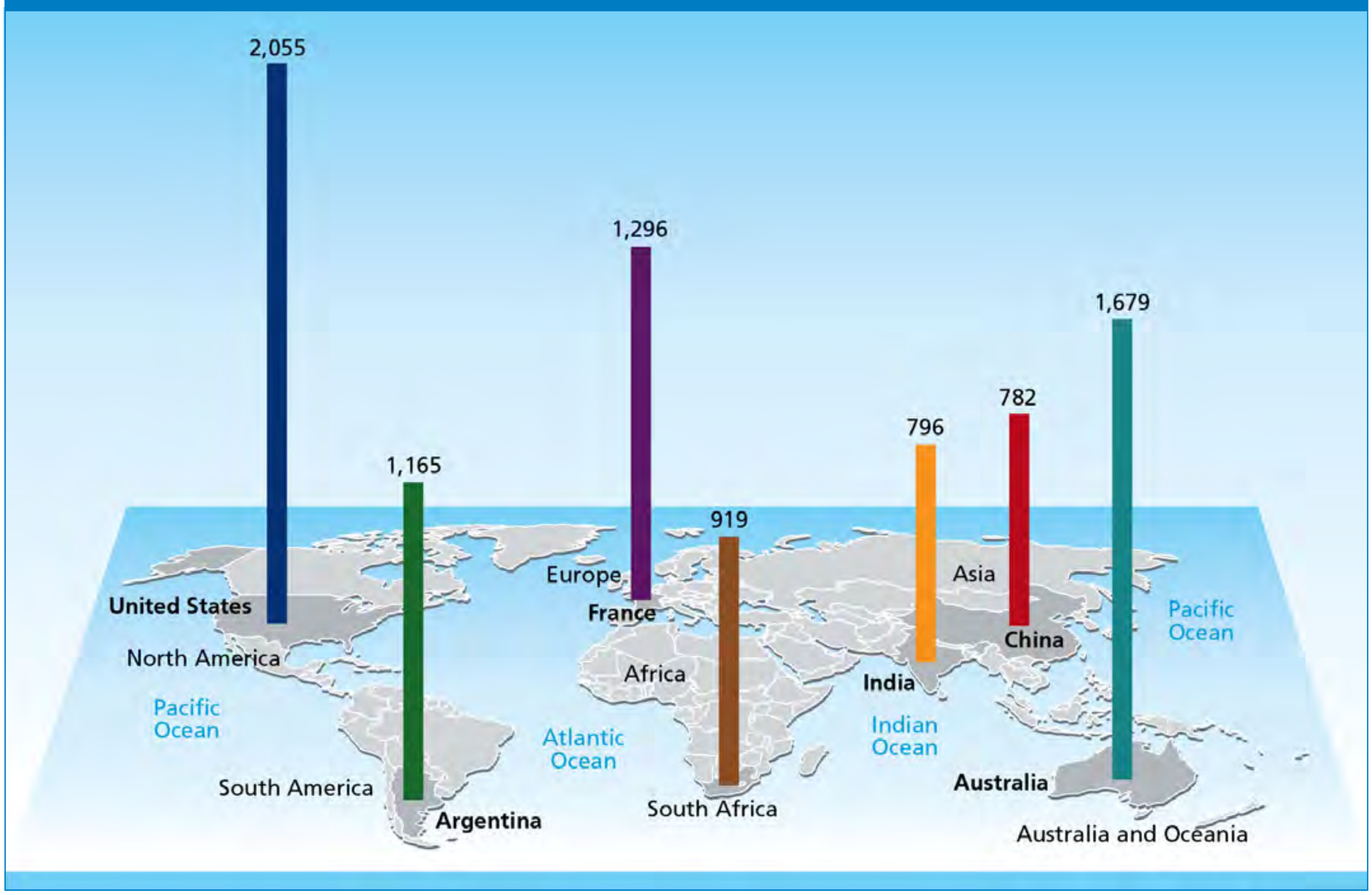
Worldwide Estimates of Per Capita Water Footprints (gal/day)



Per capita water footprint estimates are measures of national consumptive water use and reflect both direct water use by consumers as well as indirect water use (*i.e.*, virtual water use) for production of all goods and services consumed by the population (*e.g.*, agricultural commodities, meat, dairy products, industrial products). Source: Hoekstra, A.Y. and M.M. Mekonnen. 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U.S.A. 109(9):3232-7. DOI:10.1073/pnas.1109936109.

The Secret Life of Rain

By Matthew Tymchak, M.S., and Mason Stahl, Ph.D.

How much water is available for human use? Follow the raindrops, which have a complicated fate upon falling from the sky.

Depending on where a raindrop falls on the earth's surface, it may fill your next glass of water, or hide underground for decades. Understanding the path a raindrop takes after it reaches the land surface is fundamental for resolving the amount and quality of water available for human use. For example, the path of raindrops through cultivated farmland can be wholly distinct from the path of raindrops through forested woodlands. Although the underlying physical processes that control how water moves through each of these landscapes are the same, human factors can alter flowpaths and travel times.

…the path of raindrops through cultivated farmland can be wholly distinct from the path of raindrops through forested woodlands.

The portion of a landscape where all rainfall drains to a single point on a stream or river is a watershed; every piece of land on earth is part of some watershed. Although physical characteristics of individual watersheds vary widely (*e.g.,* geology, topography, climate), their primary function is the same. Watersheds act like a large funnel and channel rainfall to a point of lower elevation where it typically enters a surface water body, such as a stream or reservoir.

A generalized depiction of the transport of rainfall in a watershed is shown in the figure. For example, as rain hits the ground surface, it may travel as overland flow (runoff on the surface) or it might infiltrate the soil and move downward until it reaches the water table (*i.e.,* top of the shallowest aquifer). Once part of a groundwater aquifer, it may traverse long flowpaths and take years to decades to reach a stream (see figure).

Apart from basic watershed processes, the figure also highlights the case where flowpaths can be altered by human activity. For example, rainfall that might otherwise flow to a stream or river can be intercepted by a pumping well used to irrigate crops. The irrigation water represents a loss from the watershed to the atmosphere as water is transpired from the plants and evaporated from the ground surface. This loss of water simultaneously reduces streamflow and depresses the water table surface, since both the aboveground and underground bodies of water are hydraulically connected.

There is a set amount of water available for human use in each watershed, and it is determined by a region's water budget. Similar to a household budget, the water budget is a balance between the amount of rain coming in, storage of some water underground, and losses out of the watershed. Although losses occur naturally (*e.g.,* streamflow, evaporation), humans can increase them. The activities of humans that affect water budgets can be grouped into three overlapping categories that include the following: 1) construction and use of water storage and conveyance structures, *e.g.*, reservoirs and aqueducts; 2) land use, *e.g.*, urban development, agriculture; and 3) groundwater extraction, *e.g.*, potable use, crop or lawn irrigation (Healy *et al.*, 2007).

When disputes arise from human activities, determining the fate of raindrops becomes increasingly important. Fortunately, numerous data sets are available for most components of the water budget, and there are a variety of numerical models in the hydrologist's toolbox. These tools can be adapted to various situations to evaluate potential human impacts to a watershed. For example, a numerical model was used by a research group in Iowa to assess the effects of land use change on flood risks in the Raccoon River watershed near Des Moines, Iowa (Schilling *et al.,* 2014). In this study, the amount of perennial crop area was incrementally increased under the same climate conditions to quantify changes in streamflow, the number of flood events, and their frequency and duration. The model was also used to allocate crop type and rotation structure to help mitigate future flooding. There are numerous other examples of data analysis and modeling studies that have been used to evaluate human impacts. However, they all share one overarching theme, namely the necessity to understand and quantify the fate of rain.

WATERSHED PROCESSES

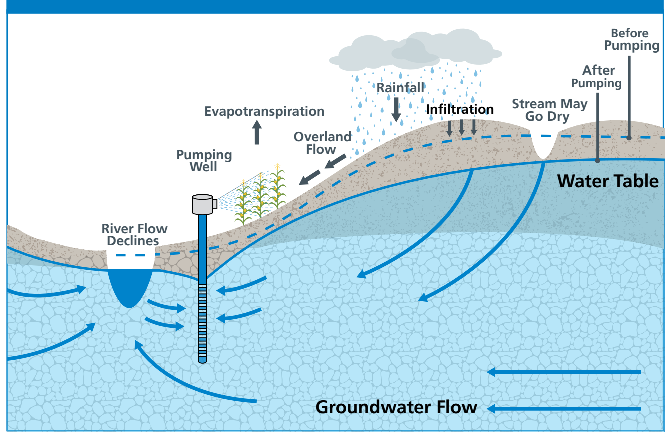


Figure adapted from Gordon *et al.,* 2012.

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Pumping Groundwater Impacts Rivers

By David Langseth, Sc.D., P.E., D.WRE, and
Ali Boroumand, Ph.D.

The combination of direct measurement and mathematical modeling offers a powerful approach for determining the impact of pumping on streamflow and making equitable decisions on how to allocate water use among various constituencies.

It is intuitive that when you withdraw water from a river, the flow rate in the river is immediately reduced by the rate at which water is withdrawn. The impacts of pumping groundwater on river flow rate, however, are more complex and far from intuitive. In fact, historic court rulings have applied terms such as "secret," "occult," and "concealed" to groundwater (Eckstein, 2005). Based on decades of study, it is now well known that pumping a well can intercept groundwater that was on its way to a discharge location, such as a river, and that pumping can significantly reduce river flow (see figure pg. 3). The amount and timing of the reduction in river flow, however, is variable. The amount of impact can be up to the full pumping rate, but it can be less. The timing of the impact can be nearly immediate, but it can also occur years after the pumping, depending on the specific situation. These impacts should be considered when allocating water use among competing demands.

…historic court rulings have applied terms such as "secret," "occult," and "concealed" to groundwater.

Methods for determining the impact of pumping on streamflow fall generally into two categories: direct measurement and mathematical modeling (Barlow and Leake, 2012). These methods are now sufficiently well established to be used reliably, though each method has advantages and disadvantages.

Direct measurement of pumping impacts is complicated by the need to account for the time delay between when the pumping occurs and when the streamflow impact occurs, and to distinguish between changes caused by pumping and changes caused by other factors such as climatological or seasonal parameters. Direct measurement methods are generally most suitable for evaluating long-term generalized pumping impacts. They are rarely suitable for evaluating impacts of pumping from a specific well or for forecasting impacts from water management actions.

Mathematical models, in contrast, can provide direct evaluation of the impacts of pumping from individual wells and from alternative water management strategies. The mathematical equations that describe natural movement of groundwater have been known since the nineteenth century, and the first analytical solutions for streamflow depletion from pumping were presented in the 1940s (Barlow and Leake, 2012). These early methods, and subsequent analytical methods, however, are based on highly simplified characterizations of hydrologic systems.

Today, while analytical models still have uses, computers enable numerical solutions of groundwater equations that can simulate the impact of pumping on river flow even for highly complex situations. The data collection and evaluation efforts needed to create a reliable numerical model, however, are high. A regional groundwater model often includes hundreds of independent parameters, most of which cannot be directly measured, and selecting the best combination of parameters requires substantial effort and expertise. An approach that blends the power of numerical modeling with the simplicity of analytical methods is to use the numerical model to develop individual response functions that represent the response of streams to pumping for possible pumping locations in the watershed, and then to use the principle of superposition to build the overall system response from the response functions.

The Republican River Compact between the states of Colorado, Kansas, and Nebraska provides an example of numerical groundwater model use to evaluate impacts of pumping on streamflow. An issue that arose some years after the initial ratification of the compact involved how groundwater pumping should be treated in the water allocation to each state. The settlement stipulation package for this issue, mediated by a Special Master to the U.S. Supreme Court, included evaluation of streamflow depletions caused by pumping using a groundwater model that was developed jointly by the parties (McKusick, 2003).

Thus, groundwater pumping is far from a dry topic, and is pivotal to evaluating many significant water use disputes.

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Barlow, P.M. and S.A. Leake. 2012. Streamflow depletion by wells – understanding and managing the effects of groundwater pumping on streamflow. U.S. Geological Survey Circular 1376. 84p.

Eckstein, G. 2005. A hydrogeological perspective of the status of groundwater resources under the UN Watercourse Convention. *Columbia J. Environ. Law.* 30(3):525-564.

McKusick, V.L. September 17, 2003. Final Report of the Special Master with Certificate of Adoption of RRCA Groundwater Model [re: *State of Kansas v. State of Nebraska and State of Colorado*]. Submitted to U.S. Supreme Court. No. 126. 134p.

By The Way…

China's solar power capacity more than doubled last year, making it the world's biggest producer of solar energy.

Source: http://www.reuters.com/article/us-china-solar-idUSKBN15J0G7.

What's New at Gradient

Awards and Announcements

Gradient, the Washington State Department of Ecology, SAE International, and other stakeholders recently kicked off the Puget Sound Clean Cars Stormwater Partnership, a collaborative effort to reduce storm water impacts associated with automotive vehicle fluid leaks in the state of Washington.

Isaac Mohar passed the American Board of Toxicology examination to become a Diplomate of American Board of Toxicology (DABT).

Dennis Milechin has earned a Graduate Certificate in Data Science from the Harvard Extension School.

Daniella Pizzurro is volunteering as a mentor for the NIH-funded Toxicology Mentoring and Skills Development Training Program.

Barbara D. Beck has been named to the Recruitment Committee of the Academy of Toxicological Sciences and to the Society of Toxicology (SOT) Toxicology Task Force on Impacting Public Health.

Michael Peterson was awarded a ToxScholar grant to visit Central Washington University and present "Toxicology 101: The Dose Makes the Poison."

Publications

Goodman, J. and **H. Lynch.** 2017. Improving the International Agency for Research on Cancer's consideration of mechanistic evidence. *Toxicol. Appl. Pharmacol.* 319:39-46. DOI:10.1016/j.taap.2017.01.020.

Goodman, J.E., C.T. Loftus, and **K. Zu**. 2017. 2,4-Dichlorophenoxyacetic Acid and non-Hodgkin's lymphoma: results from the Agricultural Health Study and an updated meta-analysis. *Ann. Epidemiol.* DOI:10:1016/j.annepidem.2017.01.008.

Goodman, J.E., K. Zu, C.T. Loftus, and **R. Prueitt**. 2017. Letter to the Editor re: Dermal TDI Exposure is not associated with Lung Cancer Risk. *Am. J. Ind. Med.* 60 (2):221-222. DOI:10.1002/ajim.22677.

Lynch, H.N., **J.E. Goodman,** and **N.B. Beck**. 2017. More Clarity Needed in the Navigation Guide Systematic Review Framework. *Environ. Int.* DOI:10.1016/j.envint.2017.01.011.

Lynch, H.N., C.T. Loftus, **J.M. Cohen, L.E. Kerper, E.M. Kennedy,** and **J.E. Goodman.** 2016. Weight-of-evidence evaluation of associations between particulate matter exposure and biomarkers of lung cancer. *Regul. Toxicol. Pharmacol.* 82:53-93. DOI:10.1016/j.yrtph.2016.10.006.

Marty, M.S., A. Blankinship, J. Chambers, L. Constantine, W. Kloas, A. Kumar, L. Lagadic, J. Meador, D. Pickford, T. Schwarz, and **T. Verslycke**. 2017. Population-relevant endpoints in the evaluation of endocrine-active substances (EAS) for ecotoxicological hazard and risk assessment. *Integr. Environ. Assess. Manag.* 13(2):317-330. DOI:10.1002/ieam.1887.

Matthiessen, P., G.T. Ankley ... **T. Verslycke** ... K. Yamazaki [48 authors total]. 2017. Recommended approaches to the scientific evaluation of ecotoxicological hazards and risks of endocrine-active substances. *Integr. Environ. Assess. Manag.* 13(2):267-279. DOI:10.1002/ieam.1885.

Peterson, M. 2016. The battle over artificial turf. *Sch. Bus. Aff.* 82(11):39.

Zu, K., G. Tao, and **J.E. Goodman**. 2016. Pleural Plaques and Lung Function in the Marysville Worker Cohort: A Re-analysis. *Inhal. Toxicol.* 28(11):514-519. DOI:10.1080/08958378.2016.1210704.

Upcoming Presentations

Washington, D.C. May 14-17, 2017. Nanotech Conference & Exposition.

- "**An Integrated Methodology Across the Dispersion Preparation-Characterization-*In Vitro* Dosimetry Continuum for Engineered Nanomaterials**." J. Cohen, G. DeLoid, S. Pirela, G. Pyrgiotakis, P. Demokritou.
- "**Nanomaterials in Food and Food Contact Substances – Hazards, Risks and Regulation**." J. Cohen.

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The Secret Life of Rain

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References:

Gordon, D.W., M.F. Peck, and J.A. Painter. 2012. Hydrologic and water-quality conditions in the lower Apalachicola–Chattahoochee–Flint and parts of the Aucilla–Suwannee–Ochlockonee River basins in Georgia and adjacent parts of Florida and Alabama during drought conditions, July 2011. U.S. Geological Survey Scientific Investigations Report 2012–5179. 79p.

Healy, R.W., T.C. Winter, J.W. LaBaugh, and O.L. Franke. 2007. Water budgets: Foundations for effective water-resources and environmental management. U.S. Geological Survey Circular 1308. 90p.

Schilling, K.E., P.W. Gassman, C.L. Kling, T. Campbell, M.K. Jha, C.F. Wolter, and J.G Arnold. 2014. The potential for agricultural land use change to reduce flood risk in a large watershed. *Hydrological Processes.* 28(8)3314-3325.

Guest Editorial: The Economic Water Balance

By Gina Waterfield, Ph.D.

As more conflicts erupt over water resources, economists will play an increasingly important role in quantifying the net social value of how disputed water resources are being allocated and used.

With growing demands placed on limited supply, disputes over water resources have become increasingly common. In some watersheds, available water may be used across municipal, commercial, industrial, and agricultural sectors, while also supporting ecosystems and environmental amenities. Quantifying the net social value of the different uses of a disputed water resource can play a critical role in such cases. Assessments of these values can be used to translate volumes of misappropriated water into monetary damages, or to highlight economically efficient ways of balancing competing demands.

…water used to irrigate a high-value crop, like almonds, generates more profit than water used to irrigate a relatively low-value crop, like cotton.

The cost of developing additional water supplies, where feasible, serves as an intuitive upper bound on the value of a water resource. In general, a resource is not worth more than the cost of replacing it, if alternatives are available. But below that bound, the value of water varies tremendously across uses and contexts. Economists can combine statistical methods with market data to generate more useful estimates of the range of net social values associated with different uses.

Consider, for example, the value of water used for agricultural irrigation. All else being equal, water used to irrigate a high-value crop, like almonds, generates more profit than water used to irrigate a relatively low-value crop, like cotton. There are also "diminishing returns" to irrigation, where an additional unit of water improves almond yields and profits less when a greater depth of irrigation has preceded it. Water also tends to be more valuable to the almond farmer in a drought year than in a high-rainfall year. Land characteristics and farm management practices also play an important role. Similar nuances apply to water use in other sectors.

Of course, water use is associated not just with benefits, but also with costs. There are private costs incurred directly by the water users, such as the costs of equipment and energy to pump irrigation water from an aquifer and distribute it to the crops. Water use is also almost invariably associated with external costs, or impacts on other users or the environment. Most obviously, water withdrawn from an aquifer or surface source (and not returned) is not available for anyone else's use. Water use can also affect the timing and quality of supply available to others.

Estimation of the costs of water use, both private and external, often depends fundamentally on hydrological analysis of the water resource. The cost to the farmer of pumping groundwater is determined, in part, by the depth to the aquifer. The costs imposed on other water users and the environment depends on complex rainfall-runoff and groundwater flow processes (see related articles).

Overall, when combined with hydrological knowledge, economic analysis is vital to understanding the full picture of the net benefits provided by a water resource. Economic analysis will thus continue to play a key role in assessing damages and balancing the social tradeoffs involved in water disputes.

Gina Waterfield, Ph.D., is an Associate in the San Francisco office of The Brattle Group, where she provides economic analyses for environmental and natural resource litigation and regulation. She can be reached at gina.waterfield@brattle.com.

Increasing Water Use Will Escalate Disputes

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Gorges Dam) and can alter flows to downstream communities and ecosystems. Increased groundwater pumping can lower aquifer levels, cause land subsidence (*e.g.,* by more than 10 feet in parts of the Southwest), and reduce the amount of water flowing to streams (see related article). Piping water from one watershed to another has already been a cause for disputes in multiple areas around the United States.

The numerous points of contention associated with increasing water supply set the stage for a likely increase in future water resource disputes. As discussed in the rest of the articles in this issue, the scientific issues at play are not simple. There are numerous complexities regarding how water falling from the sky (*e.g.,* rain, snow) makes its way through the landscape and aquifers to ultimately enter a water intake. Determining who owns that water and how to most efficiently apportion it to competing users will continue to be a complex and controversial issue. Local use will need to be evaluated in relation to local hydrology and other factors, such as climate change, that may alter the amount of water available in some areas.

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Reference:

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity *versus* quality. *Water Resources Research.* 43:W03437, DOI:10.1029/2006WR005486.

What's New at Gradient

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Miami, FL. May 22-25, 2017. Battelle Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies.

- "**Green and Sustainable Remediation Analysis: Coal Ash Surface Impoundment Closure.**" A. Boroumand, K. Herman.

Seattle, WA. June 4-7, 2017. American Industrial Hygiene Conference & Exposition (AIHce).

- "**Volatile Organic Compounds (VOC) Criteria for New Construction.**" L. Beyer, P. Haas, E. Light.

Pittsburgh, PA. June 5-8, 2017. Air & Waste Management Association Annual Meeting.

- "**Assessing Industrial Facility Vulnerability from Flooding Events in a Changing Climate.**" N. Briggs, C. Petito Boyce, S. Ikeda, D. Mayfield, M. Mayo.
- "**Human Health Risk Assessment (HHRA) for Proposed Power Plant Projects: Methodology and Case Study.**" C. Long, P. Valberg.

Reston, VA. June 13-15, 2017. 21^{st} Annual Green Chemistry & Engineering Conference (GC&E).

- "**Hazard Screening Approaches for Identifying Safer Chemicals.**" J. Cohen, S. Pacheco Shubin, T. Lewandowski.

Seattle, WA. June 20-23, 2017. 50^{th} Society of Epidemiologic Research Annual Meeting.

- "**Applying Nonparametric Methods to Analyses of Short-term Fine Particulate Matter Exposure and Hospital Admissions for Cardiovascular Diseases among Older Adults.**" L. Cox, X. Liu, L. Shi, K. Zu, J. Goodman.
- "**Concentration-response of Short-term Ozone Exposure and Hospital Admissions for Asthma in Texas.**" K. Zu, X. Liu, L. Shi, G. Tao, C. Loftus, S. Lange, J. Goodman.
- "**Good Epidemiology Practice Guidelines: A Long Time Coming.**" H. Lynch, J. Goodman, Z. Yan.
- "**2,4-Dichlorophenoxyacetic Acid and Soft Tissue Sarcoma: Meta-analysis of the Published Literature.**" T. Lam, C. Loftus, K. Zu, E. Kennedy, J. Goodman.

Denver, CO. June 24-28, 2017. The Teratology Society 57^{th} Annual Meeting.

- "**Hazard Screening Approaches for Identifying Developmental and Reproductive Toxicity in the Workplace.**" S. Pacheco Shubin, J. Cohen, D. Dodge, T. Lewandowski.

Join Gradient's *Trends* authors for a live webinar for further discussion on this Water Rights issue.

Please click here for information about this event.

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The next issue will focus on:
New Tox & Exposure Strategies under TSCA

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