9th Washington Hydrogeology Symposium

PROGRAM AND ABSTRACTS

April 23–25, 2013

Hotel Murano

Tacoma, Washington

www.wahgs.org

9th Washington Hydrogeology Symposium

GENERAL SCHEDULE

Date	Activity
Monday *April 22nd*	**Field Trip 1:** Prolific Aquifers in South Puget Sound *(all day)*
Tuesday *April 23rd*	**First Day of Symposium:** Platform Presentations *(all day)* Lunch Provided **Poster Presentation at noon** **Exhibits**
Wednesday *April 24th*	**Second Day of Symposium:** Platform Presentations *(all day)* Lunch Provided **Exhibits and Posters** **Afternoon Panels:** 6B Exempt Wells 7B Stormwater
Thursday *April 25th*	**Workshops** **Workshop 2:** Well Drilling *(all day)* **Workshop 3:** Bioremediation Fundamentals and Applications *(morning)* **Workshop 4:** Chemical and Thermal Remediation Fundamentals and Applications *(afternoon)* **Workshop 5:** MLU: A New Way to Analyze Aquifer Tests in Multi-layered Systems – a Hands-on Workshop *(morning)* **Workshop 6**: Aquifer Characterization Tests and Pressure Transducer Data Collection *(afternoon)*
Friday *April 26th*	**Field Trip 2***:* On the Trail of the Ice Age Floods, Eastern Washington *(day 1)*
Saturday *April 27th*	**Field Trip 2***:* On the Trail of the Ice Age Floods, Eastern Washington *(day 2)*
Sunday *April 28th*	**Field Trip 2***:* On the Trail of the Ice Age Floods, Eastern Washington *(day 3)*

CHAIRMAN'S WELCOME

9th Washington Hydrogeology Symposium

Welcome to the 9th Washington Hydrogeology Symposium! This year's technical program consists of 48 platform and 15 poster presentations covering all aspects of hydrogeology, water resources management, and water quality. Specific topics include Innovative Remediation Technologies, Aquifer Storage and Recovery, and CO_2 Sequestration, to name a few. These presentations will be supplemented with two facilitated panels on Stormwater Infiltration Testing and Analysis, and Exempt Wells, Prior Appropriation and Water Banking in Washington State.

The 2013 Steering Committee has pulled together two exciting field trips; one in western Washington, Prolific Aquifers in South Puget Sound, and one in eastern Washington, On the Trail of the Ice Age Floods. Five workshops will be presented, including Bioremediation Fundamentals and Applications, Chemical and Thermal Remediation Fundamentals and Applications, Well Drilling, Aquifer Testing Analysis, and Aquifer Characterization Tests and Pressure Transducer Data Collection.

We are extremely excited to have three distinguished keynote speakers; Dr. Jeffrey J. McDonnell, Dr. Susan S. Hubbard, and Dr. Steve Silliman. Dr. McDonnell was the 2011 Birdsall-Driess Distinguished Lecturer for the Geological Society of America and 2012 Borland Lecturer for AGU Hydrology Days. Dr. Hubbard is a senior scientist at Lawrence Berkeley National Laboratory, where she leads the Environmental Remediation and Water Resources Program and the Sustainable Systems Science Focus Area. Dr. Silliman is Dean of the School of Engineering and Applied Science at Gonzaga University, and has won multiple awards for teaching, service, and research, including the ASEE Outstanding Teaching Award.

Please make time to visit our Exhibitors, who offer a wide variety of state-of-the-art data collection, analysis and reporting solutions. Our Sponsors deserve a special **Thank You** during these especially difficult economic times. Through their generosity, our sponsorship goals were exceeded, and we continue to be able to offer this conference at a very affordable price. Please join us in thanking and supporting our Sponsors listed in this Program.

This year we have enhanced student participation by offering a reduced registration fee. We understand that students are our future geologists, scientists, and engineers and we wish to provide a professional environment for them to mingle and seek potential career opportunities with our Sponsors and Exhibitors.

On behalf of the 9th Washington Hydrogeology Symposium Steering Committee and myself, Welcome! We hope you will have a productive and enjoyable few days at the Symposium, and that you make plans to join us again in 2015.

Sincerely,

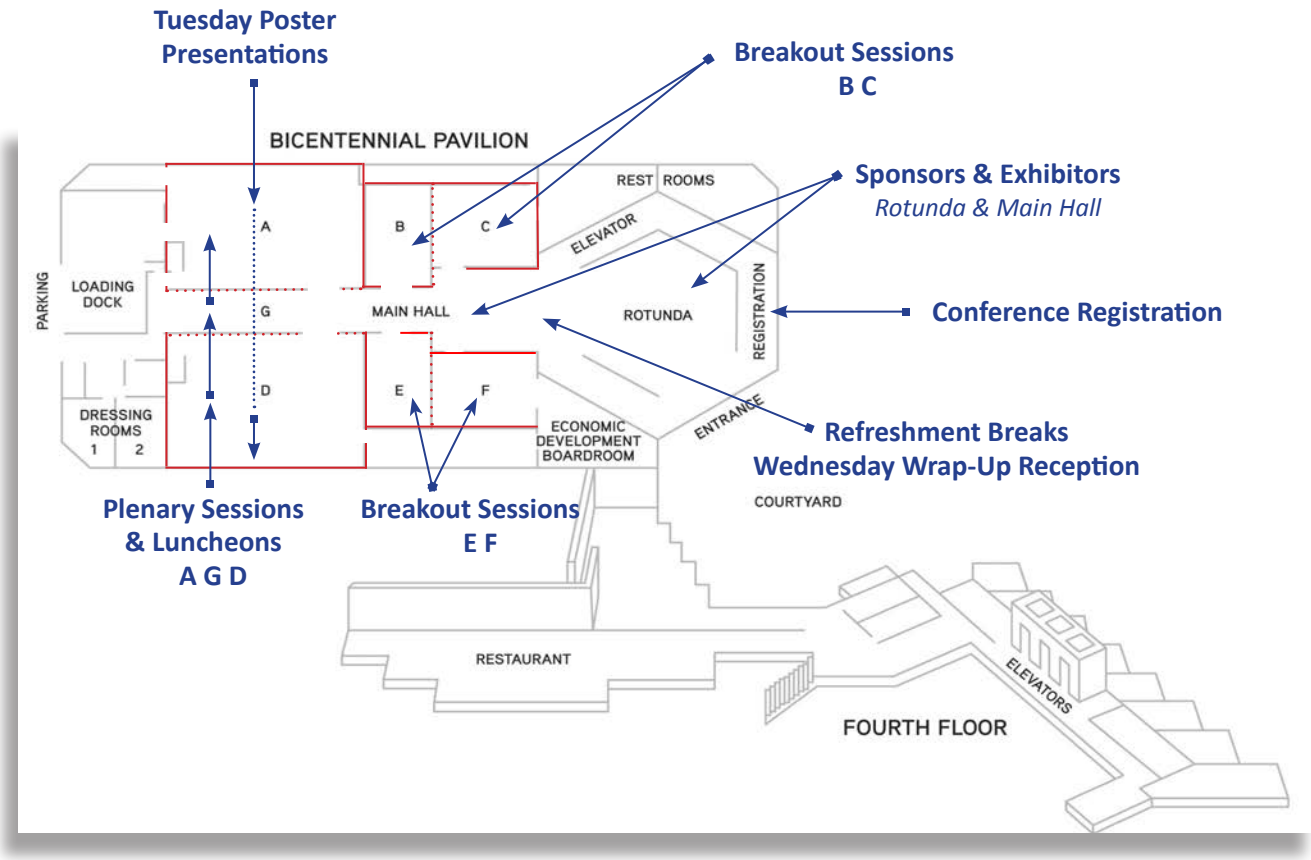
Tom Tebb

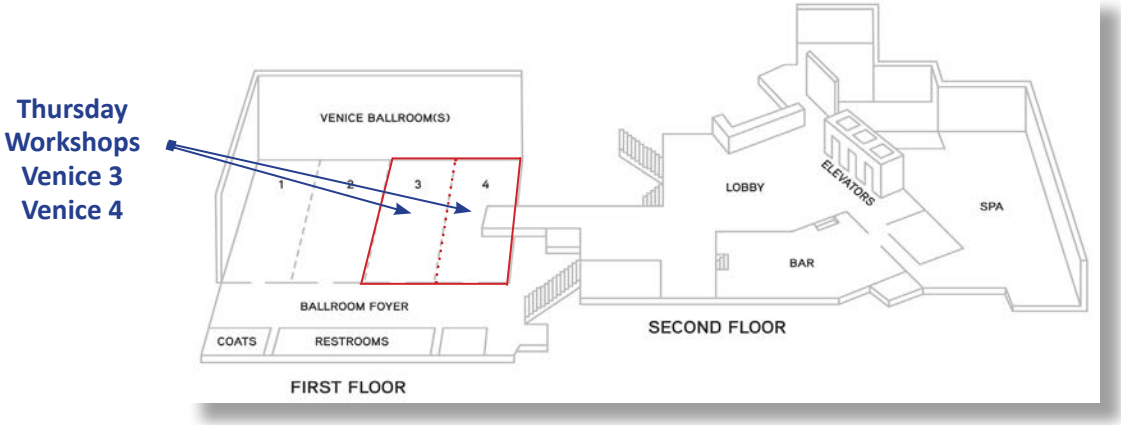
2013 Symposium Chair
Washington State Department of Ecology

9th Washington Hydrogeology Symposium

KEY LOCATIONS

Hotel Murano, Tacoma





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9th Washington Hydrogeology Symposium

GENERAL INFORMATION

Symposium Registration Booth - The Washington Hydrogeology Symposium Registration Booth is located in the Rotunda of the Bicentennial Pavilion. Staff will be available there to assist with participant check-ins, including speakers, moderators, exhibitors and sponsors, as well as to provide general symposium information.

Registration Hours

Tues., April 23 - 7:30 AM – 4:30 PM | Wed., April 24 - 8:00 AM – 4:30 PM | Thur., April 25 - 8:00 AM - 1:30 PM

Name Badges - Your name badge is your entrance ticket to all Symposium sessions, breaks, meals, and the Wrap-Up Reception.

Please wear your name badge at all times throughout the Symposium. Badge holders can be reused, so please participate in our goal to have a more consciously "green" meeting, and drop your badge holder off at the Registration Desk before you leave.

Symposium Sessions - Symposium sessions will be held in meeting rooms within the Pavilion. Thursday workshops (except for the Well Driller's workshop) will be held in the lower ballroom level of the Hotel Murano's main building. Please refer to the hotel floor plans on page ii in this program book.

Presenters should arrive at assigned presentation rooms at least 10 minutes before the session start time to load files onto the laptop provided. An audio-visual operator will be available if assistance is needed.

Special Event at the Museum of Glass | Tues., April 23, 2013 6:00 PM - 9:00 PM | Cost: $65 per person

Included in this evening event are glass blowing demonstrations in the world's largest hot shop, access to the museum's exhibits, tray passed hor d'oeuvres and a no host bar. The Museum is walking distance from the Hotel Murano.

Check at the Symposium Registration desk to see if tickets are still available.

Meals and Refreshments - Lunch is provided on Tuesday and Wednesday. If you made a special meal request (vegetarian or other), please note that a special meal ticket for Wednesday's lunch was included in your registration envelope. Please use this ticket to inform a lunch server of your meal request. On Tuesday, the lunch buffet will offer options to meet most dietary requirements.

The Symposium Wrap Up Reception will be on Wednesday afternoon from 4:30-5:30 PM. Early morning coffee and pastries will be provided each day and beverages and snacks will be available during breaks.

Recycling - The hotel has receptacles for recycling of glass, aluminum, plastic and paper, which we encourage you to use. Thanks to an environmentally conscious staff at the Hotel Murano, they will turn food scraps into garden compost, by placing leftovers into special bins in their kitchen.

Internet Access - Complimentary internet access is available in all meeting rooms, the lobby and the hotel restaurant. Overnight guests will receive a user name and password when they check in that can be used in their hotel room and in the meeting rooms. For those participants not staying in the hotel, please use the username: **hydrog** and password: **2013**. Questions about how to log in and passwords required can be answered by hotel front desk staff persons, and Symposium staff at the Registration desk.

Important Phone Numbers

Hotel Murano: 253.238.8000 | Registration Booth: 206.406.7272
Tacoma Visitors Bureau: 253.284.3254 | Emergencies: Dial 911

Please note! Join our planning committee If you are interested in participating in the planning of the 10th Washington Hydrogeology Symposium in April 2015, please sign up at the Symposium Registration desk. To kick things off, you will be invited to attend a free morning breakfast meeting on Wednesday, April 24, at 7:00 AM (RSVP only).

WIRELESS ACCESS

username: hydrog
password: 2013

Top row: left to right: Roy Jensen, Gary Stoyka, Robert Mitchell, Sue Kahle, Chris Brown, Angie Goodwin, Donna Buxton, Patricia Shanley

Bottom row: left to right: Laurie Morgan, Margo Gillaspy, Tom Tebb, Joel Purdy, Heidi Yantz, Gary Walvatne

STEERING COMMITEE

9th Washington Hydrogeology Symposium Steering Committee

Chris Brown	Pacific Northwest National Laboratory, Officer
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Jan Kvamme **Mary Jane Shirakawa**	UW Conference Management University of Washington www.uwconferences.org

Monday, April 22, 2013		
8:00 AM – 4:30 PM	Field Trip 1: Prolific Aquifers in South Puget Sound	
Tuesday, April 23, 2013		
7:30 AM	Check-In and Registration (Bicentennial Pavilion Rotunda)	
9:00 AM	**Opening Session: Welcome, Opening Remarks (Bicentennial Pavilion AGD)** Keynote 1: Jeffrey J. McDonnell, Global Institute for Water Security at the University of Saskatchewan in Saskatoon Canada. *Groundwater-Surface Water Interactions at the Watershed Scale*	
10:15 AM	Refreshment Break | Exhibits | Posters (Bicentennial Pavilion Rotunda)	
10:40 AM	**1A Groundwater Availability (Bicentennial Pavilion EF)**	**1B Innovative Remediation Technologies (Bicentennial Pavilion BC)**
SESSION 1	Lacey-Olympia-Yelm Water Rights - An Example for the Future Procurement of Municipal Water Supplies *Michael Gallagher, Department of Ecology* Groundwater Supply Conditions in Columbia Basin Municipalities: Evidence of Little Groundwater Recharge and Potential Future Water Supply Shortfalls *Kevin Lindsey, GSI Water Solutions, Inc.* Lower Deschutes Valley Groundwater Resources, Thurston County, Washington *Chris Pitre, Golder Associates Inc.* Initial Development of the McAllister Wellfield, Thurston County, WA *Justin Iverson, Golder Associates*	Donor Borings: A Cost-Effective Approach for Bioremediation of a TCE Source Based on Treatment Effectiveness and Longevity *Christophe Venot, Landau Associates* Performance of Enhanced Anaerobic Dechlorination (EAD) via Groundwater Recirculation at a NW Industrial Facility *Brian Timmins, ETEC, LLC* Implications of In Situ Biotreatment Persisting Years after Electron Donor Injection - Two Case Studies *Clint Jacob, Landau Associates* Successful Cleanup of an Industrial Site, Renton, Washington *Angie Goodwin, Hart Crowser, Inc.*
Noon	Hosted Luncheon and Poster Presentations (Bicentennial Pavilion AGD)	
1:20 PM	**2A Stormwater Infiltration (Bicentennial Pavilion EF)**	**2B Non-Point Source Contamination (Bicentennial Pavilion BC)**
SESSION 2	Deep Underground Injection Control Wells to Infiltrate Stormwater and Stabilize a Ravine *Todd Wentworth, PE, LG, AMEC Environment & Infrastructure* Simulating Underground Injection of Stormwater using MODFLOW-SURFACT *Miao Zhang, AMEC Environment & Infrastructure* Evaluating the Potential for Stormwater Infiltration on a Basin Scale Using GIS *J. Scott Kindred, Aspect Consulting, LLC* Wellhead Protection and Stormwater Recharge in the Washington Portion of the Spokane Valley - Rathdrum Prairie Sole Source Aquifer *John Porcello, GSI Water Solutions*	Design and Testing of a Process-Based Groundwater Vulnerability Assessment (P-GWAVA) System for Predicting the Concentrations of Agrichemicals in Groundwater Across the United States *Jack Barbash, U.S. Geological Survey* Identifying Sources of Nitrate in Domestic Wells in the Yakima River Basin *Matt Bachmann, U.S. Geological Survey Washington Water Science Center* Three Case Studies: Using Site Specific Characteristics to Determine if Alternative Treatment Technologies are Protective of Groundwater Quality *Melanie Redding, Washington State Department of Ecology* Washington Nitrate Prioritization Project *Laurie Morgan, Washington State Dept. of Ecology Water Quality Program*

2:40 PM	Refreshment Break | Exhibits | Posters (Bicentennial Pavilion Rotunda)	
3:00 PM	**3A Water Reuse - Aquifer Storage and Recovery (Bicentennial Pavilion EF)**	**3B Contaminant Fate and Transport 1 (Bicentennial Pavilion BC)**
SESSION 3	An Innovative Bioremediation Strategy for Treating Chlorinated VOCs in Low-Permeability Saturated Soils Using Specialized Jetting Techniques * *Sheri Knox, Solutions-IES, Inc.* The Role of Contaminants of Emerging Concern in Aquifer Recharge Projects Using Reclaimed Water *John Koreny, HDR Engineering, Inc.* Regional Evaluation of Shallow Artificial Aquifer Recharge in the Walla Walla Basin *Aristides Petrides, GSI Water Solutions* Denitrification in a Deep Basalt Aquifer: Implications for Aquifer Storage and Recovery *Dennis Nelson, GSI Water Solutions, Inc.*	Uncertainty Assessment at BC Cribs at Hanford Using the ASCEM Toolset *Vicky Freedman, Pacific Northwest National Laboratory* Nature and Extent of Vadose Contamination at the Hanford Federal Facility, WA *Dib Goswami, Washington State Dept. of Ecology* Geochemical and Isotopic Evaluation of a Potential Subsurface Combustion Event *Jessica Goin, Anchor QEA* Vadose Zone Remediation by Sustainable Soil Vapor Extraction *Gary M. Birk, P.E., Tersus Environmental*
4:20 PM	Refreshment Break | Exhibits | Posters (Bicentennial Pavilion Rotunda)	
4:30 PM	**4A Geochemistry (Bicentennial Pavilion EF)**	**4B Surface Water-Groundwater Interactions (Bicentennial Pavilion BC)**
SESSION 4	Stable Isotope Analysis of Surface Water and Precipitation in the Palouse Basin: Hydrologic Tracers of Aquifer Recharge *Nathan Moxley, Washington State University* Multitracer Models of Groundwater Age, Mixing, and Renewal in the Columbia Basin GWMA *Dimitri Vlassopoulos, Anchor QEA* Enhanced Transport of Sr by Mobile Secondary Precipitates *Wooyong Um, Pacific Northwest National Laboratory*	A New Approach to Evaluating Porewater Methane in Coarse Sediments and Armored Substratum *Benjamin Miller, University of Michigan* Groundwater-Surface Water Interaction in East Creek Basin and Implications for Projects with Substantial Permanent Groundwater Discharge *Erik Blumhagen, Shannon & Wilson* Groundwater-Surface Water Interactions and Sulfide Toxicity in Nearshore Marine Sediments – A Reactive Transport Modeling Approach *Minna Carey, Anchor QEA*
5:30 PM	Tuesday Sessions Adjourn	
6:00 PM – 9:00 PM	Special Event at the Museum of Glass, (1801 Dock Street, Tacoma)	

**This replaces a cancelled talk.*

Wednesday, April 24, 2013		
8:00 AM	Registration Desk Opens (Bicentennial Pavilion Rotunda)	
9:00 AM	Keynote 2: Steve Silliman, Dean of the School of Engineering and Applied Science at Gonzaga University *Salinity in Municipal Water Supply Wells Serving Cotonou, Benin, West Africa*	
10:00 AM	Refreshment Break | Exhibits | Posters (Bicentennial Pavilion Rotunda)	
10:20 AM	**5A Watershed Impacts (Bicentennial Pavilion EF)**	**5B Contaminant Fate and Transport 2 (Bicentennial Pavilion BC)**
SESSION 5	Paleo-Glacial Lake Columbia: A Potential Source for Regional Ground-Water Recharge for Deep Columbia River Basalt Aquifers Within the Columbia Basin *Bruce Bjornstad, Pacific Northwest National Laboratory* Evaluating Greenhouse Gas Emissions from Hydropower Complexes on Large Rivers in Eastern Washington *Evan Arntzen, Pacific Northwest National Laboratory* Modeling of Hydrologic Processes and Assessment of Climate Variability Impacts on Streamflow in the Upper Cedar River Watershed *Anurag Srivastava, Washington State University* Water Resources of Upper Kittitas County: Groundwater Availability and Linkages to Surface Water *Matt Ely, U.S. Geological Survey* Watershed Dynamics in a Changing Climate: A Look at Transportation in Washington's Mountains *Ronda Strauch, University of Washington*	Anatomy of a PCB Plume *Roy Jensen, Hart Crowser, Inc.* Endpoints for the Deep Vadose Zone at the Hanford Site, Washington *Mark Freshley, Pacific Northwest National Laboratory* Guidance for Evaluating Post Closure Care of MSW Landfills *Lee Huckins, Oregon Department of Environmental Quality* Potential for Arsenic Mobility and Groundwater Contamination from Area-Wide Contaminated Soil *Eric Weber, Landau Associates, Inc.* Accelerating Petroleum Remediation by Coupling Physical Extraction and Bioremediation *Troy Fowler, Hart Crowser*
Noon	Hosted Luncheon and Keynote 3: Susan S. Hubbard, Director of the Earth Sciences Division, and also leads the Environmental Remediation and Water Resources Program at Lawrence Berkeley National Laboratory *Strategies to Quantify Terrestrial System Behavior using Geophysical Data* (Bicentennial Pavilion AGD)	
1:20 PM	**6A CO_2 Sequestration (Bicentennial Pavilion EF)**	**6B Panel - Exempt Wells, Prior Appropriation and Water Banking in Washington State (Bicentennial Pavilion BC)**
SESSION 6	Hydrologic Characterization Results for the Wallula Basalt Carbon Sequestration Pilot Borehole *Frank Spane, Pacific Northwest National Laboratory* Wellbore Cement Carbonation by Various Phases of Carbon Dioxide During Geologic Carbon Sequestration *Wooyong Um, Pacific Northwest National Laboratory* Geochemical Impacts of Leaking CO2 from Subsurface Storage Reservoirs to an Unconfined Carbonate Aquifer: Experimental and Modeling Results *Nikolla P. Qafoku, Pacific Northwest National Laboratory* Threshold Values for Identification of Contamination Predicted by Reduced Order Models *George Last, Pacific Northwest National Laboratory*	**Moderator: Tom Tebb** **Panel Members:** *Susan Adams, Paul Jewell, Thomas Loranger, Suzanne Skinner* The goal of this panel session is to introduce specific case examples and to discuss the solutions that are being used to solve the conflicts. The panel session provides a forum for professionals involved in groundwater development, water management, land use planning and water policy to discuss with the panel participants the implications of these solutions. Learn from them what works, what doesn't and why.

2:40 PM	Refreshment Break | Exhibits | Posters (Bicentennial Pavilion Rotunda)	
3:00 PM	**7A Modeling and Data Management (Bicentennial Pavilion EF)**	**7B Panel - Stormwater Infiltration Testing and Analysis (Bicentennial Pavilion BC)**
SESSION 7	Modeling Nearshore Groundwater Contaminant Attenuation in Response to Intertidal Sediment Capping *Seann McClure, Aspect Consulting, LLC* Groundwater Monitoring Optimization Reduces Site Operating Cost *Glenn Hayman, Hayman Environmental* Managing the Thermal Regime of Sustainable Groundwater Withdrawals for Salmonid Rearing at the Eastbank Hatchery, Rocky Reach Dam, Washington *Carl Einberger, Golder Associates Inc.* Adapting the Arc Hydro Groundwater Data Model and Tools to a Hydrogeologic Framework for the Kitsap Peninsula, Kitsap, Mason and Pierce Counties, Washington *Wendy Welch, U.S. Geological Survey*	**Moderator: Roy Jensen** **Panel Members:** *Scott Kindred, Joel Massmann, Ed O'Brien, Larry West* Infiltration facilities are systems used to introduce stormwater into the ground. Infiltration is a preferred method for managing with stormwater. Successful infiltration facilities require careful design and management. The goal of this panel session to explore infiltration testing and analysis methods and the procedures necessary to successfully evaluate sites for infiltration.
4:30 PM – 5:30 PM	Reception – Wrap Up and Raffle (Bicentennial Pavilion Rotunda)	
5:30 PM	2013 Symposium Adjourns	
Thursday, April 25, 2013		
8:00 AM – 4:00 PM	Workshop 2: Well Drilling Workshop (USGS Warehouse at 8914 Lakeview Avenue Southwest Lakewood, WA 98499)	
8:00 AM – NOON	Workshop 3: Bioremediation Fundamentals and Applications (Venice 3)	Workshop 5: MLU: A New Way to Analyze Aquifer Tests in Multi-Layered Systems (Venice 4)
1:00 PM – 5:00 PM *1:30 PM- 4:30 PM	Workshop 4: Chemical and Thermal Remediation Fundamentals and Applications (Venice 3)	*Workshop 6: MLU: Aquifer Characterization Tests and Pressure Transducer Data Collection (Venice 4) **note time:* 1:30 pm – 4:30
Friday - Sunday, April 26-28, 2013		
ALL DAY	Field Trip 2: On the Trail of the Ice Age Floods (Eastern Washington)	

Jeffrey J. McDonnell, Ph.D.

Global Institute for Water Security
University of Saskatchewan

Topic: Groundwater-Surface Water Interactions at the Watershed Scale

Groundwater-surface water interactions in the headwaters of river networks are poorly understood and poorly characterized. Direct hydrometric measurements have been limited due to the logistical challenges associated with drilling through hard rock in steep, remote and often roadless terrain. Here I present new work on bedrock groundwater dynamics in headwater systems in the Oregon Cascades and Oregon Coast Range aimed at quantifying bedrock groundwater contributions to hillslope and catchment runoff. I illustrate these effects through stable isotope analysis of runoff components and the mean residence time analysis of surface water and groundwater. Results suggest that despite similar rainfall-runoff dynamics, these systems have distinctly different groundwater-surface water interactions, where mean residence time of headwater streamflow is 1-3 years in the Cascades and 3-11 years in the Coast range. More importantly, the scaling of surface water mean residence time in the Cascades is linked to internal topographic structure of individual sub-catchments whereas Coast range sites show no evidence of this; and streamwater residence times scale linearly with watershed area. I place these findings within a hydrogeological storage framework and discuss implications for watershed-scale climate and landuse change effects in the Pacific Northwest.

Jeffrey J. McDonnell has been the Richardson Chair in Watershed Science and University Distinguished Professor of Hydrology at Oregon State University since 1999. In July 2012, he joined the Global Institute for Water Security at the University of Saskatchewan in Saskatoon Canada. Jeff's work focuses on new ways to measure, model and understand streamflow generation processes. Jeff has co-authored ~200 articles on watershed hydrology and co-edited the Elsevier textbook "Isotope Tracers in Catchment Hydrology". He has served as the Senior Advisory Editor of the "Encyclopedia of Hydrological Sciences", published by John Wiley and Sons and is currently Editor-in-Chief of the IAHS Book Series "Benchmark Papers in Hydrology". Jeff is a Fellow of the American Geophysical Union and the International Water Academy and recipient of several awards, including the Dalton Medal from the European Geophysical Union, the Gordon Warwick Award from the British Geomorphological Research Group, the Nystrom Award from the Association of American Geographers and a D.Sc. from the University of Canterbury. Jeff was the 2011 Birdsall-Driess Distinguished Lecturer for the Geological Society of America and 2012 Borland Lecturer for AGU Hydrology Days.

Steve Silliman, Ph.D.

Dean, School of Engineering and Applied Science
Gonzaga University

Topic: Salinity in Municipal Water Supply Wells Serving Cotonou, Benin, West Africa

Cotonou is the largest population center (~1 million people) in the country of Benin, West Africa. The city relies entirely on groundwater withdrawal for its domestic water supply. Concern exists that recent increases in salinity observed in the wells are related to salt-water intrusion from the ocean and Lake Nokoue (a large coastal lake). Analysis of groundwater levels, lake levels, pump tests, water chemistry, and numerical modeling suggests that this is a complex hydrologic system with interplay among local groundwater flow, regional flow from the north, regional recharge, exchange between Lake Nokoue and the ocean, and localized recharge from Lake Nokoue. Characterization and estimation in this system is further complicated by limitations in the technologies that can be utilized and extent of field characterization that can be pursued (due both to challenges in site access and severe budget limitations).

Steve Silliman received his BSE in Civil Engineering from Princeton University in 1979. He completed a Masters and Ph.D. at the University of Arizona, in the Department of Hydrology and Water Resources, in 1981 and 1986, respectively. Since that time, he has pursued research in a number of areas of groundwater hydrology ranging from wellhead protection, to chemical/microbial transport, to water-resources in developing countries (with focus on Benin, West Africa). As of July 1, 2012, Dr. Silliman is Dean of the School of Engineering and Applied Science at Gonzaga University in Spokane, Washington. Prior to this position, he spent more than 26 years at the University of Notre Dame where he served as Professor and Associate Chair of the Department of Civil Engineering and Geological Sciences, as well as Associate Dean for Undergraduate Programs in the College of Engineering. Dr. Silliman has won multiple awards for teaching, service, and research. These include the ASEE Outstanding Teaching Award as well as the ASEE Global Engineering and Engineering Technology Award (both in 2006), nomination for the University of Oklahoma World Water Prize (2009), and selection as the National Ground Water Association Distinguished Darcy Lecturer for 2011.

Susan S. Hubbard Ph.D.

Earth Sciences Division Director
Lawrence Berkeley National Laboratory

Strategies to Quantify Terrestrial System Behavior Using Geophysical Data

Quantification of hydrological and biogeochemical properties and their couplings are needed for predicting the behavior of terrestrial environments, including the ability of the system to sequester contaminants and carbon. However, such quantification is often based on small-scale observations that do not adequately provide information about controls on larger-scale system behavior. This study presents two recently developed strategies to quantify properties and processes across scales; both strategies involve the use of geophysical methods and stochastic integration approaches. The first case study describes a "reactive facies" concept as an organizing principle to integrate laboratory and disparate field datasets, in order to make reliable and computationally tractable yet mechanistic predictions of long-term plume mobility over field-relevant scales. Reactive facies are subsurface units that have linked distribution of properties that have been documented to influence reactive transport. We develop and test the reactive facies concept within a uranium contaminated region of the Savannah River Site using Bayesian approaches and geophysical datasets. Reactive transport modeling results suggest that reactive facies exert significant control on plume evolution, highlighting the usefulness of the approach for spatially distributing properties that control flow and transport over field-relevant scales. The second case study focuses on developing methods to quantify Arctic terrestrial ecosystem functioning as needed to address how permafrost thaw and degradation - and the associated changes in hydrology, soil biogeochemical processes, and plant community dynamics - affect feedbacks to the climate system. We explore the use of remote sensing and surface geophysical data to characterize subsurface and land surface properties, their linkages, and implications for predicting the trajectory of the landscape with global change.

Susan Hubbard is the Director of the Earth Sciences Division and also leads the Environmental Remediation and Water Resources Program at Lawrence Berkeley National Laboratory. Susan Hubbard's research focuses on advancing the use of geophysical methods for shallow subsurface characterization and monitoring, with a particular emphasis on development of data integration methods and application of those methods to terrestrial ecosystems, water resources, and environmental-remediation problems. She co-edited the first book on hydrogeophysics and has published over 60 papers on this topic. She serves on several scientific advisory boards, including the Department of Energy Biological and Environmental Research Advisory Committee, which provides the most funding, nationally, for remediation science research. She is the Associate Director for the Berkeley Water Center, a Co-Editor for the Vadose Zone Journal, and an Associate Editor JGR-Biogeosciences. She is the recipient of the 2009 Frank Frischknecht award for leadership and innovation in near-surface geophysics, was the 2010 Geological Society of America (GSA) Birdsall Dreiss Distinguished Lecturer, and became a GSA Fellow in 2011.

Panel Sessions

Panel 6B: Exempt Wells, Prior Appropriation and Water Banking in Washington State

As the saying goes…"Whiskey is for drinking, water is for fighting…" Water use in the west is based on the general principal of prior appropriation or "first in time, first in right." However, many western states have built into their water code an exception for what is considered to be small uses of water that are typically associated with individual rural development, stock watering, lawn and gardening.

Domestic wells in Washington State are a common use of groundwater that is exempt from the water rights management process. Exempt domestic wells supply water for typically rural residential development in many areas of Washington State.

Expansion in the use of exempt domestic wells has raised concerns about the sustainability of the groundwater supply in the Yakima, Dungeness and Skagit river basins. These new domestic groundwater uses are creating conflict between flows for fish, traditional water rights holders and new domestic groundwater users because of surface and groundwater interactions and well interferences.

The goal of this panel session is to introduce specific case examples and to discuss the solutions that are being used to solve the conflicts. The panel session provides a forum for professionals involved in groundwater development, water management, land use planning and water policy to discuss with the panel participants the implications of these solutions and to learn from them what works and what doesn't and why.

Panel Members include:

Tom Tebb (Moderator), Regional Director, Central Regional Office, Washington State Department of Ecology

Tom Tebb has over 27 years of environmental and engineering experience in both the private sector and government service. Currently, Tom is the Regional Director for the Department of Ecology in its Central Regional Office located in Yakima, Washington. Tom has held this position since 2008. Tom has over 20 years of experience with the Department of Ecology and has served as a manager in four different programs during his tenure with the Agency. Those Programs include Nuclear Waste, Shorelands and Environmental Assistance, Water Quality and Water Resources. Tom received his Bachelors of Science degree from Western Washington University in Environmental Geology in 1984. Tom is a licensed Geologist, Hydrogeologist, and Engineering Geologist in the State of Washington.

Susan Adams, Executive Director, Washington Water Trust

Susan Adams joined Washington Water Trust in 2004. Susan has over 20 years of executive management, policy development, and negotiation experience with private, public and nonprofit organizations working on natural resource issues. Prior to Washington Water Trust, Susan managed natural resources education, communications and public relations for the Oregon Department of Fish and Wildlife. While in Oregon, she also participated in regional water supply planning in collaboration with diverse stakeholders throughout the Portland metropolitan area to ensure sustainable water resources for future generations. Susan's experience includes business development and marketing for Honeywell Marine Systems, United Way and private consulting in both Washington and Oregon. She holds a B.A. in Communications and Business from Michigan State University and has pursued graduate studies at the University of Washington and Antioch University with an emphasis on systems design, leadership and change management.

Paul Jewell, Kittitas County Commissioner

Paul is in his second term as a County Commissioner. His responsibilities include setting county policy, adopting and implementing laws, and carrying out the day-to-day operations of the County. Paul also serves as the County's lead for all water issues. He is a member of the exempt well working group for the Washington State Association of Counties (WSAC), is a member of the Columbia River Policy Advisory Group, and is the Chairman of WSAC's Columbia River Counties Caucus.

Thomas Loranger, Water Resources Program Manager, Washington State Department of Ecology

Tom has worked at the Washington State Department of Ecology for 23 years. He worked on policy and regulation review in Ecology's Waste Management and Toxics Reduction Programs for 10 years. He worked on Salmon Recovery planning in the Shorelands Program for 4 years and has been a member of the Water Resources Leadership Team for 9 years. He has been acting Water Resources Program Manager since February 2013. Tom holds a B.S. in Environmental Studies and an M.S. in Environmental Science.

Suzanne Skinner, Executive Director, Center for Environmental Law & Policy

Suzanne Skinner is the Executive Director of the Center for Environmental Law & Policy. Prior to joining CELP, she served as the Civil Director of the Seattle City Attorney's Office, an Administrative Law Judge for the (former) Environmental Hearings Office, an attorney for American Rivers, and an assistant United States attorney in New York. She has a J.D. from Northeastern University Law School and undergraduate degrees from the University of Washington in Zoology and English.

Panel 7B: Stormwater Infiltration Testing and Analysis

Infiltration facilities are systems used to introduce stormwater into the ground. Infiltration is a preferred method for managing with stormwater. Successful infiltration facilities require careful design and management. The goal of this panel session to explore infiltration testing and analysis methods and the procedures necessary to successfully evaluate sites for infiltration.

Panel Members include:

Roy Jensen, LHG (Moderator), Senior Hydrogeologist, Hart Crowser

Roy Jensen, LHG, has 21 years of experience. He has particular expertise in groundwater monitoring, tidal influence studies, groundwater and contaminant transport modeling, and borehole geophysics. He also provides hydrogeologic support for a variety of geotechnical projects including construction dewatering, evaluation of groundwater seepage for slope stability problems, and surface water infiltration evaluation. He has managed and directed environmental investigation and remediation projects for numerous properties. His project experience includes developing water sources. He has completed numerous hydrogeologic assessments of properties as required for land use planning and environment impact studies.

Scott Kindred, P.E., Associate Water Resource Engineer, Aspect Consulting

With expertise in hydrogeology, contaminant fate and transport, and civil design, Scott Kindred is uniquely qualified to address the range of issues associated with stormwater infiltration, and specializes in the design and implementation of stormwater infiltration systems. Scott was responsible for the site characterization, design, and testing of a series of deep (>70 ft) underground injection control (UIC) wells in Kittitas County, a large infiltration system that included over 150 deep dug drains, a large infiltration system at Fort Lewis, and numerous additional infiltration projects. In addition, Scott has been the project manager and technical contributor for numerous environmental remediation projects, with experience on CERCLA and MTCA sites, site assessment and remediation design, Phase I and Phase II Environmental Site Assessments, and landfill closure. He specializes in managing large, multi-disciplinary projects relating to property development and environmental remediation and has worked extensively on mining, industrial, and nuclear facilities.

Joel Massmann, Ph.D, P.E., Principal Engineer, Keta Waters

Dr. Massmann received B.S. and M.S. degrees in Civil Engineering from the Ohio State University and the Ph.D. degree from the University of British Columbia. He has taught courses in civil engineering at the University of Washington, the University of Illinois, and Michigan Technological University. Dr. Massmann's work on environmental issues has received national recognition, including the Rudolf Hering Medal from the American Society of Civil Engineering in 1990 and the Presidential Young Investigator Award from the National Science Foundation in 1988. He has served as a consultant to the U.S. EPA Science Advisory Board (1992-1997) and as a member of the Environmental Restoration Priority System Panel for the National Research Council (1992-1994).

Joel Massmann, Ph.D, P.E., Principal Engineer, Keta Waters - continued

He has also served as a consultant to the Finnish Ministry of the Environment and to the Swedish Nuclear Fuel and Waste Management Company (SKB). Professor Massmann also served on the Columbia River Comprehensive Impact Assessment Peer Review Committee (1995-1997) and on the Hanford Advisory Board (1999-2001). He was appointed to the Fate and Transport Subcommittee of the Washington Department of Ecology Science Advisory Board (1996-2000) and assisted them in developing risk-based clean-up standards at contaminated sites. He also served on the Washington Department of Ecology Technical Advisory Group charged with establishing the standards for review of applications for underground artificial storage projects (2000-2002) and as a consultant and external reviewer for the British Columbia Science Advisory Board for Contaminated Sites (2004).

Ed O'Brien, P.E., Environmental Engineer, Ecology

Ed O'Brien is a civil engineer licensed in Washington. Has worked on developing stormwater permits and guidance for the State of Washington for over 20 years.

Larry West, LHG, Director of Groundwater Services, Shannon & Wilson

Larry West has 40 years of experience in groundwater management, development, control and protection. For over 35 years, Mr. West has focused on construction dewatering including the evaluation and design of dewatering systems for temporary and permanent applications supporting construction of treatment plants, pipelines, deep excavation for garages and tunnel access shafts. Larry was formerly a construction dewatering contractor and has served as a dewatering consultant to owners, engineers and contractors since the 1980s. His expertise includes the design of sump systems, wells, vacuum wellpoints, educator/ejector systems and recharge systems to mitigate settlement and contaminant mobilization during dewatering. Larry specializes in development of dewatering evaluations and designs that address changing/differing site conditions and dewatering specifications to minimize change orders. Mr. West has conducted over 100 construction dewatering evaluations and dewatering system designs across the United States and overseas.

Oral Abstracts

Lacey-Olympia-Yelm Water Rights
An Example for the Future Procurement of Municipal Water Supplies

Michael Gallagher, Department of Ecology

In December 2010, the City of Lacey submitted to Ecology a mitigation plan for six water right applications, from six different wells located in the Hawks Prairie and east Lacey area with a combined total of 7392 acre-feet per year (AFY) of new water. Also in December 2010, the City of Olympia (jointly with the Nisqually Tribe) submitted a water right mitigation plan to transfer their 29,209 AFY of surface water rights from McAllister Springs to groundwater rights at a new "McAllister Wellfield", located about 1.25 miles south of McAllister Springs. In February 2011, the City of Yelm submitted a water right mitigation plan for one water right application totaling 942 AFY of new water. Each water right application package had modeled impacts in the Nisqually and Deschutes Basins and McAllister, Woodland Creek and Yelm Creek Sub-basins.

Olympia (and the Nisqually Tribe), Lacey and Yelm coordinated their efforts regarding future water supply needs for each entity. All three cities used the same regional groundwater model and agreed to have their modeling consultants coordinate any changes with each other and to peer-review the model each time it was changed.

In addition, the Cities combined their planning efforts and financial investment to propose a series of mitigation actions including recharging reclaimed wastewater and purchasing and retiring existing water rights and land purchases for riparian improvements and other "out-of-kind" mitigation actions to address modeled groundwater and surface water depletions that could be expected to occur in the Nisqually and Deschutes Basins and McAllister, Woodland Creek and Yelm Creek Sub-basins. Ecology also invoked the "Overriding Consideration of Public Interest" (OCPI) provision [RCW 90.54.020(3)(a)] since not all mitigation covered year-round pumping impacts from all of the new wells at full build-out.

During the winter and spring of 2012, Ecology approved and permitted Olympia's water right changes from McAllister Springs to the new McAllister Wellfield and approved all of Lacey's new water right applications. Ecology also approved Yelm's application for new water. Yelm's permit was appealed by a small group of local residents living near Yelm and their appeal is scheduled to be heard by the Pollution Control Hearings Board in December 2012. Overall, this joint mitigation effort can serve as a good example for how other municipalities and water systems can effectively and sustainably obtain new water for expected long-term growth in basins that have instream flow rules.

Groundwater Supply Conditions in Columbia Basin Municipalities: Evidence of Little Groundwater Recharge and Potential Future Water Supply Shortfalls

Kevin Lindsey, GSI Water Solutions, Inc.

John Porcello, GSI Water Solutions, Inc.

Matt Tonkin, S. S. Papadopulos & Associates, Inc.

Patrick Royer, Columbia Basin GWMA

Paul Stoker, Columbia Basin GWMA

Groundwater is the primary source of potable water for 25 municipalities in the Columbia Basin Ground Water Management Area (CBGWMA) of Adams, Franklin, Grant, and Lincoln Counties, Washington. Evaluating data from a variety of sources, CBGWMA found that most of these municipalities are pumping predominantly fossil groundwater, even in areas where natural and artificial surface waters are present. Coupled with this, water levels and production rates are declining in most municipal wells, in both non-irrigated areas and in surface water irrigated areas, including within the Columbia Basin Irrigation Project where water levels are falling and some of the oldest groundwater found within the CBGWMA is being pumped.

Of 124 municipal wells evaluated, 22 were found to be decommissioned or non-operational. These wells generally were taken out of production because of poor water quality, physical deterioration, or water production shortfalls. Of the remaining 102 operational wells groundwater supply conditions were evaluated using data supplied by the municipality, collected for this project, and/or publically available. This evaluation identified several risk factors that suggest most wells and municipalities in the CBGWMA will experience water production shortfalls in the next several decades.

These risk factors include: (1) static and dynamic groundwater level decline rates in excess of 2 ft/year; (2) dynamic drawdowns of over 100 feet; (3) current and predicted static and dynamic water levels dropping below 700 feet below ground surface; (4) groundwater geochemical data that indicates wells are pumping fossil groundwater with little or no modern recharge; and (5) projected future water demand that exceeds current pumping capacity by 2030. With respect to these factors: (1) almost half of the 76 wells with pumping tests have drawdowns over 100 feet, suggesting either well or aquifer limitations on water production; (2) Over ⅓ of the 84 wells with water level data have decline rates exceeding 2 feet/year, suggesting aquifer storage depletion is occurring; (3) at least ¼ of 57 wells with water level and pumping test data likely will have drawdowns that will exceed 700 feet below ground surface in the next several decades; and (4) groundwater geochemical data collected from 75 wells shows ⅓ pumping fossil groundwater, ¼ pumping predominantly modern groundwater, and the remainder pumping mixed, but fossil dominated, groundwater. Taking all of these together, about ¼ of the wells with data show at least one risk factor and ⅓ of them have two or more. Coupling these risks with predicted future water demands, at least half of the municipalities in CBGWMA likely will not meet their water production targets by 2030.

Placing these wells into their hydrogeologic context CBGWMA finds the wells with the greatest number of risk factors are in the central CBGWMA, and in portions of CBGWMA bound by geologic features that inhibit lateral and vertical groundwater movement, thus restricting recharge. The few wells that do not appear to be at risk generally are shallow, near surface water sources, and/or in highland areas around the fringe of the GWMA.

Lower Deschutes Valley Groundwater Resources, Thurston County, Washington

Chris Pitre, Golder Associates Inc.

Timothy Walsh, Washington Department of Natural Resources

Groundwater in the Lower Deschutes Valley has provided high quality drinking water to the cities of Olympia and Tumwater (and the former Olympia Brewery) since the late 1800s. But groundwater development has been a hit-or-miss proposition. The brewery has installed approximately 100 wells, and the city of Tumwater over 20 wells, in the pursuit of productive wells.

Groundwater seepage to the Deschutes River also contributes significantly to the ecological health of the river. Addressing development pressures on the groundwater resource requires a good understanding of hydraulic continuity between groundwater and the river to allow informed decisions on balancing benefits and impacts. Such an understanding has evolved over the past few decades to better inform water resources management.

Analysis of LiDAR imagery, well logs, and radiocarbon dates show the stratigraphy of the Lower Deschutes Valley to be more complex than previously recognized. An in-filled erosional trough roughly parallels the Deschutes River starting near the confluence of Spurgeon Creek with the Deschutes River, to approximately 500 feet below sea level near Budd Inlet of Puget Sound. This trough is in-filled by loosely consolidated fine sediments.

In the middle of this alignment, near Pioneer Park, the middle of the trough fill sequence (~180 feet below ground surface; 300 feet below sea level) has a radiocarbon date of 24,000 years before present (bp). The underlying strata is hard, greenish, overconsolidated clayey terrestrial materials with organic content, and has an infinite radiocarbon date (i.e., >46,000 years bp).

Quaternary glacial sea levels were several hundred feet lower than present. The north-south trough is interpreted to have formed by erosion during lowered sea levels associated with Quaternary glaciations, including the most recent Vashon and older glaciations. Portions of the Deschutes Valley may have been eroded and in-filled several times to varying degrees during different glaciations.

East-west surficial Vashon recessional outwash channels have been identified by LiDAR imagery analysis that parallel the face of the retreating Vashon glacier and feed into the main Deschutes Valley trough (e.g., along Spurgeon Creek, and near the Indian Summer golf club). These channels have eroded the Vashon till away, down-cut into the underlying advance outwash, and are filled with post-Vashon glacial recessional fill. Another channel is recognized south of Tumwater Hill, extending from the City of Tumwater's Palermo Well Field, west toward Black Lake.

Deposition in the Deschutes Valley has alternated between north and south water flows. The large-scale structure of the Lower Deschutes River is consistent with that of a delta prograding northward. Cross-bedding structures and drop stones at surface indicate a southward flow consistent with Vashon meltwaters discharging through the Chehalis Basin. Today's geomorphic expression has the imprint of northward fluvial erosion, including the northward flow of the Deschutes River, and the dendritic erosion in Olympia's Watershed Park.

The Lower Deschutes Valley stratigraphy appears to have been deposited under fluvially-dominated processes, during periglacial and interglacial times. The presence of sub-glacial deposits has not been evaluated. Recognition of the extents over which the Vashon till is absent, in both the in-filled trough, as well as in ancestral erosional side channels, improves upon earlier understandings of the hydrogeology.

This understanding is important to water resources management including: protecting drinking water sources from groundwater contamination; developing groundwater; and, managing ecological habitat. The understanding of the stratigraphy will evolve as the available data is examined in greater detail and re-interpreted, and more data becomes available.

Initial Development of the McAllister Wellfield, Thurston County, WA

Justin Iverson, Golder Associates

Derek Holom, Golder Associates

Mike Johnson, Gray & Osborne

Tim Richardson, City of Olympia

The City of Olympia is committed to providing safe and reliable drinking water to its customers — now and well into the future. In order to meet this commitment, the City is developing the McAllister Wellfield, a new groundwater source that will replace McAllister Springs as the City's primary supply of drinking water. The McAllister Wellfield will be jointly developed with the Nisqually Indian Tribe in order to provide a secure supply of water for both communities for generations to come.

The City began investigating the McAllister Gravel Aquifer in the mid-1990s, during which time they installed several test wells and monitoring wells. In 2012, the Department of Ecology approved and permitted Olympia's water right changes and the City initiated Phase 1 of the McAllister Wellfield construction project. Phase 1 includes installation of one to two new well(s) and rehabilitation of two existing wells to develop a 17 MGD municipal groundwater supply. Future phases, including installation of a well by the partnering Nisqually Indian Tribe, will bring the total wellfield capacity to a planned 26 MGD.

This presentation will describe development of a large groundwater supply from the McAllister Wellfield, including discussion of the lithology, depositional environment, and extent of the McAllister Gravel Aquifer, natural-pack screen design and development in gap-graded sands and gravels, water management during a planned 5,500 gpm pumping test, and pumping test analysis with respect to aquifer hydraulic properties, well capacity, and well efficiency.

Donor Borings: A Cost-Effective Approach for Bioremediation of a TCE Source Based on Treatment Effectiveness and Longevity

Christophe Venot, Landau Associates

Clint Jacob, Landau Associates

Jerry Ninteman, Landau Associates

Nicholas Garson, The Boeing Company

Alan Sugino, The Boeing Company

Daniel McCormack, The Boeing Company

This presentation will discuss the longevity and treatment resulting from "donor borings" installed in 2009 to promote anaerobic bioremediation of a trichloroethene (TCE) source zone at an aerospace manufacturing plant in Everett, Washington. A prior attempt to stimulate biological treatment through injection of electron donor was largely unsuccessful due to tight aquifer conditions. Donor borings have provided more than two years of source zone treatment in a low permeability portion of an unconfined, advance outwash aquifer. The extended period of treatment and use of inexpensive and off-spec materials make the donor borings a very cost-effective treatment method.

Anaerobic bioremediation of TCE is accomplished through the addition of organic carbon substrates which serve as electron donor for biologically mediated reductive dechlorination of TCE and breakdown products. Electron donor is used by native aquifer bacteria for reductive dechlorination and to create the highly reducing aquifer conditions required for complete degradation of TCE and breakdown products. Reductive dechlorination of TCE results in the removal of chlorine atoms and the formation of sequential degradation products cis-1-2-dichloroethylene (cDCE), vinyl chloride (VC), and non-toxic end products ethene and/or ethane.

Thirteen donor borings were installed in 2009 in three staggered rows to form a "picket fence" of emplaced donor that is distributed to the downgradient aquifer by groundwater flow between the borings. Borings were backfilled with a granular slurry of LactOil™ (vegetable oil and ethyl lactate), cheese whey, and pea gravel designed based on bench testing and field pilot testing. Use of off-spec whey was in keeping with our client's stated goal of sustainable remediation through reduced natural resources consumption. Donor borings have resulted in an extensive downgradient treatment zone with reduced aquifer redox conditions and decreasing concentrations of TCE and breakdown products. Treatment longevity has been greater than originally anticipated.

Performance of Enhanced Anaerobic Dechlorination (EAD) via Groundwater Recirculation at a North West Industrial Facility

Brian Timmins, ETEC, LLC

Jacob Neal, Landau Associates, Inc.

An enhanced anaerobic dechlorination (EAD) remediation project (in situ) was conducted in the NW from January 2010 until January 2011. A groundwater extraction and recirculation approach was selected to distribute a low-cost, soluble, nutrient-amended substrate to stimulate EAD across two distinct groundwater plumes in short a timeframe, while maintaining a high degree of hydraulic control in the saturated zones. Bioaugmentation was not required due to the successful stimulation of indigenous bacteria capable of complete dechlorination. Chemicals of concern include tetrachloroethene (PCE) and trichloroethene (TCE) and their associated dechlorination daughter products; cis-1,2-dichloroethene (cis-DCE), and vinyl chloride (VC).

The groundwater plume surface areas were 100 ft wide x 240 ft long and 120 ft wide x 200 ft long, with saturated zone thicknesses of approximately 20 ft (two distinct saturated zones at different horizons were remediated). Injection and extraction wells were designed and installed in a manner that provided a high degree of communication and amendment distribution in order to maximize contact with the impacted zone and to minimize the remediation timeframe. Saturated zone lithologies varied depending on depth, but generally consisted of silt, sand, and gravel.

Baseline conditions showed groundwater concentrations of total chlorinated solvents as high as 6-14 mg/L. After 6 months of substrate addition and active recirculation, site-wide dechlorination was observed at all locations showing excellent distribution of the amendments. Quarterly groundwater data (VOCs and MNA data) collected over 24 months (12 months of post-remediation data will be included) will be made available for the presentation. System design, operation, and costs will also be presented.

The results show that the approach successfully stimulated an indigenous microbial consortium capable of complete dechlorination, and maintained a high degree of hydraulic control/capture to prevent contaminant migration during treatment in both groundwater zones. In addition, the in situ remediation was conducted with minor disturbances to the existing business. The results demonstrate that EAD using groundwater recirculation is an extremely fast, complete, and cost-effective approach when compared to other remediation alternatives.

Implications of In Situ Biotreatment Persisting Years after Electron Donor Injection: Two Case Studies

Clint Jacob, Landau Associates

Christophe Venot, Landau Associates

Eric Weber, Landau Associates

Carl Bach, The Boeing Company

James Bet, The Boeing Company

There has been discussion among bioremediation practitioners that in situ biotreatment may occur for a longer period of time following active bio-stimulation than was previously anticipated. Prolonged treatment may be the result of endogenous decay of stimulated populations of bacteria providing a long-lasting electron donor source, back-diffusion of donor from immobile porosity (dead-end pore spaces), and potentially other factors.

Prolonged residual treatment would have important implications, including:

1. Designing a shorter period of active treatment utilizing fewer injection events
2. Substantial enhancement of MNA following biostimulation
3. A long post-treatment period before natural aquifer conditions are reestablished and potential contaminant rebound can be fully evaluated

This presentation will evaluate data from two sites near Seattle Washington where persistently reduced aquifer redox conditions and complete reductive dechlorination of TCE have been observed at more than 2 years and more than 3.5 years following the last donor injection event. Both sites utilized a combination of vegetable oil and sodium lactate donor substrates injected every 6 months over 2.5-year (5 injections) and 1-year (3 injections) periods of active stimulation. Bioaugmentation with non-native dechlorinating bacteria was performed at one of the sites. The presentation will include evaluation of aquifer redox data, total organic carbon (TOC) as an indicator of electron donor, contaminant degradation, and bacterial population.

Successful Cleanup of an Industrial Site, Renton, Washington

Angie Goodwin, Hart Crowser, Inc.

Roy Jensen, Hart Crowser, Inc.

Industrial operations were conducted at a large facility in Renton from 1907 until 1988. The site was designated a NPL site in 1990 with oversight provided by the Department of Ecology. Cleanup at the site was one of the first negotiated under a consent degree governed by MTCA. Site investigations began in 1988 and a RI/FS was released in 1989/1990 followed by an approved cleanup plan in 1991. A summary of the remedial investigations, cleanup work, and the results of ongoing groundwater monitoring will be presented.

The site is underlain by a layered and variable sequence of river-valley deposits to a depth of over 100 feet. Four hydrogeologic units were identified including (1) Fill/Aquitard; (2) Upper Sand; (3) Middle Aquitard; and (4) Lower Sand. Constituents of concern in soil and groundwater were identified to be TPH, cPAHs, PCBs and metals. Soil contamination was restricted to the Fill/Aquitard unit.

Cleanup work associated with the site was conducted in five phases between 1991 and 1997. Cleanup actions included: (1) excavation and biotreatment of petroleum contaminated soils; (2) excavation and stabilization of soils containing metals and cPAHs; (3) excavation and off-site disposal of soil containing PCBs; (4). installation of a protective soil cover to prevent direct contact with contaminated soils; and (5) groundwater and surface water monitoring, and institutional controls.

A monitoring well network of 30 wells was established within the Upper and Lower Sand units to monitor progress of the cleanup beginning in 1998. Since 1998 TPH, PAH and VOCs groundwater concentrations have generally declined to below cleanup levels. Low level concentrations of arsenic were found in the majority of the wells. Elevated arsenic concentrations persist in at least 8 wells at concentration ranging from 5 to 40 ug/L. The data also show that the arsenic plume is not migrating off the site. Geochemical parameters indicative of reducing conditions are present in a majority of the wells. The presence of organic materials such as peat and residual petroleum in area soils fosters reducing conditions in site groundwater. The historical use of arsenic at the site cannot explain the widespread distribution of arsenic in groundwater. Rather, the data indicate that naturally occurring arsenic in soil is being mobilized by the reducing conditions in groundwater in the vicinity of the site.

Deep Underground Injection Control Wells to Infiltrate Stormwater and Stabilize a Ravine

Todd Wentworth, PE, LG, AMEC Environment & Infrastructure

Miao Zhang, AMEC Environment & Infrastructure

Deep underground injection control (UIC) wells allow stormwater infiltration to bypass impermeable near surface soils for low impact development (LID) of a new elementary school. This use of deep UIC wells eliminates stormwater detention facilities. Instead, the wells accommodate the peak storm flow, and water quality is achieved by catch basin dead storage, and filter inserts.

The former elementary school routed all stormwater to a central pipe that discharged to a ravine on private property, causing channel incision and landslide scarps over 30 feet deep. As part of the complete school renovation, over 50 deep UIC wells, 3 feet in diameter, infiltrate stormwater 60 to 80 feet below the site in order to prevent further erosion of the drainage ravine and to avoid the need for underground detention vaults. The results of two pilot infiltration tests were used to predict water levels in the UIC wells and the radius of influence beyond the wells based on the design storm hydrographs. AMEC monitored the installation of the UIC wells and conducted full-scale infiltration testing, which allowed design improvements to the wells during construction.

This innovative stormwater design succeeded because the designers carefully considered the site-specific development constraints, topographic limitations, and the favorable geology beneath the site.

Simulating Underground Injection of Stormwater using MODFLOW-SURFACT

Miao Zhang, AMEC Environment & Infrastructure

Todd Wentworth, AMEC Environment & Infrastructure

An underground injection control (UIC) well is selected to infiltrate stormwater generated on a public elementary school in Kirkland, Washington where groundwater is over 200 feet below ground surface. Geotechnical investigation identified a permeable layer of advance outwash sand below at least 40 feet of less permeable glacial till. Pilot test UIC wells with the bottom 10 or 20 feet exposed to advance outwash sand were installed. Infiltration tests were conducted by injecting municipal water in the pilot test wells at controlled rates and monitoring water levels over time.

A three-dimensional variably-saturated flow model was developed using the code MODFLOW-SURFACT to simulate the movement of injected water in unsaturated soil. Values of hydrogeologic parameters, including saturated hydraulic conductivity, porosity, and van Genuchten parameters, were initially estimated based on grain size distribution of site soil samples. During model calibration, the hydrogeologic parameters were adjusted so that a reasonable match was obtained between the simulated and measured water levels in the pilot test wells. The calibrated model was used to predict water levels in UIC wells and radiuses of influence for a series of injection rates and durations. The predicted water levels and radiuses of influence were used by civil designers to divide the school property into drainage basins and develop design runoff hydrographs. The design hydrographs were used as model input to verify that the design stormwater flow rates will maintain a minimum freeboard of 10 feet in UIC wells.

During construction, controlled-rate infiltration tests were conducted at select UIC wells. It was found that the allowable injection rates that meet the minimum freeboard requirement were higher than previously predicted. It was also observed that the average grain size of advance outwash at the UIC wells was larger than at pilot test wells. Re-calibration of the MODFLOW-SURFACT model to match the more recent infiltration tests suggested that the increase in injection rate is likely a result of higher saturated hydraulic conductivity for the advance outwash sand. The modeling results helped answer questions such as whether to replace UIC wells that encountered perched groundwater and needed to be abandoned. The UIC wells have recently been completed, and will begin to infiltrate stormwater in the fall of 2012.

Evaluating the Potential for Stormwater Infiltration on a Basin Scale Using GIS

J. Scott Kindred, Aspect Consulting, LLC

Parker Wittman, Aspect Consulting, LLC

Stormwater has been identified as a major contributor to water quality issues in Puget Sound and other water bodies across Washington State. In addition, the large impervious surfaces in urban areas have increased peak stream flows, resulting in stream channel erosion, sedimentation, and loss of habitat, as well as a reduction in base flows during summer and fall months. Solving these issues will require treatment of stormwater to remove toxic constituents and reducing peak flows. Low impact development (LID) has been identified as a useful approach to address these issues and is now a required element of stormwater management in Washington State. LID approaches usually include infiltration of stormwater as a means to reduce peak flows and improve cost efficiency.

Experience has shown that the feasibility of stormwater infiltration varies considerably across the landscape. Major factors that influence stormwater infiltration rates include the permeability of the soils beneath the facility, the depth to groundwater, and the presence of perching layers. In addition, the potential impacts of stormwater infiltration on sensitive slopes, man-made structures, and wetlands, must be addressed before significantly increasing the amount of groundwater recharge.

Although site-specific assessments are critical to support the design and placement of LID facilities that rely on infiltration, municipalities are beginning to recognize that they need to understand the hydrogeologic characteristics of the entire basin to support basin planning efforts and address the potential implications associated with widespread adoption of stormwater infiltration.

This presentation will introduce a basin-scale approach for evaluating the feasibility of stormwater infiltration. This approach relies on large scale mapping of geology, slope, sensitive areas such as wetlands, and depth to groundwater. GIS layers are created for each of these characteristics and the layers are overlain to create maps of polygons representing different hydrogeomorphic units. Each unique hydrogeomorphic unit is evaluated for both shallow and deep infiltration feasibility. Based on these evaluations, maps of both deep and shallow infiltration feasibility are created. Several case studies from across Puget Sound will be presented.

Wellhead Protection and Stormwater Recharge in the Washington Portion of the Spokane Valley - Rathdrum Prairie Sole Source Aquifer

John Porcello, GSI Water Solutions

Matthew Kohlbecker, GSI Water Solutions

Lloyd Brewer, City of Spokane

Doug Greenlund, City of Spokane

The Spokane Valley - Rathdrum Prairie (SVRP) Aquifer is a Sole Source Aquifer that provides drinking water to more than 500,000 people in Spokane County, Washington, and in Boundary and Kootenai Counties, Idaho. The absence of surficial fine-grained soils leaves the aquifer susceptible to contamination from human activities.

In the mid-1990s, 22 Group A water systems in the Washington portion of the aquifer convened as the Spokane Aquifer Joint Board (SAJB) for the purpose of stewarding the development of a coordinated wellhead protection program. In 2012, with the support of grant funding provided by the Washington Department of Health, the SAJB and an inter-governmental policy coordinating committee completed a significant update of the regional wellhead protection program by updating their finite-element groundwater model and quantitatively evaluating the relationship between stormwater management, aquifer recharge, and the water quality protection goals of the wellhead protection program.

The groundwater model was updated by enlarging the modeled area to include the Idaho portion of the SVRP; refining the finite-element mesh to provide high resolution at public system wellfields (where wells are sometimes spaced less than 100 feet apart); incorporating current pumping rates and well locations; and updating the aquifer thickness and hydrologic terms using recent findings from the U.S. Geological Survey Bi-State modeling effort that was completed in 2007. The resulting finite-element model simulates an area of nearly 400 square miles using 44,703 nodes that are spaced between 20 and 550 feet apart. This represents a significant improvement in resolution compared to the rectangular grid of the Bi-State model, which uses approximately 5,200 square cells that are one-quarter mile on a side.

The study of stormwater recharge to the SVRP aquifer evaluated the sensitivity of groundwater capture zone delineations to stormwater infiltration, and identified issues for the SAJB and policy committee to consider in their development of standards for siting recharge facilities in and near wellhead protection management areas. This study concluded that high-magnitude low-frequency precipitation and recharge events would likely alter only those capture zones lying close to recharge facilities. The study also found that for non-degradable stormwater constituents (such as chloride generated by roadway deicing activities), the separation distance between production wells and upgradient stormwater recharge facilities is not likely to be a significant factor controlling water quality at the well. Instead, a more important consideration for protecting groundwater quality is the percentage of groundwater pumping within a wellhead protection area that is ultimately derived from proximate stormwater recharge, particularly that which is first-flush and less treated – a concept that the SAJB policy committee is incorporating into stormwater management recommendations it is presenting to local jurisdictions for adoption into Critical Area Ordinances.

Design and Testing of a Process-Based Groundwater Vulnerability Assessment (P-GWAVA) System for Predicting the Concentrations of Agrichemicals in Groundwater Across the United States

Jack Barbash, U.S. Geological Survey

Frank Voss, U.S. Geological Survey

Over the past three decades, many approaches have been employed to predict the vulnerability of groundwater to contamination by surface-derived solutes over large areas. However, relatively few have involved the use of solute transport-and-fate simulations and compared their predictions with observed data. We have developed a process-based groundwater vulnerability assessment (P-GWAVA) system that uses transport-and-fate simulations—along with the most detailed information available on a national scale for soil properties, chemical use, climate and other input data—to predict the concentrations of agrichemicals in the vadose zone (up to 3 m depth) anywhere within the 48 conterminous United States. In addition to using data directly from their sources for many model input parameters, the P-GWAVA system also employs data on soil properties and temperature to estimate a wider range of site-specific input parameters than have ever been quantified over regional to national scales—including surface crust permeability, macroporosity, Brooks-Corey parameters (for describing soil water characteristic curves), solute transformation rates, diffusion rates, and partition coefficients. By using the Root-Zone Water-Quality Model (RZWQM), the system also accounts for several important processes that have been neglected by most other vulnerability assessment methods—especially the effects of preferential transport and various agricultural management practices. Because the simulations are carried out at large numbers of sites, they are conducted without calibration.

We compared the concentrations of atrazine and deethylatrazine (DEA, an atrazine transformation product) predicted by the P-GWAVA simulations at a depth of 3 m in the vadose zone with those measured in shallow groundwater at 453 agricultural sites throughout the U.S. Corn Belt. Statistically significant, positive correlations ($p \leq 0.0001$) were observed between predicted and measured concentrations for both atrazine (Spearman $\rho = 0.25$) and DEA ($\rho = 0.41$). Among the 17 sampling networks with 10 or more sites, the P-GWAVA predictions explained 24 and 56 percent of the variance in the observed frequencies of detection of atrazine ($R2 = 0.24$; $p = 0.046$) and DEA ($R2 = 0.56$; $p = 0.0006$), respectively.

Concentration residuals (i.e., predicted minus measured values) were significantly correlated with depth to water at individual sites for both atrazine ($\rho = 0.13$; $p = 0.005$) and DEA ($\rho = - 0.096$; $p = 0.04$). The positive relation with water-table depth for atrazine (greater over-prediction with increasing water-table depth) and the negative relation for DEA were consistent with previous research suggesting that the extent of atrazine conversion to DEA—an aerobic process—increases with increasing vadose-zone thickness. The over-prediction of concentrations also increased significantly with the percentage of nearby area in corn cultivation—relative to soybeans—for atrazine, which was presumed to be applied annually to corn, but is not applied to soybeans ($\rho = 0.30$; $p \leq 0.0001$). The opposite pattern was observed for DEA ($\rho = - 0.29$; $p \leq 0.0001$). This suggests that in areas where atrazine is applied in multiple years, microbial adaptation—a process by which an applied compound undergoes faster biotransformation with repeated applications—may exert more control over atrazine flux to groundwater than the total amount applied.

Identifying Sources of Nitrate in Domestic Wells in the Yakima River Basin

Matt Bachmann, U.S. Geological Survey Washington Water Science Center

Twenty percent of the domestic water wells in the lower Yakima River basin sampled by the U.S. Environmental Protection Agency in 2010 had nitrate levels that exceeded the drinking water standard of 10 milligrams per liter. The Yakima River basin groundwater-flow model, which was recently completed by the U.S. Geological Survey, was used to identify the recharge areas supplying these wells as part of a coordinated effort to identify the sources of nitrate pollution in the basin.

Significant potential sources of nitrogen in groundwater in the Yakima River basin include concentrated animal feeding operations (CAFOs) and irrigated agriculture; both activities have at times utilized sub-optimal nutrient management practices. The CAFOs generate large volumes of animal manure which are typically stored in pits and lagoons that sometimes overflow during high rainfall events; agricultural fertilizer usage in the basin has steadily increased over time and fertilizer may have been applied in excess of crop requirements. The combination of localized (CAFOs) and non-point (irrigated agriculture) sources of nitrate to the lower basin's shallow aquifer system complicates the task of distinguishing between sources of contamination.

The U.S. Geological Survey model of the Yakima River basin simulates three-dimensional groundwater flows during a 42-year period and explicitly represents historical crop-specific irrigation and groundwater-well extraction rates. The simulated flow field that results from these human perturbations to the natural hydrologic system can be used to identify the flow history and geographic origin of water at any point within the model domain. The model was used to track water backwards in time from the areas of identified high-nitrate domestic wells to recharge sources at land surface.

Three Case Studies: Using Site Specific Characteristics to Determine if Alternative Treatment Technologies are Protective of Groundwater Quality

Melanie Redding, Washington State Department of Ecology

Minimum treatment standards are established for facilities discharging to the environment, with the goal to protect groundwater quality from contamination. These treatment standards are not prescriptive, and alternative treatment technologies are allowed, as long as it can be demonstrated that compliance with the groundwater quality standards will be maintained. Three facilities using alternative treatment technologies are evaluated on a case-by-case basis. All three facilities have been historically land applying their wastewater year-round using crop uptake and soils as treatment. Winter storage is not used, and groundwater contamination is documented or suspected at all three sites.

Washington State requires that all wastewater be treated with AKART (all known, available, and reasonable methods of prevention, control, and treatment) prior to being discharged to the environment. AKART for industrial land treatment systems in Washington typically includes winter storage and the agronomic application of wastewater during the growing season. Previously Ecology has also considered other options for managing excess wastewater including discharge to a surface water body, and discharge to a publically owned treatment works (POTW). This is the industry standard unless a facility can present site-specific conditions and a wastewater management strategy that demonstrates an alternate treatment system will be equally protective of the environment.

The objective of these assessments is to provide an independent evaluation of all relevant reports, site-specific data, and literature in order to provide a technically defensible AKART determination regarding winter storage of wastewater. These reviews also consider compliance with Washington State Groundwater Quality Standards and the antidegradation policy.

These assessments analyzed compliance data for statistical trends, compliance with the groundwater quality standards, other potential sources of groundwater contamination, historical practices, hydrogeological influences, contaminant transport, the ability of the soils to adequately store contaminants, the ability of existing wells to contain existing contamination as well as other compelling information.

Washington Nitrate Prioritization Project

Laurie Morgan, Washington State Dept. of Ecology Water Quality Program

Nitrates in groundwater have arisen as an important concern in several areas of the state, including the Sumas-Blaine aquifer in Whatcom County, the Lower Yakima Basin in Yakima County, and the Columbia Basin Ground Water Management Area, which includes Adams, Franklin, Grant and Lincoln counties.

As a result, many studies involving sampling of nitrates in groundwater have been done by the U.S. Geological Survey, the Dept. of Ecology, and local government, as well as academia and at least one study by a non-profit.

Public drinking water supplies must also be sampled regularly. The Washington State Dept. of Health Drinking Water Program oversees sampling from public water supply systems, and the sampling data is housed in their database.

Nitrate sampling results from agency databases (U.S. Geological Survey, Washington Dept. of Health and Washington Dept. of Ecology) have been plotted using GIS to show where in the state nitrates have been elevated.

Several efforts at analyzing where nitrates tend to occur and under what conditions have been undertaken by the U.S. Geological Survey and others. Two of the U.S. Geological Survey studies that cover the entire state are particularly helpful for the Washington Nitrate Prioritization Project:

> *Estimating the probability of elevated nitrate concentrations in ground water in Washington State: U.S. Geological Survey Scientific Investigations Report, Lonna Frans, 2008.*

Vulnerability of Shallow Groundwater and Drinking-Water Wells to Nitrate in the United States, Bernard Nolan and others, 2006.

These maps are being compared to kriging of the compiled nitrate data – all three maps show a similar distribution of vulnerability to nitrates in groundwater at the statewide scale.

After high nitrate areas are delineated on a statewide map, a prioritization scheme can be applied to rank the areas. Idaho has developed a prioritization process that includes populations at risk and the severity of nitrate contamination. Washington is exploring potential analysis and ranking criteria, such as: Population and public health, water quality data and trends, nitrogen sources, threats to public water supply systems and domestic wells, sole source aquifers, and nutrient impacts on surface water.

Once these Nitrate Prioritization Areas have been inventoried and ranked, a strategy for tracking changes in nutrient loading and conditions in groundwater could be developed and implemented. Washington is also exploring the possibility of an online map so that everyone could see groundwater related information, starting with nitrate priority areas and helpful information such as general groundwater flow directions and aquifer facts as resources allow.

An Innovative Bioremediation Strategy for Treating Chlorinated VOCs in Low-Permeability Saturated Soils Using Specialized Jetting Techniques

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Susumu Uesawa, Chemical Grouting Co., Ltd.

Mei-Chin Yeh, EOS Remediation LLC

Background/Objectives. In an international collaboration, EOS Remediation, LLC (EOS Remediation) and Chemical Grout Co. Ltd (CGC) are working together to bring bioremediation in low permeability saturated soils to the next level. The team combined a CGC-developed specialized construction technique with a specially formulated, all natural, sustainable substrate to promote in situ bioremediation in low permeability soils impacted by chlorinated volatile organic compounds (cVOCs). The goal was to create a more effective remediation approach that would improve the remedial timeframe in a cost-effective manner when compared with other technologies.

Approach/Activities. A former dry cleaning site located in Tokyo, Japan was selected for this demonstration. The contaminants of concern include perchloroethylene (PCE) and trichloroethylene (TCE), as well as the associated degradation daughter products. The objectives of the field demonstration were to: 1) to increase immediate contact between contaminants, EOS® substrate, and microbes to accelerate biodegradation in low permeability soil matrices, and 2) to decrease the distance that hydrogen gas generated by fermentation must diffuse through the saturated soil to stimulate reductive dechlorination, thereby decreasing the remedial time frame and cleanup costs.

CGC's injection technique uses a specialized jetting process to introduce the substrate into soils within the saturated treatment zone. The jetting process increases soil permeability resulting in improved transport of electron donor, and potentially hydrogen, to a larger treatment zone. The EOS® substrate employed was formulated specifically for this demonstration and was optimized to perform well under high pressures associated with the jetting technique. In October 2011, three highly contaminated test locations at a Tokyo dry cleaning facility were chosen for injection. The Japan EPA cleanup goals are targeted toward soil leachate concentrations from saturated soils beneath the groundwater table and groundwater concentrations. Starting soil leachate concentrations of PCE and TCE ranged from 24 mg/L and 2.7 mg/L, respectively. The EOS® test formulation was injected in two of the three test locations using CGC's jetting technique, and injected into the third cell using a pneumatic fracturing technique. Trends in groundwater and soil leachate contaminant concentrations have been monitored for over a year.

Results/Lessons Learned. The results gathered from this collaboration demonstrate that CGC's jetting technique effectively delivered an optimized emulsified oil substrate into low permeability zones resulting in enhanced reductive dechlorination of target cVOCs. cVOC concentrations were reduced as much as 90% and 80% in some groundwater and soil leachate samples, respectively. Chlorine number calculations on the molar concentrations of cVOCs in groundwater declined from 3.5 (mostly TCE) to 0.7 (mostly ethene), which supported biodegradation as the mechanism for removal. However, bioremediation of soil leachate is a relatively slow process and additional time will be required to meet several of the soil cleanup criteria. This presentation will describe additional background information and results of this collaborative solution to this common, worldwide problem.

The Role of Contaminants of Emerging Concern in Aquifer Recharge Projects Using Reclaimed Water

John Koreny, HDR Engineering, Inc.

Ben McConkey, Lott Clean Water Alliance

Reclaimed water aquifer recharge is being used to expand water supply for municipalities across the U.S. and here in the Pacific Northwest. Contaminants of emerging concern (CECs) have typically been an issue for municipal water supply projects using rivers with significant wastewater discharges for source water. However, CECs are now being scrutinized at reclaimed water aquifer recharge projects. CECs present several new issues for ground water recharge projects including low detection limits, increased analytical costs and the difficulty of determining the influence of background contamination. This presentation will summarize the processes that are being used to evaluate CECs at six of the largest reclaimed water aquifer recharge projects in Washington, California, Florida and Arizona. We will examine the monitoring and field investigation programs typically used to evaluate the presence and fate and transport of CECs from the beginning of a project and through pilot studies and project operation.

Regional Evaluation of Shallow Artificial Aquifer Recharge in the Walla Walla Basin

Aristides Petrides, GSI Water Solutions

This research project presents the development and application of surface and groundwater models to evaluate water resource allocation scenarios and the feasibility of infiltration basins for managed artificial recharge (MAR) projects. A regional model of the gravel aquifer was developed with a multi-layer finite-element model using the Integrated Water Flow Model (IWFM) software (developed by the California Department of Water Resources). At the site-scale, the analysis used field data from three field pilot tests to develop vadose zone infiltration models (using the HYDRUS-3D software) that evaluated the efficiency of infiltration from different surface areas and geometric configurations of infiltration basins and gallery ponds. Final recommendations were made to support a regional aquifer replenishment program and, at site specific, recharge rates evaluated from pilot projects of surface managed artificial aquifer recharge were scale to develop design criteria for full scale projects.

Denitrification in a Deep Basalt Aquifer: Implications for Aquifer Storage and Recovery

Dennis Nelson, GSI Water Solutions, Inc.

Jason Melady, GSI Water Solutions, Inc.

Aquifer storage and recovery (ASR) can provide a means of storing water for irrigation in agricultural areas where water availability is limited. The Umatilla Basin in north central Oregon receives <20 inches of annual precipitation and is underlain by the Columbia River Basalt Group (CRBG), transmissive confined aquifer(s) with low recharge rates. Overdrafting CRBG aquifers to irrigate agricultural land has depleted the CRBG and groundwater use has been restricted. ASR can provide irrigation water and supply recharge to the depleted aquifer.

Two agricultural operations in the Basin began using ASR in 2006 to provide water for irrigation. Source water for ASR storage is pumped from a shallow alluvial aquifer, which has variable nitrate concentrations ranging between <3 mg/L to >9 mg/L. Oregon ASR rules stipulate that nitrate in injected water be limited to a maximum of 7 mg/L. Nitrate in the recovered water, however, decreases quickly to < 3 mg/L, suggesting that nitrate may not persist within the CRBG during ASR storage. In contrast to nitrate, other constituents in the recovered water show little variation, inconsistent with migration or mixing as an explanation of the nitrate decrease. Nitrogen isotopic ratios (15N) increase markedly, ranging from +3.5 to > +50, and correlate inversely with nitrate concentrations. This variation occurs within < 3 weeks and recovery of < 10% of the originally injected volume. These observations suggest that rapid denitrification occurs, indicating that nitrate, and therefore ASR, pose little long-term risk to water quality in the CRBG aquifer.

Uncertainty Assessment at BC Cribs at Hanford Using the ASCEM Toolset

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Uncertainty assessments in subsurface applications typically neglect uncertainty in the conceptual model, and attribute uncertainty to errors in parameters and inputs. At the BC Cribs site at Hanford in southeastern Washington State, conceptualization of the system is highly uncertain because only sparse information is available for the geologic conceptual model and the physical and chemical properties of the sediments. In this contribution, uncertainty in the conceptual model is explored using the ASCEM (Advanced Simulation Capability for Environmental Management) toolset. The ASCEM toolset includes a high performance flow and reactive transport simulator (Amanzi), as well as a user environment called Akuna. Akuna provides a range of tools to manage environmental and simulator data sets, perform model setup, manage simulation data, and visualize results. Core toolsets beneath the user interface provide algorithms for performing sensitivity analyses, parameter estimation, and uncertainty quantification. In this contribution, the uncertainty in technetium-99 transport through a three-dimensional, heterogeneous vadose-zone system is quantified with Monte Carlo simulation. Results show that significant prediction uncertainty in simulated concentrations can be introduced by conceptual model variation. It is also shown that the ASCEM toolset represents an integrated modeling environment that facilitates model setup, parameter optimization, and uncertainty analyses through high-performance computing.

Nature and Extent of Vadose Contamination at the Hanford Federal Facility, WA

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John Price, Washington State Dept. Ecology

The U.S. Department of Energy (DOE) Hanford Site in south central Washington State lies along the Columbia River and is one of DOE's largest legacy waste management sites. Enormous radionuclide and chemical inventories exist below-ground. These include Resource Conservation and Recovery Act (RCRA) storage facilities where hazardous and radioactive contaminants were discharged and leaked to the soil surface and to the deep vadose zone and groundwater. The vadose zone is also contaminated from facilities regulated by the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) Act. By one estimate, Hanford now contains as much as 28,300 cubic meters of soil contaminated with radionuclides from liquid wastes released near processing facilities. The Hanford Federal Facility Agreement and Consent Order, Tri-Party Agreement (TPA) has set the completion of the cleanup of these sites by 2024.

There are four major categories of vadose contamination areas at the Hanford Site. The first is laterally extensive with intermediate depth (ground surface to about 45 meters depth) mostly related to high volume effluent discharge into cribs, ponds and ditches of designated CERCLA facilities. The second is laterally less extensive mostly related to leaks from RCRA tank farms. The later contamination is often commingled at depth with wastes from adjacent CERCLA facilities. The third category is from the high volume CERCLA facilities, and typically extends from the surface to more than 60 meters below ground. Contamination from the later category crosses the entire thickness of the vadose zone and reached groundwater. The fourth category is the lower volume waste sites and generally not reaching groundwater. Current TPA has set various options to clean up these sites.

Geochemical and Isotopic Evaluation of a Potential Subsurface Combustion Event

Jessica Goin, Anchor QEA

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Soil vapor extraction (SVE) provides groundwater protectiveness for the aquifer below a combined (industrial/municipal) waste landfill in Eastern Washington. SVE prevents downward migration of volatile organic compounds (VOCs) present in the vadose zone. The SVE system was recently modified to increase the VOC removal capacity for long-term groundwater protectiveness and site improvement. During testing of the modified SVE system, increased temperatures and carbon monoxide concentrations were observed in vapor extraction wells. These changes raised concerns from the Washington Department of Ecology of a potential subsurface fire at the landfill; however, neither parameter reached levels generally considered to be definitive of subsurface combustion. In response to these concerns, a program was implemented to assess physical and geochemical indicators of subsurface combustion at the site.

The physical investigation included observation of potential cap settlement areas, a survey of subsurface temperatures, an aerial thermal infrared survey, and examination of well-heads for evidence of smoke or soot. No rapid or dramatic settling was observed. Subsurface well-casing temperatures were below the 170 degrees Fahrenheit FEMA threshold indicating subsurface combustion. The only hot spots identified in the aerial survey were associated with construction waste some distance from the industrial waste area, and no areas of dramatic settlement were identified in the aerial survey. No smoke or soot was observed in the well-heads.

The geochemical investigation included analysis of the landfill gas and VOCs from a biogeochemical perspective, analysis of trace gases indicative of combustion and stable isotope analysis of specific landfill gas components. Trace gas combustion indicators (nitric oxide, ammonia and hydrogen cyanide) were not detected. Additionally, the relationship between nitrogen dioxide and nitrous oxide concentrations was more consistent with bacterial activity than combustion. The relationships among oxygen, carbon dioxide, carbon monoxide, methane, and the major VOCs were also consistent with bacterial degradation. Compound-specific stable isotope analyses were performed on carbon dioxide (13C/12C and 18O/16O), carbon monoxide (13C/12C and 18O/16O), and methane (13C/12C and D/H). Two isotopically distinct sources of bacterial methane were identified: methanogenesis associated with decomposition of municipal wastes and VOC degradation in the industrial waste area. Carbon dioxide isotope signatures are not consistent with combustion sources. The isotope signatures of carbon monoxide indicate that it is mainly derived from bacterial degradation of VOCs, with increasing concentrations explained by additional production during methanotrophy (bacterial methane oxidation).

Vadose Zone Remediation by Sustainable Soil Vapor Extraction

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A growing trend in environmental remediation is the use of natural processes. These approaches are reducing the costs of cleanup and intruding less on the environment. The MicroBlower™ technology developed by the U.S. Department of Energy's Savannah River National Laboratory is an example of such an approach.

Targeting the "vadose zone" during remediation traditionally has been considered difficult. MicroBlower™ is a cost-effective device specifically designed for remediation of organic compounds in the vadose zone. The system is applicable for remediating sites with low levels of contamination and for transitioning sites from active source technologies such as active soil vapor extraction to natural attenuation. It can also be a better choice for remediating small source zones that are often found in "tight zones" that are controlled by diffusion rate. The MicroBlower™ was developed to address residual volatile organic compound (VOC) contamination after shutdown of active soil vapor extraction systems. In addition, the system has been deployed to control recalcitrant sources that are controlled by diffusion rates.

MicroBlower™ uses a small, low power vacuum blower to extract or inject gases into the subsurface for remediation. Because the components of the system have a long operating life, the system is useful for long-term cleanup operations, particularly where mass transfer limits the rate of remediation. MicroBlower™ is effective in targeting small source zones where conventional SVE is too excessive.

While similar in design to an active soil vapor extraction (ASVE) blower, the MicroBlower™ is a low-cost alternative designed to run on renewable sources of energy to treat volatile organic compound (VOC) contamination in the unsaturated zone. The system uses a small, low power vacuum blower to extract or inject gases into the subsurface for characterization or remediation. MicroBlowers require only between 20 and 40 watts and can be powered using photovoltaic panels, wind generators, 24-volt battery bank recharged by either photovoltaic panels or wind generators or 24-volt power from a 110 to 24 volt transformer. MicroBlower™ offers the advantage of a reduced carbon footprint and very low operating expenses.

MicroBlowers are ideal for remote locations with limited or no ancillary infrastructure. By using renewable sources of energy, the MicroBlower™ eliminates the need for generators and fuel storage at remote locations. MicroBlowers offer the advantage of a reduced carbon footprint and very low operating and maintenance expenses.

This technology has the potential to offer significant cost savings to the groundwater remediation industry. Presently, there are limited regulations concerning the contaminants in the vadose zone. However, if the vadose zone is not remediated, contamination will migrate downward and re-contaminate the groundwater. With the groundwater no longer in compliance, the responsible parties must bear the cost of remediating the groundwater again. By installing the MicroBlower, the risk of the groundwater being re-contaminated from the vadoze zone would be alleviated. Removing contaminates from the vadoze zone before they impact the groundwater is often cheaper, easier and protective of the groundwater. This paper will also present results of several case studies.

Stable Isotope Analysis of Surface Water and Precipitation in the Palouse Basin: Hydrologic Tracers of Aquifer Recharge

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Groundwater levels have been declining in the Grande Ronde basalt aquifer of the Palouse Basin in southeast Washington and north central Idaho at an average rate of about 0.4 m (1.3 ft) per year for more than 80 years. Repeated studies have demonstrated the apparent age of this water to be >10,000 years, suggesting primary recharge during the Pleistocene, and implying modern recharge is extremely limited. The majority of the approximately 60,000 people across the Palouse Basin depend almost entirely on this deep aquifer for drinking water, and although much has been learned from nearly continual study of this complex groundwater basin over the past 50 years, no sources of recharge have been definitively identified. Recent work by the Washington Department of Ecology has identified one of the most promising leads yet, demonstrating that a section of losing stream on the South Fork of the Palouse River (SFPR) exists between the communities of Pullman and Albion, Washington. Utilizing previously established isotope characteristics of the Palouse Basin, stable isotopes of oxygen and hydrogen were used as hydrologic tracers to investigate water movement in this stretch of the SFPR. Stable isotope data and more traditionally collected hydrologic information, including water levels and tritium (^{3}H), are all consistent with the premise that this reach of the SFPR is a losing stream. When combined with X-ray fluorescence spectroscopy (XRF) data from previously unsampled basalt outcrops along the reach, a more important conclusion is reached that this stream loss is actually contributing recharge to the Grande Ronde aquifer system. Stable isotope data for groundwater have also yielded unexpected clues to the structural geology along the study reach, suggesting the orientation of subsurface folding or faulting, inferred from what appears to be directional recharge. Analyses of precipitation and surface water samples from multiple watersheds have provided additional contributions to stable isotope hydrology across the region. Isotope characteristics have proven to be a valuable tool in identifying climatic and anthropogenic input to the hydrologic system, clearly identifying input to the SFPR from waste water treatment plants, and the effect of elevation on isotope concentrations in precipitation upstream from a surface water sampling location. Both of these inputs add benchmarks helpful in narrowing potential recharge source zones from portions of losing streams, further illustrating the increasing usefulness of stable isotopes to forensic and remedial groundwater investigations. Stable isotope analysis has yielded high quality data at a fraction of the cost of alternatives such as ^{3}H, ^{14}C, or more involved physical hydrogeological study methods requiring drilling or aquifer testing. Stable isotopes have proven to fill a valuable data gap in recharge investigations where traditional hydrodynamic methods may not be feasible.

Multitracer Models of Groundwater Age, Mixing, and Renewal in the Columbia Basin GWMA

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Minna Carey, Anchor QEA

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Hydrological tracer data for over 400 irrigation, municipal, and domestic supply wells sampled between 2008 and 2010 were analyzed to determine relationships between groundwater age, recharge sources, and mixing of young and older waters within the basalt aquifer system of the Columbia Basin Groundwater Management Area (GWMA). Produced groundwater can generally be classified into one of three categories: (1) young water (recharged within the last 60 years), (2) paleowater (old groundwater, typically more than 10,000 years old), and (3) mixed-age waters containing both young and old components. Of 271 wells sampled for carbon-14, 38% of Grande Ronde Formation wells produce paleowaters (characterized by the absence of tritium) with radiocarbon ages ranging from 11,700 to 34,800 years old. In contrast, only 13% of wells open to the shallower Wanapum Formation and 20% of wells open to both the Wanapum and Grande Ronde produce paleowaters with ages ranging from 4,300 to 36,500 years. The vast majority (95%) of the paleowaters sampled are greater than 10,000 years old, representing recharge during the Holocene, under wetter climate conditions than the present.

Mixing proportions and age distributions of the young water fraction in mixed-age waters were estimated for 74 wells from chlorofluorocarbon (CFC-11, CFC-12, and CFC-113) concentrations. Binary CFC mixing models indicate a skewed distribution in the proportion of young water, with less than 5% young water in 28% of the wells sampled, and less than 30% in 57% of the wells. The estimated age of the young fraction ranges from 6 to 60 years with a median age (50th percentile) of 25 years and inter-quartile range (25th to 75th percentiles) of 21 to 28 years. In basalt wells containing a young water fraction less than 15 years old, the young water generally makes up less than 5% of the water produced. Exponential mixing models were used to calculate the groundwater age distribution in terms of the mean residence time (MRT). MRT calculated from CFC-12 concentrations show a bimodal distribution, with 32% of sampled wells having MRT less than 50 years and 22% with MRT of 1,000 years or more. Wells with groundwater MRT less than 50 years are generally restricted to locations within the study area where a shallow sediment aquifer overlies the basalt aquifers, and include wells drilled into sediments, as well as deeper basalt wells that are also open to the sedimentary aquifer due to well construction. CFC data from basalt wells not open to sedimentary aquifers generally indicate groundwater MRT greater than 100 years. The spatial distribution of wells producing at least some component of young water is not uniform across the GWMA, and appears to be related to existence and proximity to geological features that can provide windows and pathways for present-day surface water recharge to enter the basalt aquifer.

Enhanced Transport of Sr by Mobile Secondary Precipitates

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Colloid-facilitated radionuclide transport in geological media is a major concern at nuclear facilities. At Hanford site, a number of studies have shown that colloid particles can potentially facilitate the subsurface transport and mobilization of radionuclides at contaminated sites. In the subsurface environment, the transport of colloids in aqueous suspension is generally believed to be mainly influenced by media water content, fluid flow rate and flow pattern, ionic strength, and pH of the pore water. The effect of solution ionic strength (IS) and pH on colloid deposition and release in porous media has been widely studied due to their important roles on colloid mobilization. Although a number of studies have discussed colloid-facilitated transport of radionuclides at Hanford site, few studies have focused on the effect of colloid-sized neo-formed secondary precipitates containing Sr, especially predicting colloid-facilitated Sr transport under potentially changed geochemical background conditions. Knowledge of secondary precipitates-sediment interactions and our ability to predict the facilitated mobilization of Sr in the natural environments are still quite limited. We tested here whether neo-formed secondary precipitates containing contaminants behave like mobile colloids, and thus influence long-term contaminant transport.

Results of column experiments suggest that neo-formed secondary precipitates (sodalite and cancrinite) at the Hanford Site could behave like normal native colloids that can facilitate radionuclide transport. Initially immobilized radionuclide within secondary precipitates could remobilize given a change of background geochemical conditions. From this study, the remobilization of neo-formed colloid-sized nitrate cancrinite precipitates was found to be closely dependent on geochemical conditions, primarily ionic strength and pH of the background solution, as well as the flow rate. The mobility of the neo-formed precipitates increased with increased solution flow rate caused by the increased hydrodynamic shear force applied on the colloids or reacted sediments where secondary precipitates were formed. The mobility of the neo-formed precipitates also increased as solution ionic strength decreased and solution pH increased because of the increase of the repulsive force between secondary precipitates-sediment interfaces. Towards final closure of the Hanford Site, especially for conditions where sediment pore water is fed by rainwater recharge after removal of the tank waste sources, pore water contents and flow rates could be locally and temporally increased by snowmelt events or natural (or artificial) infiltration. All of these changes could increase the subsurface flow rate, dilute ionic strength of the background solution and neutralize the solution pH; these factors could affect the mobility of Sr-containing secondary precipitates, which can be a potential source for radionuclide transport in Hanford Site subsurface environments.

A New Approach to Evaluating Porewater Methane in Coarse Sediments and Armored Substratum

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Methane (CH_4) flux from freshwater lakes has been long acknowledged and studied as an important component of carbon cycling in these systems. CH_4 is commonly measured in the water column via capture of bubbles as they ascend toward the water surface. During this process, CH_4 levels vary with oxygen (O_2) content of surface waters, as oxidation transforms CH_4 to CO_2 and $^2H_2$. Previously, information gathered about CH_4 emissions within lakebed sediments (the hyporheic zone), where methanogenesis occurs, has been limited to habitats characterized by very fine-grained sediments. During March and September 2012, the hyporheic zone within several littoral embayments of Snake and Columbia River hydropower reservoirs was surveyed for evasion of CH_4 and other important greenhouse gases. Discussed here is a novel technique to directly measure the products of methanogensis within the hyporheic zone. Minipiezometers were installed in the hyporheic zone from a boat in variable water depths of up to 4.5 m. Piezometer screens were installed to a depth of approximately 10 cm within hyporheic substrates, which generally consisted of coarse gravel, as well as finer sand and silt substrates. Hyporheic water was captured, pumped to the surface, equilibrated, and measured for CH_4 and other dissolved gases via gas chromatography. Preliminary results range from 0.36 mM to 4.86 mM CH_4 within these sediment porewaters. Results were compared to dissolved and bubble concentrations of CH_4 measured concurrently throughout the water column to better understand the ebullition dynamics of CH_4. The minipiezometer method is particularly useful in areas where coarse sediments or armored substratum precludes the use of other sampling techniques.

Groundwater-Surface Water Interaction in East Creek Basin and Implications for Projects with Substantial Permanent Groundwater Discharge

Erik Blumhagen, Shannon & Wilson

Li Ma, Shannon & Wilson

This presentation discusses our basin-level hydrologic impact study for the proposed new Factoria Recycling and Transfer Station (FRTS) in Bellevue, Washington. This includes the development of a conceptual basin water budget model and hydrologic impact evaluation for the FRTS project. This presentation addresses permanent drainage/dewatering for the site in the context of groundwater-surface water interaction.

HDR is preparing a drainage report for the City of Bellevue (City) for the FRTS project. Our study is intended to support HDR in performing a downstream analysis to quantify potential changes to the 100-year peak flow rate of storm and surface water leaving the FRTS site.

The City's existing code requires a comparison of the pre- and post-construction flow rates to determine the necessity for flow control facilities. Increases in the 100 year peak flow rate of less than 0.1 cubic foot per second (cfs) do not require flow control facilities.

Results from our 2011 draft hydrogeologic and dewatering study indicated potentially high discharge rates from the proposed new FRTS permanent drainage systems (up to 4.5 cfs). Therefore, given the reported historical flooding issues in the basin and the potential magnitude of additional discharge, a more rigorous evaluation of the basin water budget model was warranted.

Results from the calibrated base model indicate a simulated pre-construction flow in East Creek at the bottom of East Creek basin of 6.58 cfs. This flow is near the middle of the range of 1.2 to 11.4 cfs from previously measured flow at the East Creek stream gauging station, and simulated flow in East Creek at the bottom of East Creek basin.

For the post-construction condition, results from the base model indicate a flow of about 2.63 cfs from the FRTS permanent drainage system. The model indicates a flow in East Creek of about 4.58 cfs, 2.00 cfs less than the pre-construction creek flow; however, when the FRTS permanent drainage system discharge is routed to East Creek, the result is a net increase of about 0.63 cfs in East Creek flow for the post-construction condition.

Groundwater-Surface Water Interactions and Sulfide Toxicity in Nearshore Marine Sediments A Reactive Transport Modeling Approach

Minna Carey, Anchor QEA

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Elevated surface sediment porewater sulfide concentrations have previously been measured at various wood waste sites in Puget Sound, but have generally been limited to relatively shallow subtidal surface sediments immediately overlying significant wood waste deposits. Elevated porewater sulfide concentrations in these shallow subtidal areas, which may be toxic to sensitive aquatic plants and animals, are the result of bacterial sulfate reduction coupled with the biodegradation of wood waste.

Sediment capping presents one option for mitigating sulfide toxicity by physical isolation of the reductant (i.e., wood waste) from the electron acceptors (i.e., seawater sulfate). A major factor influencing sediment sulfide levels and toxicity is the complex interaction between groundwater and surface water. A sediment early diagenesis model (SEDM) incorporating biogeochemical oxidation-reduction (redox) dynamics and submarine groundwater discharge was developed and applied to evaluate the effectiveness of capping on sediment sulfide toxicity in nearshore marine sediments. The modeling was applied to a former sawmill site in Puget Sound.

Potential complex groundwater–surface water interactions include: areas of high groundwater advection discharging into nearshore marine sediments; areas of low groundwater advection where solute transport is dominated by diffusion, allowing downward migration of solutes in surface water into the sediments; brackish porewater recirculation cells in which saline porewater mixes with submarine fresh water; as well as the influence of tidal fluctuations on groundwater–surface water interactions. The conceptual model for the SEDM involved placement of quartz or iron-rich sand caps directly above wood waste impacted sediment, with submarine groundwater discharging through the wood waste and ultimately the sand cap; a diffusion-only scenario was also modeled. As an initial condition, the cap and wood waste were entrained with seawater, with constant concentration boundary conditions applied at the top of the cap (seawater) and bottom of the wood waste deposit (local groundwater). The SEDM was implemented using the one-dimensional geochemical reactive transport software PHREEQC and included equilibrium aqueous speciation reactions as well as kinetically controlled redox reactions. The modeled redox reactions, involving the oxidation of organic matter, occur in a step-wise manner, with oxygen as the preferred terminal electron acceptor, followed by nitrate, ferric iron, sulfate, and carbonate (i.e., methanogenesis).

Model results indicate that in areas with high upward groundwater advection, sulfate penetration into the sediment is limited and natural or emplaced caps can be effective at preventing sulfate reduction and mitigating sulfide toxicity. While areas with relatively low groundwater advection allow sulfate to penetrate into the sediments, the presence of iron in the capping material (e.g., iron carbonate [siderite]), where geochemical conditions favor siderite dissolution, induces precipitation of iron sulfides such as mackinawite (FeS) or pyrite (FeS_2), limiting porewater sulfide levels and toxicity. The presence of relatively low porewater sulfide concentrations (below the 0.05 mg/L detection limit) in deeper subtidal wood waste deposits in Puget Sound is consistent with this geochemical model.

Future efforts being considered include expansion of the model to two dimensions to evaluate remedial design implications of spatial variations in groundwater discharge.

Paleo-Glacial Lake Columbia: A Potential Source for Regional Ground-Water Recharge for Deep Columbia River Basalt Aquifers Within the Columbia Basin

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Several previous investigations have utilized stable-isotopes ($\delta^{18}O$, δD) and ^{14}C groundwater analyses to suggest that recharge to deep Columbia River basalt (CRB) aquifers may be primarily related to episodic Pleistocene hydrologic events (e.g., cataclysmic flooding from paleo-glacial Lake Missoula [GLM]) and not to more recent, areally-pervasive, precipitation-driven recharge derived under current climatic conditions (Larson et al. 2000, Douglas et al. 2007, Brown et al. 2010). Of particular note, Brown et al. (2010) cite the presence of depleted stable-isotope content of deep CRB groundwaters within the north-central Columbia Basin and relate this to temporal recharge events occurring during repeated GLM outburst floods. Basalt aquifer recharge is proposed to have occurred within the Channeled Scabland region where Pleistocene flood waters could have directly recharged exposed, pervious CRB interflow zones. It should be noted, however, that the duration of each GLM flood was brief (few days or less) and therefore may not represent the primary source of Pleistocene recharge to deep CRB aquifers.

It is proposed that a more available, long-term source for groundwater recharge to the CRB was glacial Lake Columbia (GLC). GLC formed when the Okanogan Lobe of the Cordilleran Ice Sheet blocked the Columbia River valley near present-day Grand Coulee Dam and existed for several thousand years, both between and after dozens of GLM floods during the last glacial (late-Wisconsin) cycle. GLC was situated along the northern border of CRB aquifer systems and located near the regional topographic high that facilitated the predominant, areal, north-to-south, gravity-driven groundwater flow within the CRB that currently exists within the Columbia Basin. Initially, maximum lake levels within GLC reached elevations of ~730 m MSL behind the Okanogan Lobe. Later, as GLM floods eroded drainage divides into the Channeled Scabland, lake levels ultimately lowered to 700 m MSL. These former lake levels of GLC were above present-day potentiometric conditions for basalt aquifers suggesting that a favorable, long-term hydraulic gradient condition existed for deep CRB recharge to occur. This is particularly true along the Hawk Creek tributary reach. The potential for similar types of recharge also likely occurred during previous Pleistocene glacial cycles.

Former annual recharge rates are estimated using a basic channel, constant-head equation, assumed hydraulic properties and head difference conditions between GLC and the CRB. These rates significantly exceed the current regional, annual recharge estimated from pervasive precipitation or that resulting from short-term Pleistocene-age GLM outburst floods within the Channeled Scabland.

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Evaluating Greenhouse Gas Emissions from Hydropower Complexes on Large Rivers in Eastern Washington

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Inland water bodies, such as freshwater lakes, are known to be net emitters of carbon dioxide (CO_2) and methane (CH_4). In recent years, significant greenhouse gas (GHG) emissions from tropical, boreal, and mid-latitude reservoirs have also been reported. At a time when hydropower is increasing worldwide, better understanding of seasonal and regional variation in GHG emissions is needed in order to develop a predictive understanding of such fluxes within man-made impoundments. We examined reservoir impoundments created by power-producing dam complexes within xeric eastern Washington locations. Sampling environments on the Snake (Lower Monumental Dam Complex) and Columbia Rivers (Priest Rapids Dam Complex) included tributary, mainstem, embayment, forebay, and tailrace areas during winter and summer 2012. At each sampling location, GHG measurements included multiple exchange pathways: surface gas flux, degassing as water passed through dams during power generation, and ebullition within littoral embayments. Measurements were also carried out in a free-flowing reach of the Columbia River (the Hanford Reach) to estimate unaltered conditions. Surface flux resulted in very low emissions, with reservoirs acting as a sink for CO_2 (up to –262 mg m-2 d-1, which is within the range previously reported for similarly located reservoirs). Surface flux of CH_4 remained below 1 mg CH_4 m-2d-1, a value well below fluxes reported previously for temperate reservoirs. Water passing through hydroelectric projects acted as a sink for CO_2 during winter and a small source during summer, with mean degassing fluxes of –117 and 4.5 t CO_2 d-1, respectively. Degassing of CH_4 was minimal, with mean fluxes of 3.1 × 10-6 and –5.6 × 10-4 t CH_4 d-1 during winter and summer, respectively. Gas efflux due to ebullition was greater in coves located within reservoirs than in coves within the free flowing Hanford Reach, and CH_4 efflux exceeded that of CO_2. CH_4 ebullition varied widely across sampling locations, ranging from 10.5 to 1039 mg CH_4 m-2 d-1, with mean fluxes of 324 mg CH_4 m-2 d-1in Lower Monumental Dam reservoir and 482 mg CH_4 m-2d-1 in the Priest Rapids Dam reservoir. The magnitude of CH_4 efflux due to ebullition was relatively high, falling within the range recently reported for other temperate reservoirs in Europe and Asia. The new findings further suggest that there is a need to understand global CH_4 emissions from littoral embayments of temperate hydroelectric reservoirs when estimating the impact of CH_4 emissions on climate change.

Modeling of Hydrologic Processes and Assessment of Climate Variability Impacts on Streamflow in the Upper Cedar River Watershed

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The assessment of water yield from watersheds into the streams is critical to sound management of aquatic life and meeting water supply demands. The Upper Cedar River watershed is the main source of drinking water supply for the city of Seattle, Washington. Groundwater baseflow plays a key role in regulating streamflow and maintaining aquatic and wildlife habitat. Numerous studies have been conducted to relate groundwater recharge and discharge from aquifers. Quantification of groundwater recharge and baseflow from lands with different topography, soil characteristics, geology, vegetation, and climate is beneficial in the monitoring and management of water resources.

The Water Erosion Prediction Project (WEPP) model is a physically-based continuous simulation model. Recent improvements to WEPP include enhanced computation of deep percolation, subsurface lateral flow, frost simulation, and channel routing. These additions have significantly improved the performance of the WEPP model for forested watersheds. For the model to be applicable to Cedar River watershed, the spatial variation in climatic inputs and a baseflow component needs to be incorporated to adequately represent hydrologic conditions in the watershed. Therefore, our specific objectives are to (i) incorporate the variation in climatic inputs into WEPP to assess its impact on groundwater recharge; (ii) including a linear-reservoir approach for estimating groundwater baseflow in the WEPP model (v2012.8); and (iii) evaluate the performance of the improved WEPP model by applying it to Cedar River watershed.

WEPP simulations were carried out for the period of 1980 to 2012. Four weather stations located in the upper Cedar River watershed were used to capture spatial variability of precipitation using the Thiessen polygon method. A linear-reservoir model assuming that outflow is a linear fraction of groundwater reservoir was used to estimate baseflow. WEPP results with varying climatic inputs and the baseflow model adequately represented the hydrologic processes in the watershed.

Water Resources of Upper Kittitas County: Groundwater Availability and Linkages to Surface Water

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Surface waters in the Yakima River basin, located in central Washington, are considered over allocated and since about 1960, new water demands have been met by the use of groundwater. However, a recent U.S. Geological Survey study indicated that groundwater and surface water in the Yakima River basin are interconnected. In 2007 an emergency rule was implemented that established a withdrawal from appropriation of all unappropriated groundwater in western (Upper) Kittitas County, until sufficient information was known about potential effects from groundwater pumping on senior surface-water rights and tributary streamflows.

In order to address these questions, the U.S. Geological Survey began a cooperative study in 2010 with the Washington State Department of Ecology and Kittitas County to (1) define the hydrogeology of the study area, (2) provide information regarding groundwater occurrence and availability, (3) describe the potential extent of groundwater and surface water continuity, and (4) determine the potential effects on streamflow resulting from groundwater withdrawals.

The Upper Kittitas County study area covers about 860 square miles from the east slope of the Cascade Range to the confluence of Swauk Creek and the Yakima River. The study area is highly folded and faulted and is underlain by various consolidated igneous, sedimentary, and metamorphic rocks, ranging in age from Paleozoic to Tertiary, and more recent unconsolidated deposits. The study area thus contains a complex assortment of Quaternary deposits to Paleozoic bedrock units.

As part of a multidisciplinary approach, water-level data, measurements of groundwater and surface-water interactions, and chemical and isotopic data were collected; hydrogeologic units were defined and their hydraulic characteristics estimated; and exempt groundwater use estimates were updated. Preliminary analysis of stream discharge and temperature data indicates that groundwater contributes to streamflow. Our initial analysis of data on stable isotopes of water suggests that study area groundwater is compartmentalized, and the isotopic character of both groundwater and stream water are consistent with the presence of groundwater-supported streams. Indicators of groundwater residence time demonstrate that the shallow groundwater system can be highly dynamic and contain large but variable components of young groundwater, whereas deeper groundwater and groundwater near discharge zones has much longer residence times. These preliminary results and additional analysis and data will be used to describe the hydrogeologic framework of Upper Kittitas County, develop a conceptual model of groundwater flow, and construct hydrologic budgets.

Watershed Dynamics in a Changing Climate: A Look at Transportation in Washington's Mountains

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The response of Washington watersheds to projected changes in climate will vary in space and time with consequences for water quantity and quality. This presentation provides a general overview of regional climate impacts and shifts in watershed dynamics for basins in the mountainous areas of Washington. An emerging pattern indicates a spatial correlation between the intensity of basin hydrologic responses and the areas where climate change also triggers modifications in vegetation patterns and disturbance regimes. Results demonstrate how impacts from projected watershed shifts, like increased flooding, could affect Washington's transportation infrastructure in mountainous regions. Linking hydrologic changes and hydrogeomorphic responses are critical for identifying risks and planning adaptation strategies that reduce risks to life, property, and resources. A suite of adaptation strategies are explored as part of an interagency vulnerability assessment designed to increase awareness of climate change impacts and integrate this awareness into agency resource management.

Anatomy of a PCB Plume

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PCBs are generally considered to be immobile in groundwater because of their low solubility and very high affinity for binding to soil. We have been investigating a plume at an industrial site in Washington in which PCBs have migrated as much as 1,500 feet from the presumed source area. The origin of the plume, and the chemical and hydrogeological conditions favorable for the establishment of a PCB plume will be discussed.

Detected PCBs concentrations in groundwater are very low ranging from 0.0045 to 3.4 ug/L. The plume is a relatively long (1800 feet) and narrow (400 feet). The plume appears to be stable and currently is not expanding, which is consistent with a release date occurring more than 30 years ago.

The type of PCB present is Aroclor 1242/1248 based on the analysis of both soil and groundwater samples. The source and release mechanism of the PCBs is not fully understood but was probably related to the use of hydraulic oil. The PCBs in groundwater do not appear to be associated with petroleum since no petroleum-related constituents have detected with the PCBs. Also, there is no clear association between PCBs with suspended solids in groundwater samples.

The aquifer beneath the plume is very productive and extremely permeable. Depth to groundwater is generally 60 to 70 feet and fluctuates seasonally by as much as 15 feet. The unsaturated zone and the thick unconfined aquifer consists of primarily of gravel and sand with minor amounts of silt and clay, and a low organic carbon content. Hydraulic conductivity ranges from 200 to 3,000 feet/day. Groundwater travel times based in part on tracer tests are from 90 to 600 feet/day.

Favorable site conditions that led to the development of PCB plume include rapid groundwater flow, the absence of significant fines and low organic carbon content in the aquifer. The absence of fines and lack of organic carbon content prevent sorption of the PCBs to the aquifer matrix. Colloidal transport of PCBs may also be an important factor in plume development.

Endpoints for the Deep Vadose Zone at the Hanford Site, Washington

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Requirements for site remediation and closure are often overly conservative, costly, and in some cases, technically impractical to achieve. Use of risk-informed alternate endpoints provide a means to achieve remediation goals that are permitted by regulations and are protective of human health and the environment. A framework is presented that is centered around developing and refining conceptual models in conjunction with assessing risks and alternative endpoints. The framework is centered around system-based assessments which integrate site data with a scientific understanding of the processes that control the distribution and transport of contaminants in the subsurface and pathways to receptors. These approaches are critical for evaluating contaminants in the vadose zone which often are long-term sources of groundwater contamination, often driving decision-making that is not rooted in risk evaluation. Significant natural attenuation processes control vadose zone contaminant transport and discharge to groundwater, and include both hydrogeologic, biochemical, and microbiological processes that serve to retain contaminants within porous media and physical processes that mitigate the rate of water flux. The physical processes controlling fluid flow in the vadose zone are quite different and generally have a more significant attenuation impact on contaminant transport relative to groundwater systems. An example of deep vadose zone contamination and how these approaches and framework can be effectively applied and quantitatively measured is described for the Hanford Site BC Cribs and Trenches.

Guidance for Evaluating Post Closure Care of MSW Landfills

Lee Huckins, Oregon Department of Environmental Quality

Numerous Solid Waste Managers and Staff

Post closure care begins after a landfill closes. Generally, this post closure maintenance period must continue for at least 30 years as required by Federal and State standards and rules. Since Subtitle D went into effect in 1991, many landfills are rapidly approaching the end of their post closure period. However, by being an approved state, Oregon DEQ can end post closure care early if the permittee can demonstrate that a reduced period of post closure care is sufficient to protect human health and the environment. The post closure case can also be lengthened, if Oregon DEQ demonstrates that a longer postclosure period is necessary to protect human health and the environment.

Oregon DEQ is working on a guidance for staff to evaluate requests for early termination of solid waste permits or the extension of the solid waste permit past the 30 year period. Oregon's approach involves using a series of flow charts evaluating the following landfill systems:

1. Leachate Collection and Leak Detection System;
2. Landfill Gas Detection and Control System;
3. Groundwater Monitoring System; and
4. Cap and Cover System

Oregon DEQ intends to use these flow charts to determine if any of the above systems can be discontinued during the post closure period. If Oregon DEQ determines that all of the above systems are no longer needed and can be shut down, Oregon DEQ may consider a reduction in financial assurance and monitoring or ending the post closure period.

Potential for Arsenic Mobility and Groundwater Contamination from Area-Wide Contaminated Soil

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Many areas of the world have experienced area-wide soil contamination from human activities, such as metal smelting. In this study, groundwater quality associated with area-wide arsenic soil contamination from a metal smelter and from widespread use of agricultural pesticides was evaluated, as well as current methods for predicting groundwater arsenic concentrations. Background review was conducted to provide a conceptual model of arsenic mobility in soil. The conceptual model supported the hypothesis that arsenic is relatively immobile in soil and does not pose a significant threat to groundwater. Available soil and groundwater data were analyzed to determine the mobility of arsenic in soil and the relationship between soil and groundwater arsenic concentrations within the smelter and agricultural plumes. This data showed high arsenic concentrations are limited to shallow soil layers, and no significant correlation between soil and groundwater arsenic concentrations was observed. The EPA partitioning model for predicting groundwater contaminant concentrations from soil concentrations was then evaluated. A comparison of available groundwater data collected in the field and results obtained using the EPA partitioning model suggests that the standard distribution coefficient used by the EPA does not accurately represent arsenic mobility in soil. Alternate input parameters were proposed and used to calculate new groundwater arsenic concentrations. The groundwater concentrations calculated using the alternate input parameters correlated more closely with available field data. It was determined that the alternate input parameters for the EPA partitioning model were more representative of soil conditions in the smelter and agricultural plumes and thus resulted in more accurate predictions of groundwater contaminant concentrations.

Accelerating Petroleum Remediation by Coupling Physical Extraction and Bioremediation

Troy Fowler, Hart Crowser

Chris Martin, Hart Crowser

Remediation of a 7-acre, free-phase gasoline (product) plume has been accelerated by combining physical and enhanced biological treatment technologies. The strategy reduced the estimated remediation timeframe by 60 percent, reduced estimated power consumption by 800 megawatt-hours, and preserved approximately 150 million gallons of groundwater for this arid agricultural area. The project met key cleanup goals and will enter monitored attenuation within 5 years of beginning the remedy.

Simultaneous product, groundwater, and vapor extraction reduced the initial 2.1-foot product thickness to a maximum of 0.2 foot within 18 months. Enhanced oxidative bioremediation was then deployed concurrent with physical extraction using existing infrastructure. During this enhanced remedial phase, extracted groundwater was treated using standard air-stripping techniques and re-injected with AnoxEA-aq, a supplemental oxidant blend and microbial nutrient amendment. The closed-loop recirculation approach eliminated NPDES-regulated discharge and preserved groundwater resources. Amendment slug injections into upgradient monitoring wells provided targeted treatment of areas with high residual contamination levels. Analytical data confirm that this strategy both directly destroyed residual petroleum and enhanced physical removal performance.

Hydrologic Characterization Results for the Wallula Basalt Carbon Sequestration Pilot Borehole

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Continental flood basalts represent one of the largest geologic formational structures on the planet and exist in regions of the U.S. (and other countries such as India) where sedimentary basin storage capacity is limited. Consequently, demonstration of commercial-scale storage in deep flood basalts is important in meeting global CO_2 emissions targets.

In 2009 the U.S. Department of Energy Big Sky Regional Carbon Sequestration Partnership completed drilling the first continental flood basalt CO_2 sequestration pilot borehole to a total depth of 4110 ft at the Boise White Paper Mill property near the town of Wallula in southeastern Washington state. The characterization program included reconnaissance-level hydrologic tests on selected basalt interflow reservoir zones and flow-interior/caprock intervals during and after completion of the borehole drilling activities to support selection of a candidate injection reservoir for subsequent CO_2 sequestration studies. Based on the results of the active borehole characterization program, an injection reservoir was identified within the Grand Ronde Basalt between a depth interval of 2716 and 2870 ft that appeared to meet CO_2 injection objectives and Washington state permit requirements, including;

- in-situ, static formation fluid temperature and pressure conditions above supercritical CO_2 conditions,
- presence of non-potable drinking water within the candidate injection, and
- hydraulic properties that indicate sufficient reservoir formation injectivity and overlying caprock sealing characteristics to facilitate injection and storage of up to 1,000 tons of CO_2 during a subsequent field pilot study phase.

Following well completion activities in June 2009, reservoir zone pressure (i.e., hydraulic head) was monitored for an extended period (July 2009 through December 2010) to evaluate long-term seasonal and short-term, temporal reservoir response dynamics to natural and human-related stress activities. After baseline pressure monitoring was completed, a series of hydrologic well tests were conducted in 2011 to assess the possible effects of well completion activities on the injection reservoir, to determine intermediate-scale reservoir hydraulic properties, and to detect presence of any hydrologic boundaries in the reservoir. A reservoir heterogeneity or potential boundary at an unresolved distance from the well was detected based on the hydrologic test response during these intermediate-scale hydrologic tests. To resolve the observed reservoir condition, an extended duration (20-day), high-stress (>600 psi) pumping test was conducted in 2012 to delineate the source and extent of the detected reservoir heterogeneity. Derivative analysis of test response indicates the presence of a heterogeneous, composite/zonal reservoir condition caused by the existence of a higher permeability, radial-flow dominated inner-zone that extends ≥175 ft from the well and then transitions to a lower permeability zone that extends to the radius-of-investigation imposed by the test (≈1000 ft). Derivative analysis of the late-time reservoir pressure response and recovery data also indicates the establishment of infinite-acting radial flow conditions that is inconsistent with significant reservoir leakage. Fluoride concentrations measured in groundwater samples extracted during the 20-day test were found to be elevated (i.e., >6 mg/L) and remained relatively uniform with time. This fluoride test profile during pumping is also consistent with the lack of significant vertical leakage to the injection reservoir from overlying, shallower groundwater, which has lower fluoride concentrations. Based on this set of favorable data, the project is recommending that the Department of Energy proceed with CO_2 injection and monitoring.

Wellbore Cement Carbonation by Various Phases of Carbon Dioxide During Geologic Carbon Sequestration

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Portland cement is commonly used as a sealing material for wellbores in geological carbon sequestration. Potential leakage pathways of stored CO_2 may occur at the interface between casing and cement, cement and host rock, or through the cement pores and fractures. During geologic carbon sequestration, cement materials in the injection well will be contacted by dry supercritical CO_2 within a few meters from the injection well, while the cement materials in the existing wells can be exposed to wet supercritical CO_2 or CO_2-saturated water. In addition, wellbore cement at shallow depths above the groundwater table can be exposed to wet CO_2(g) leaked from the deep reservoir. This study focused on the potential chemical and physical alteration processes of hydrated Portland cement in the wellbore by various phases of CO_2 that can be present along the wellbore from the deep carbon injection and storage depth (50 °C and 10 MPa) to the shallow subsurface (20 °C and 1 atm) during geologic carbon sequestration.

After Portland cement columns were exposed to wet and dry supercritical, aqueous and gaseous phases of CO_2 over different time scales, the changes in physical and chemical properties of the carbonated Portland cement were investigated using a number of advanced characterization methods, such as SEM-EDS, BET, XRD, and XMT techniques. Portland cement carbonation reaction at high P-T conditions resulted in approximate degradation depths of 1, 1.5, and 3.5 mm by CO_2-saturated groundwater after 1, 2, and 5 months, respectively. However, much less degradation occurred in the cement columns exposed to wet supercritical CO_2. Cement carbonation at high P-T conditions formed three distinctive degraded zones characterized by a systematic change in the ratio of Ca to C atom % as the result of dissolution of $Ca(OH)_2$ and C-S-H phases, as well as precipitation and dissolution of calcite. Analysis of SEM images, as well as BET analysis showed the outer degradation zone appears structurally weak and unstable due to the development of pores and fractures resulting from depletion of portlandite, as well as dissolution of calcite and C-S-H phases in cement matrix. As the Portland cement reacted with wet CO_2(g) at low P-T conditions representing the wellbore environment at a shallow depth near the ground surface, the reaction was dominated by the precipitation of calcite on the outside surface of the cement column because of more restricted diffusion of Ca and CO_2(g) due to low water content. The widespread precipitation of micron-sized calcite in the cement also caused decreases in pore volume and surface area.

The risk of CO_2 leakage through the wellbore environment appears to be higher for wellbore cement reacting with CO_2 at the carbon injection depth with high P-T conditions, where cement dissolution reactions are dominant compared to the shallow depth with low P-T conditions. However, wellbore cement with reduced porosity due to calcite precipitation and coating at shallower depths could also provide a barrier for the leakage of CO_2 to the ground surface.

Geochemical Impacts of Leaking CO2 from Subsurface Storage Reservoirs to an Unconfined Carbonate Aquifer: Experimental and Modeling Results

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Deep subsurface storage and sequestration of CO_2 has been identified as a potential mitigation technique for rising atmospheric CO_2 concentrations. Sequestered CO_2 represents a potential risk to overlying aquifers if the CO_2 leaks from the deep storage reservoir. In order to evaluate potential risks to groundwater quality, the groundwater group of PNNL is working to develop a systematic understanding on how CO_2 leakage may cause important changes in aquifer chemistry and mineralogy by promoting dissolution/precipitation, adsorption/desorption, and redox reactions in an unconfined, oxidizing carbonate aquifer, i.e., Edwards Aquifer in Texas. In addition, the groundwater group of PNNL is working to develop groundwater geochemistry reduced order models (ROM) for the same aquifer.

The experimental part of this effort includes: 1) Wet chemical acid extractions (8M HNO3 solution at 90 0C); 2) Batch leaching experiments; and 3) Pre- and post-treatment solid phase characterization studies. Major variables tested included experimental time (0-336 hours), CO_2 flow rate (50 to 350 ml/min), solution composition (presence of contaminants), brine concentration (0.1 and 1 M NaCl), rock type and size fraction. Results from acid extractions demonstrated that the solid phase had appreciable amounts of potential contaminants (As, Cd, Cr, Cu, Pb and Zn). Results from the first set of batch experiments demonstrated that the aqueous phase pH decreases from about 8 to 5.8 – 6 immediately after CO_2 gas exposure, promoting mineral dissolution. Aqueous Ca concentrations were controlled by calcite dissolution, while concentrations of other major cations (Mg, Sr, Ba, Na, and K) were controlled by dissolution and cation exchange reactions. The changes in aqueous Si concentrations were insignificant, while concentrations of Al and Fe, and those of potential contaminants, were below detection limits. Further chemical analyses and experiments with a variety of rocks are currently underway.

The groundwater geochemistry ROM for the Edwards Aquifer used a Wellbore Leakage ROM developed at Los Alamos National Laboratory. The model covered a 5x8 km area of the aquifer. The model included heterogeneous hydraulic properties, and equilibrium, kinetic and sorption reactions between groundwater, leaked CO_2 gas, brine, and the aquifer carbonate and clay minerals. Latin Hypercube sampling was used to generate 1024 samples of input parameters. For each of these input samples, the STOMP simulator was used to predict the flux of CO_2 to the atmosphere, and the volume, length and width of the aquifer where pH was less than the MCL standard, and TDS, arsenic, cadmium and lead exceeded MCL standards. The most sensitive parameters proved to be the CO_2 and brine leakage rates from the well, with equilibrium coefficients for calcite and dolomite, as well as the number of illite and kaolinite sorption sites proving to be of secondary importance. The goodness of fit was excellent for the CO_2 flux to the atmosphere, and very good for predicting the volumes of groundwater exceeding the pH, TDS, As, Cd and Pb threshold values.

The results from these investigations will provide useful information to support site selection, risk assessment, and public education efforts associated with geological, deep subsurface CO_2 storage and sequestration.

Threshold Values for Identification of Contamination Predicted by Reduced Order Models

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Carbon capture and storage (CCS) is being evaluated as a potential mitigation approach for rising atmospheric CO_2 concentrations. Once sequestered, the CO_2 represents a potential risk to overlying aquifers should it ever leak from the deep storage reservoir. CO_2 dissolution into the groundwater will result in a decrease in pH, which in turn could mobilize trace metals present in the aquifer sediments. The purpose of this study was to examine baseline data sets and statistical protocols for determining statistically significant changes between background concentrations and predicted concentrations that could be used to represent a contamination plume in the second generation (Gen II) models being developed by the National Risk Assessment Partnership's Groundwater Protection team.

The initial effort examined selected portions of two aquifer systems: the urban shallow-unconfined aquifer system of the Edwards-Trinity Aquifer System (being used to develop the reduced order model for carbonate-rock aquifers), and a portion of the High Plains Aquifer (an unconsolidated and semi consolidated sand and gravel aquifer being used to develop the reduced order model for sandstone aquifers). Threshold values were determined for Cd, Pb, As, pH, and total dissolved solids based on an interwell approach for determining background groundwater concentrations as recommended in the U.S. Environmental Protection Agency's Unified Guidance for Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities (EPA 2009).

The resulting threshold values are intended to inform a "no change" scenario with respect to groundwater impacts, rather than use a maximum concentration limit or secondary drinking water standard that in some cases could be significantly higher than existing concentrations in the aquifer. These threshold values are intended for use in helping to predict the area of potential impacts if CO_2 leaks from a reservoir. They are not intended for use as alternate regulatory limits.

Development of "generic" threshold values that could be used for different locations and reservoir types appears unlikely. Instead the threshold values must be based on site-specific groundwater quality data. However, the scarcity of existing data, proximity of the data to the target model domain, potential spatial heterogeneity, and temporal trends make development of "clean" statistically robust data sets and use of valid statistical assumptions challenging. In some cases the calculated threshold values may exceed regulatory standards. Other approaches such as a hybrid intrawell-interwell approach also examined in this study may provide other mechanisms for calculating threshold limits.

Modeling Nearshore Groundwater Contaminant Attenuation in Response to Intertidal Sediment Capping

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For MTCA cleanup sites within marine waterfront settings, upland groundwater quality must meet cleanup standards protective of discharge to the adjacent marine environment. Tidally influenced nearshore aquifers represent hydraulically and geochemically dynamic environments, within which substantial natural attenuation of groundwater contaminant concentrations can occur; furthermore, the magnitude of attenuation typically increases the closer groundwater gets to the surface water interface (or sediment bioactive zone), which represents the point of exposure upon which the groundwater cleanup standards are based. At most MTCA sites, upland groundwater quality is measured at shoreline monitoring wells; directly measuring porewater quality within the sediment bioactive zone is much less common. As such, conventional upland groundwater monitoring can overstate risks to the marine environment and lead to misguided remedy selection.

Yet it is often desirable to establish groundwater screening levels protective of the marine environment which can be applied using conventional groundwater monitoring techniques at upland shoreline wells. The groundwater screening levels should account for attenuation along the groundwater flowpath between the monitoring wells and the sediment due to physical mixing of surface water and groundwater under the influence of tidal fluctuations. Absent direct measurement of attenuation, groundwater modeling can aid in estimating attenuation factors to arrive at protective screening levels applicable at shoreline wells.

This approach was applied at the former Georgia Pacific West Site in Bellingham, WA, to develop groundwater screening levels for mercury in a shallow fill aquifer abutting the Whatcom Waterway. The presence of mercury in the offshore sediments, and their planned future capping, made estimating attenuation factors from empirical data alone difficult. Therefore, attenuation factors under current and future capped conditions were predicted by constructing and calibrating a transient 2-D numerical groundwater flow and contaminant transport model along a representative transect, using MODFLOW and MT3DMS. The transect included a broad intertidal zone, resulting in cyclical drying and rewetting of many MODFLOW grid cells. To address that numerical challenge, the recently released MODFLOW-NWT package was used, which allowed for robust simulation of groundwater-surface water interaction across the broad intertidal zone, providing higher resolution than previous MODFLOW solvers.

Once calibrated to current conditions, the model predicted attenuation factors (AFs) of about 80 and 600 at the point of highest concentration discharge under current and future capped conditions, respectively; the 8-fold increase in AFs results primarily from increased groundwater flowpath length and enhanced mixing within the higher permeability sediment cap. Using available empirical data, a safety factor was then applied to the estimated AFs to establish groundwater remediation levels to be used during remedial alternative development in the FS. The resultant remediation levels incorporate mechanical attenuation between the shoreline monitoring wells and the sediment under current and future capped conditions, while conservatively incorporating empirical data to account for uncertainty, without additional data collection or performing a computationally expensive uncertainty analyses.

Groundwater Monitoring Optimization Reduces Site Operating Cost

Glenn Hayman, Hayman Environmental

Cleanup of contaminated soil and groundwater is very expensive and time consuming. A significant portion of the cost of site cleanup is groundwater monitoring (planning, sampling, analyzing and reporting). Monitoring costs are commonly 40% to 70% of a site's annual operating cost. Quantitative and qualitative optimization of a groundwater monitoring program can reduce the cost of monitoring while providing a defensible basis for the reduced monitoring. Groundwater monitoring optimization typically reduces monitoring by 30% in the first year with additional reductions in subsequent years.

At a western Washington superfund site groundwater samples had been collected from 147 wells with 106 wells sampled annually. At this site groundwater monitoring planning, field work, chemical analysis and reporting costs exceeded $190,000 annually.

An initial qualitative evaluation of the monitoring program was conducted in 2004. Similar wells were grouped together. Each group was evaluated using a consistent set of rules. This qualitative evaluation resulted in the number of groundwater monitoring samples collected annually being reduced by 39%.

Subsequently, a combined quantitative and qualitative evaluation of the groundwater monitoring program was conducted to further optimize the number of samples collected and the frequency of groundwater sampling. The quantitative evaluation utilized Monitoring And Remediation Optimization Systems (MAROS) software to process the data, recommend sampling frequency and determine monitoring well redundancy. A qualitative review of the MAROS output was conducted to ensure the monitoring program objectives were met. This optimization effort reduced groundwater monitoring by an additional 42%.

The multiple rounds of optimization resulted in 68 fewer wells being sampled quarterly and semiannually. New sampling frequencies of biennial (every 2 years) and every 5 years were created. There were 35 wells in these new categories. No further sampling was required for 30 wells. In total, optimizing the groundwater monitoring resulted in a 65% reduction in the number of groundwater samples being collected and saving approximately $121,000 annually. The cost of the optimization was recovered in less than one year an impressive return on investment.

The results of the optimization were reviewed and approved by the Washington Department of Ecology and the Environmental Protection Agency. The application of both quantitative and qualitative processes provided the defensible rationale required for the agencies to approve such a substantial reduction in groundwater monitoring at this superfund site.

Managing the Thermal Regime of Sustainable Groundwater Withdrawals for Salmonid Rearing at the Eastbank Hatchery, Rocky Reach Dam, Washington

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Sam Dilly, PUD No. 1 of Chelan County

Public Utility District No. 1 of Chelan County (PUD) operates a large capacity wellfield in the Eastbank Aquifer system, adjacent to the Columbia River at the Rocky Reach Dam. The aquifer system is a highly valuable resource that supplies water for the PUD's Eastbank Hatchery operation, as well as the cities of Wenatchee, East Wenatchee, and surrounding areas. Maintaining adequate groundwater withdrawal rates and appropriate thermal conditions for rearing hatchery fish are of utmost importance for the PUD. A data collection and modeling investigation was initiated by the PUD to improve the conceptual model for hydraulic and thermal behavior of the aquifer and to support long-term, sustainable wellfield management strategies.

The aquifer system is also used for regional public water supply by the City of Wenatchee, East Wenatchee, and surrounding areas. It is likely that an expanded service area for public water supplied by the municipal wellfield will increase demand for groundwater from the Eastbank Aquifer system in the future. As part of this modeling study, the PUD is evaluating the effects of projected increases in aquifer withdrawals from the regional wellfield, to support a cooperative effort in managing the overall sustainability of the Eastbank Aquifer system.

The Eastbank Aquifer system is relatively small in size, but is highly productive. The aquifer system is bounded by the Columbia River, low permeability bedrock, and a grout and clay cutoff wall associated with construction of the Rocky Reach dam. The aquifer system is dominated by coarse gravel with a clay confining unit present between the upper and lower gravel units over much of the system. The Columbia River is in strong hydraulic continuity with the aquifer system. The river exhibits significant seasonal changes in temperatures that can both reduce or increase temperatures in the aquifer. The effects of river temperatures on the aquifer are highly influenced by wellfield withdrawals and changes to pumping schedules.

Control of wellfield temperatures is critical to successful Eastbank Hatchery salmonid production, and long-term strategies for wellfield management focused on flow and temperature optimization are key to effective resource utilization. A management tool for the PUD was developed with a FEFLOW model built and calibrated to dynamic heads, flows, and high-resolution temperature observations. Specific resource management scenarios were investigated to understand the influence of wellfield operation on groundwater temperatures and water level in the aquifer. These include scenarios with reduced hatchery demand due to improved efficiency, modifications in pumping schedules to optimize seasonal temperatures, and increased demand by the regional water supply wellfield, including addition of new production wells. The modeling investigation has significantly improved understanding of the hydraulic and thermal dynamics of the Eastbank Aquifer system, including its interaction with wellfield withdrawals, the Columbia River, and the existing cutoff wall.

Adapting the Arc Hydro Groundwater Data Model and Tools to a Hydrogeologic Framework for the Kitsap Peninsula, Kitsap, Mason and Pierce Counties, Washington

Wendy Welch, U.S. Geological Survey

In October 2010, the U.S. Geological Survey Washington Water Science Center, in partnership with the Water Purveyors Association of Kitsap County began a project to characterize the water resources and create a numerical groundwater flow model of the Kitsap Peninsula. As part of that project, a detailed hydrogeologic framework of the area was needed. The Kitsap Peninsula covers about 787 square miles in the southern Puget Sound Lowland of Pierce, Mason, and Kitsap Counties in western Washington. The watershed is underlain by thick sequences of unconsolidated sediments that are the result of multiple Pleistocene glacial and interglacial periods. Defining extents and thicknesses of the aquifers and confining units within these unconsolidated sediments is essential to understanding groundwater flow and interactions with surface water features.

To manage a dataset of more than 2,000 wells and construct a hydrogeologic framework, AquaveoTM Arc Hydro Groundwater data model and tools (for ArcGIS) were adapted to the Kitsap Groundwater project. The data model is a geodatabase design for representing groundwater information and attributes in a standardized structure. Digital surficial geologic maps, well locations, and borehole logs are examples of data that were imported into the geodatabase. The Groundwater Analyst and Subsurface Analyst tools were used to evaluate the data, create hydrogeologic cross sections, and produce new datasets for framework construction and numerical model development. New datasets included extents and three-dimensional representations of the hydrogeologic units.

The primary objective in implementing a structured geodatabase design is to develop a standard methodology for managing, representing, and analyzing multidimensional groundwater data within ArcGIS. An all-inclusive and flexible design is critical to maintain the integrity of the data in regional groundwater projects and to provide a basis for future hydrogeologic frameworks within the Washington Water Science Center.

Poster Abstracts

Conceptual Model for the Kitsap Peninsula, Kitsap, Mason, and Pierce Counties, Washington

Lonna Frans, U.S. Geological Survey

Wendy Welch, U.S. Geological Survey

The Kitsap Peninsula covers approximately 787 square miles in the southern Puget Sound Lowland of Kitsap, Pierce, and Mason Counties in western Washington. The watershed is underlain by as much as 2,000 feet of unconsolidated sediments that are the result of multiple Pleistocene glacial and interglacial periods. Defining extents and thicknesses of the aquifers and confining units within these unconsolidated sediments is essential to understanding groundwater flow and interaction with surface-water features.

In October 2010, the U.S. Geological Survey (U.S. Geological Survey) Washington Water Science Center in partnership with the Water Purveyors Association of Kitsap County began a project to characterize the water resources and create a numerical groundwater flow model of the Kitsap Peninsula. As part of that project, a more detailed conceptual model and hydrogeologic framework of the area was needed.

Four major elements were completed to construct the hydrogeologic framework. A digital surficial hydrogeologic map was compiled by merging existing 1:100,000 and 1:24,000 geologic maps. A dataset of more than 2,000 wells was assembled from the U.S. Geological Survey National Water Information System database and hydrogeologic unit assignments were made incorporating surficial geology, drillers' logs, and previous investigations. Cross-sections were created to illustrate the likely correlations between hydrogeologic units across the entire study area. Finally, maps were created to show the extents of the hydrogeologic units and the interpolated elevations of the unit tops.

Hydraulic parameters will be estimated for hydrogeologic units using available data from aquifer tests, drillers' reports and published values. Water-level maps are also being prepared for principal aquifers within the basin in order to better understand groundwater flow directions, and horizontal and vertical water-level gradients.

Hydrogeology of the Little Spokane River Basin, Washington

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Theresa Olsen, U.S. Geological Survey

Lisl Fasser, U.S. Geological Survey

The Little Spokane River Basin includes an area of about 675 square miles in northeastern Washington State, covering parts of Spokane, Stevens, and Pend Oreille Counties. Streams originate in the northern part of the basin and contribute flow to the Little Spokane River which flows about 49 miles to its confluence with the Spokane River, near Spokane. The basin relies on spring snowmelt from the high elevation areas of the basin and groundwater discharge to the river to maintain stream flows during the summer and fall.

Spokane County is concerned about the effects of future groundwater development that may occur throughout the basin. With increased subdivision and development, an increase in exempt groundwater use is expected to continue, but the potential effects of this growth on the Little Spokane River and the basin aquifers are unknown. In order to obtain information necessary to evaluate these concerns, the U.S. Geological Survey is carrying out a study to describe the hydrogeologic framework of the basin. This work is intended to be followed by subsequent studies that will provide the information needed for the eventual construction and calibration of a numerical groundwater flow model. Such a model could then be used by the County to evaluate the possible regional impacts of different groundwater-use and climate scenarios on the groundwater and surface-water system of the basin.

An analysis of the hydrogeologic framework has been completed using well logs, geologic mapping, and field observations. Existing and new groundwater data were compiled and used to evaluate the flow system. A simplified geologic map is presented with hydrogeologic cross sections constructed for the study area. Principal hydrogeologic units are illustrated, including maps of the tops and extents of the major units. Hydraulic parameters estimated for hydrogeologic units, using available data from aquifer tests, driller reports, and published values, are provided in table format. Water-level maps of the basin illustrate the hydraulic head and general groundwater flow directions.

Geochemistry of a ~13,000 Year Sediment Core from the Most Contaminated Lake in Washington: Waughop Lake, Pierce County

Elli McKinley, University of Puget Sound

Jeffrey Tepper, University of Puget Sound

Kena Fox-Dobbs, University of Puget Sound

Waughop Lake, located in Lakewood, Washington, is currently experiencing severe eutrophication and toxic algal blooms that have led to closures of the lake. The lake has high phosphorous levels, and has been designated the most contaminated lake in western Washington. Anthropogenic sources of nutrient-loading in the lake over the past century were likely animal waste disposal, and septic system leakage. Unsuccessful remediation actions in 2008 included treatment with calcium hydroxide and algaecide. To better understand the origins of the current problems and the options for future remediation we collected a 655 cm sediment core from the center of the lake. The goal of this study is to reconstruct the environmental history of the lake over the past 8,000+ years, focusing in particular on changes in nutrient loading and productivity over the past ~150 years.

Our core penetrated the 7,700 BP Mt. Mazama ash layer at 420 cm depth, indicating Waughop Lake is well over 8,000 years old. Extrapolated sedimentation rates suggest an age close to 13,000 years. The upper 100 cm of lake sediment will be analyzed using ^{210}Pb dating methods to obtain more accurate sedimentation rates. Concentrations of heavy metals show a significant peak at 80 cm depth indicating the production of copper from the local ASARCO smelter around 1900. From this, a rough sedimentation rate has been calculated to 0.04 cm/yr, and a rate of 0.7 cm/yr between present and 1900. During the time period of peak smelter activity average heavy metal concentrations were 5x to 20x higher than background levels (As: 6.08 to 31.8 ppm, Cu: 7.7 to 61.72 ppm, Fe: 880 to 5,014.7 ppm, Mn: 39.6 to 169.6 ppm, and Pb: 10.42 to 200.29 ppm).

The ratio of carbon to nitrogen concentrations (weight %) of the organic fraction of the sediments is relatively uniform (C/N=12) from 0 to 500 cm depth. C/N ratios are higher in the lowest ~155 cm of the core (C/N=14-16), which indicates a relatively higher contribution of vascular plant material (C/N>20), versus aquatic algae primary production (C/N<10) to sediment organics in the distant past. Over the last ~80 years the δ^{15}N values of sediment organics remained uniform at ~4‰. We compare δ^{15}N values from the upper, anthropogenically-impacted section of the core (post 1900), to the lower core (pre 1900), to investigate how the recent sediment δ^{15}N values record source(s) of nutrient-loading.

Predicting Slope Failure in the Jones Creek Watershed, Acme, WA

Brandon Brayfield, Western Washington University

Robert Mitchell, Western Washington University

Mountain watersheds in the Pacific Northwest are particularly susceptible to shallow landslides and debris flows during periods of intense precipitation. The Jones Creek watershed near Acme, WA, is a 6.7 km^2 basin that hosts several active landslides, ranging in area from 400 m^2 to 1600 m^2. Shallow mass wasting on the unvegetated landslide toes, and deep-seated rotational slide movement can lead to landslide dam outburst floods and debris flows. There are approximately 100 buildings constructed on a 0.75 km^2 alluvial fan deposited by debris flows sourced in the watershed. Predicting the occurrence of mass wasting and deep-seated movement events as they relate to the duration and intensity of antecedent precipitation conditions is important for land-use planning and emergency preparedness in the surrounding Acme community.

We use the Distributed-Hydrology-Soil-Vegetation Model (DSHVM), coupled with an infinite-slope failure model to determine the probability of shallow mass-wasting events for a variety of precipitation scenarios. The DHSVM uses meteorological data, paired with spatially distributed soil and land cover data, to simulate a water and energy balance at the pixel scale of a digital elevation model. Stream flow measurements taken frequently during the 2011-2012 winter season are used to calibrate the DHSVM hydrology simulations, with favorable results. The infinite-slope model is dependent on the DHSVM-simulated hydrology and uses a stochastic approach to predict the probability of slope failure on a cell-by-cell basis.

We also use Rocscience Slide software to model the influence of groundwater and soil mechanical properties on deep-seated slope stability, and to estimate failure plane geometries for each of the landslides. Slide uses a comprehensive suite of tools for probabilistic modeling of complex failures, and incorporates a standalone finite element model for groundwater flow.

Ongoing research includes calibrating the infinite slope failure model to historical mass wasting events in the basin, and a sensitivity analysis of the soil mechanical properties that control slope stability (soil cohesion, angle of internal friction, root cohesion, and vegetation surcharge). We will use the calibrated models to evaluate a precipitation duration-intensity threshold for the initiation of slope failure in the basin.

Modeling Groundwater Flow Conditions in the Chimacum Creek Watershed

Kenneth Johnson, U.S. Geological Survey

Lonna Frans, U.S. Geological Survey

Joseph Jones, U.S. Geological Survey

Population growth is increasing demand for water in the Quilcene-Snow Water Resource Inventory Area 17 (WRIA 17) near Port Hadlock, on the Olympic Peninsula. A main concern is Chimacum Creek, because of the potential impact of low flows on threatened and endangered salmon species. Local interested parties have prepared a Watershed Plan for WRIA 17 (WRIA 17 Planning Unit, 2003) and the Washington Department of Ecology responded with a water management rule for the basin. The US Geological Survey, Washington Water Science Center, has been working with the local parties and Ecology to develop a scientific basis for management of the water resources in the WRIA (Simonds et al., 2004, Jones et al., 2011). The latest effort has been development of a groundwater flow model to assess how groundwater withdrawals impact stream flows.

The model consists of six hydrogeologic units and model layers, and 245 columns and 313 rows. Inflows of water primarily come from precipitation recharge, groundwater inflows from adjacent basins to the north, and return flows from residential indoor and outdoor consumption both at individual wells and across public water system service areas, and from agricultural irrigation. Outflows from the model are mainly to submarine discharges in Port Townsend, Oak, and Discovery Bays; to surface water systems such as Chimacum Creek and its tributary East Fork Chimacum Creek; and to public supply, irrigation, and self-supply water wells.

The model was implemented in MODFLOW 2005 and calibrated by adjusting aquifer properties and boundary conductances and with PEST (Doherty 2004), using field measurements of 310 groundwater levels at 57 wells and 119 base flows at 13 streamflow sites observed between 2002 and 2009. Steady-state calibration was successful, with a residual mean of 4.8 +/- 16.0 feet in water level (0.8% of the 622 feet range of observed water level altitudes) and baseflow agreements of 0.6 +/- 1.6 cfs (6% of the 11.2 cfs range of observations). Transient calibration fit the water levels adequately (1.1 +/- 8.9 feet) but was less successful for stream flows (0.2 +/- 7.2 cfs). Hydrographs of transient stream flow indicate that chaotic flow instabilities propagate along the Creek, because of an interaction between boundary conditions and storage in the underlying unconfined aquifer, and the resulting noise limits the accuracy of the transient calibration.

The model was used to determine flow directions from the streams (or other boundary conditions) to the major public water supply wells. By locating hypothetical pumping wells at locations across the modeled area and calculating the percent capture or interception that comes from the creek, possible water supply withdrawal sites were developed that would minimize impacts on the stream. Scenarios were also developed with the local cooperators to compare drawdown and flows for future consumption conditions such as full use of water rights, probable growth, implementation of sanitary sewers in the Urban Growth Area, and curtailment of pumping for agricultural irrigation.

Hydrogeologic Characterization of Squalicum Valley, Whatcom County, Washington

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This study is designed to characterize the unconfined groundwater aquifer in Squalicum Valley, the largest glacial basin in the Lake Whatcom watershed, Whatcom County, WA. Based on lake water budgets, lake modeling, and limited field studies, Lake Whatcom receives a substantial portion of recharge from groundwater. Approximately 80% of the lake watershed is fractured bedrock, mainly sandstone and siltstone of the Chuckanut Formation, estimated to provide less than 30% of the lake's groundwater budget. Valleys filled with late Fraser glacial deposits discharge the remainder; Squalicum Valley alone is hypothesized to provide more than 20% of the lake's groundwater recharge. Lake Whatcom is subject to a TMDL and provides drinking water for nearly 100,000 citizens, thus for both water quantity and quality, it is important to refine groundwater estimates. As a step toward this goal we intend to fully characterize the aquifer system in Squalicum Valley, and determine potential groundwater discharge from the valley to the lake.

Squalicum Valley lies on the north shore of Lake Whatcom and covers an area approximately 4.5 square miles. Hydrogeologic glacial deposits in the valley rest on bedrock and slope southwest toward the lake basin. To characterize the hydrogeology of Squalicum Valley, we are incorporating field data collected from over 120 wells including seasonal depth-to-water measurements andprecise GPS elevations and positions, and stratigraphy from 180 well logs. Preliminary results show that glacial deposits consist of a deep confined aquifer of highly transmissive advance outwash gravels capped by a 50-75 ft thick stratum of silty-clay drift. Coarse heterogeneous outwash deposits up to 150 ft thick sit atop the confining unit and hold discontinuous unconfined and perched aquifers. Confined and unconfined aquifers are recharged by precipitation and predominantly by pressurized flow through the fractured bedrock. Two perennial streams receive an unknown volume of seasonal groundwater discharge, but it is unlikely the inflow comes from the confined aquifer. Most residential wells are drilled into the confined aquifer, and exhibit elevated water levels. Several flowing artesian wells have been developed near the lake shore, indicating the contact between the aquifer stratum and the upper confining layer is exposed below the surface level of the lake.

Well-log data, water levels, and hydraulic parameter estimates will be used with Groundwater Modeling System software (GMS) to develop a three-dimensional conceptual stratigraphic model, determine general groundwater flow patterns in Squalicum Valley, and investigate seasonal volumes of groundwater discharge to Lake Whatcom.

Monitoring Groundwater Quality at the Water Table Beneath Areas of Dairy Manure Application to Assess Manure Management Strategies, Whatcom County, Washington

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There are many watersheds in Washington State where water resources are heavily impacted and where agriculture and increasing population pressures are co-located. Poorly managed agriculture (in particular, excess manure application) has often been advanced as a leading contributor to water pollution in these watersheds. A cooperative study is being conducted by the Whatcom Conservation District and U.S. Geological Survey Washington Water Science Center to test an alternate strategy for scheduling manure application to fields. The new method is not based solely on the calendar year as is the current method, but rather is based on an analysis of field hydrologic properties, crop growth requirements, and near-term environmental conditions.

The focus of the groundwater element of this study is on monitoring spatial and temporal changes in the concentrations of nutrients and fecal bacteria in groundwater near the water table beneath study plots receiving manure applications. The water table is monitored at various times during the agricultural and dormant season, and variations in height of the water table are accommodated by isolating the uppermost 6 inches of the saturated zone using a system of inflatable packers placed within sampled wells. Multiple samples per field plot are used to assess local scale variation in water quality concentrations resulting from hydrogeologic heterogeneity so that differences from contrasting manure management strategies can be better distinguished.

Preliminary sample results indicate no fecal bacteria in groundwater beneath either study plot. However spatial and temporal differences in concentrations of nitrate and chloride do exist between wells, and within individual wells at the isolated water table zone (0-6 inches) and the isolated zone beneath the water table (greater than 12 inches). The median of the relative percent difference of nitrate concentrations between the water table and the zone beneath the water table at all wells over one year is seven percent, but was as high 29 percent, which is ten times larger than the median relative percent difference between replicate nitrate samples (0.7 percent).

An Update to the Collection of New Geothermal Data for Washington State

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Exploration and development for geothermal energy relies heavily upon a wide variety of data types ranging from water chemistry to geophysics. In 2011, the Department of Energy funded a three year effort by the nation's state geological surveys to compile and collect all varieties of geothermal related data for inclusion into the National Geothermal Data System (NGDS). As a result of this effort, the Washington State Department of Natural Resources Division of Geology and Earth Resources (DGER) – Washington Geological Survey is creating an extensive Washington geothermal database that includes the development and revision of more than 14 datasets of existing geothermal and geological data. DGER was also funded to collect new geothermal related data including a successful drilling program of four new temperature-gradient holes located throughout the state. The aim of the project is not only to create a national geothermal database, but also to facilitate more exploration and development of both high and low temperature geothermal energy in the state of Washington.

DGER was able to research and compile an extraordinary amount of data from geotechnical subsurface catalogs, thermal wells, monitoring wells, temperature gradient wells, oil and gas well records, thermal springs, and water chemistry. Other data include geophysical and geologic maps, whole rock chemistry, seismicity, active faults, and geochronology. New geothermal data collected from field work includes temperature-gradient logs from 50 holes of opportunity, 90 additional thermal & mineral spring temperature and chemistry samples, and the drilling of four new temperature-gradient holes. The locations for these holes were identified based on the integration and analysis of existing and recently compiled geothermal data and drilled in the fall of 2012. Derivative products as a result of this project include geothermal potential and favorability maps. These maps use the data compiled during this study and integrates them to identify high potential or high favorability areas throughout Washington based on characteristics such as increased permeability, local temperature-gradients and bottom-hole temperatures, geophysical data, water chemistry, and distance to power lines.

Over the duration of this project, Washington's relevant data has been gathered and made available to the public via the National Geothermal Data System and the DGER Washington State Geological Information Portal site http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/geology_portal.aspx .

Impacts of Climatic Variability on the Thermal Structure of Lake Whatcom, Whatcom County

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Scientists have shown that many lakes around the world are warming due to increased temperatures associated with global warming, especially in northern latitudes. Lake temperature increases have been strongly linked to increased night-time temperature because there is less nighttime convective cooling, resulting in less heat lost to the atmosphere at night. Other meteorological variables linked to the warming trends include relative humidity, cloud cover, rainfall, and solar radiation. Regionally, for example, Lake Washington in Seattle, WA has exhibited a warming trend that was correlated to an increase in long wave radiation due to increasing minimum air temperatures. The Pacific Northwest has experienced an increase in air temperature of about 0.8°C since 1900. We examined temperature records of Lake Whatcom to determine if the lake exhibits such warming trend due to global warming. Lake Whatcom is located east of Bellingham, WA at 48.7° N latitude and has a surface area of about 20 km^2 and a volume of about 0.97 km^3. Sill ridges partition the lake into three major basins. Basin 1 and basin 2 are shallow, with depths on the order of 20 m; basin 3 has depths to 102 m and accounts for about 96 % of the total lake volume. Lake Whatcom has environmental significance because it serves as the drinking water source for the city of Bellingham and surrounding communities.

A forty-four year time series of monthly temperature measurements was examined from four separate locations in the lake; one from each of the shallower basins up to 20 m, and two locations in the deeper basin 3 to maximum depths of 90 m. The measurements were processed at all four sites into profiles consisting of measurements every meter for the top ten meters, and then every 5 meters to the bottom of each basin. A volume weighted time series was developed from the profiles for each basin as a whole, and for the epilimnion and hypolimnion of basin 3. Additional volume weighted time series were developed at each location for a winter segment when the lake was completely mixed and isothermal, and for a summer segment consisting of the warmest months of each year. When a trend free pre-whitening procedure was used to remove the effects of autocorrelation, no significant warming trend was observed in any of the volume-weighted time series developed for Lake Whatcom. We hypothesize that Lake Whatcom's small surface area to volume ratio and adjacent high relief limit radiation influences on the lake.

The Lucky Dog Structure: Geologic Constraints on Valley Floor Morphology and Surface and Groundwater Drainage in the Lower Skokomish River Valley, Mason County, Washington

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Brendan Miller, University of Washington

Recent geologic mapping at the lower Skokomish River valley and delta has produced evidence for a geologic structure that may in part explain why the Skokomish River along its lower reaches seems to be particularly prone to flooding. Lidar data indicate that a northwest-trending, gentle berm runs northwest across the lower Skokomish River valley. Historic records and geomorphic analysis of the valley floor morphology indicate that this berm is no product of ordinary fluvial processes or manmade landform modifications. The geometry of the feature, geomagnetic field strength gradients, and geologic observations suggest instead surface deformation from a geologic structure that has warped the valley floor during the late Holocene. Geologic mapping has documented deformation in sedimentary exposures in two smaller valleys northwest of the valley floor berm consistent with a southeast-trending fold or fault across the valley floor. Radiocarbon dates suggest that the structure impounded a broad wetland along its western margin approximately 1,000 years ago, and we infer from the valley floor morphology that the structure influences shallow subsurface drainage and, particularly at flood stage, surface water drainage and flooding patterns in the lower Skokomish valley. The findings are presented in a recently published "Geologic map of the Skokomish Valley and Union 7.5-minute quadrangles, Mason County, Washington", and a complementary report, "Supplement to geologic maps of the Lilliwaup, Skokomish Valley, and Union 7.5-minute quadrangles, Mason County, Washington—Geologic setting and development around the Great Bend of Hood Canal". These documents are available, respectively, at

http://www.dnr.wa.gov/Publications/ger_ofr2010-3_geol_map_skokomish_valley_union_24k.zip and

http://www.dnr.wa.gov/Publications/ger_ofr2010-5_lilliwaup_skokomish_valley_union_suppl_24k.pdf

Changes in Diatom Speciation Due to Anthropogenic Changes in Gravelly Lake, Washington

Jack Nakagawa, University of Puget Sound

Jeff Tepper, University of Puget Sound

Gravelly Lake is a glacial kettle lake in Lakewood, Washington. Its inputs are limited, with no major surficial inflows, and it relies on groundwater percolation from the south west—notably from the large and proximal American Lake. This lake is also notable for its complex lakeside anthropological history: from Native American society, to European settler farming, to modern industry (particularly with the ASARCO smelting activity in the 20th century). These produced harsh extremes of chemical input: tribes sometimes used fire to maintain the area as prairie for hunting (vastly different from the lush forested modern lake); European farmers loaded the lake with nutrients (especially Phosphorus); modern industry added heavy metals. Previous studies by other students at the University of Puget Sound have investigated the changes through time of stable isotopes and biogenic silica in the same lake. The goal of this study is to better understand how the anthropological changes have affected the biological productivity of the lake, focusing on freshwater diatom speciation. Roughly 1.5 meters of sediment were core sampled from the approximate center of the lake. This core was sampled at intervals and tested using Loss on Ignition to determine total organics, and treated with hydrogen peroxide and mounted on microscope slides to spot-count diatom species. The most common species throughout the core were planktonic (floating) Stephanodiscus, Cyclostephanos, Asterionella, and Aulacoseira. Benthic (lake-bottom) species were secondary throughout the core. In particular, the very large, Phosphorus-loving Stephanodiscus Niagarae increased in significance, blooming at about 40cm of depth—interpreted as the influx of nutrients from western farming. This study was undertaken in the fall of 2011 to the fall of 2012.

Development of a Washington State Model for Potential Debris Flows from Wildfires

Isabelle Sarikhan, Washington Department of Natural Resources, Division of Geology and Earth Resources

Stephen Slaughter, Washington Department of Natural Resources, Division of Geology and Earth Resources

Robert Mitchell, Western Washington University, Geology Department

Dave Norman, Washington Department of Natural Resources, Division of Geology and Earth Resources

Tim Walsh, Washington Department of Natural Resources, Division of Geology and Earth Resources

Wildfires in Washington State have burned over 1.3 million acres from 1973 to 2011; with over 300,000 additional burned acres in 2012. Burn areas are vulnerable to soil erosion and slope instability due to hydrophobic soils and difficult regrowth of vegetation. These conditions lead to the downslope hazards of debris flow mobilization that can adversely impact communities and infrastructure for years following a wildfire. The majority of burn area landslides develop from intense precipitation, usually from thunderstorms or cloudbursts that occur primarily in the spring through early fall. Long term hazards can be exacerbated by the reduction of tree rooting strength (Zeimer, 1981), redevelopment of canopy coverage (Horel, 2006) and rejuvenation of the soils and ground vegetation on a scale of a decade or more. Additionally, debris flows from burned areas can travel long distances, impacting communities and infrastructure, such as highways, miles away from burn areas. An example is the May 2011 Pearrygin Creek debris flow in northeast Washington, which initiated in the burn area of the 2006 Tripod Fire , impacting structures and roads over 5 miles outside of the fire perimeter.

Current landslide prediction tools use multi-regression statistical models with inputs that include modeled burn intensity, slope gradient, soil type, soil erosion potential, and rainfall intensity. Used primarily in the southwest United States, the orographical precipitation, vegetation, and lithology inputs of the current multi-regression statistical models are not calibrated for the Pacific Northwest and a new or recalibrated model must be developed.

The development of a prediction model of debris flows initiated from burn areas will include inputs of the models currently in use; however, the addition of spatial time scaling of hazards, calibration of local precipitation thresholds, and a mass-wasting simulator model would increase the usability by local governments and emergency managers to reduce and/or better respond to debris flow impacts to communities and infrastructure. Finally, the addition of a real-time debris flow reporting system would allow for rapid warnings to threatened communities and travelers on nearby highways.

La Nina Events Lead to More Robust Flow Distributions for Small Streams in Thurston County: A Statistical Study of Water Years 2008, 2009, 2010, 2011 and 2012

Nadine Romero, Water Resources - Thurston County

Mark Biever, Water Resources - Thurston County

Howard Hama, Water Resources - Thurston County

During the last 5 water years annual stream discharge for four watersheds has nearly tripled due to a return to normal rainfall conditions of 54 inches in Water Years 2010 and 2011. A persistent La Nina in 2010 through spring of 2012 has allowed ground water systems to recharge in Thurston County.

Statistics and frequency analyses were performed on the computed stream flow record for four gaging stations including: Percival, Woodland and Woodard Creeks and Black River. We find that the broad distribution of rainfall during this past La Nina has created robust and varied stream flow distributions including higher summer low flows and baseflows. Lake levels and ground water systems followed suite and reached their highest levels in decades requiring some land use restrictions in urban-rural areas. In addition, major rivers such as the Deschutes, Nisqually and Chehalis were above the 95% percentile through mid-August of 2012 for the 38 to 82-year records.

While extreme event patterns have not developed in the last 3 years (where daily precipitation is above 2 inches or monthly totals above 10 inches) we find that Neutral and El Nino conditions create daily events greater than 3 to 4 inches which are associated with 'AR' events (meteorology term for 'atmospheric rivers'). We also find that these extreme daily events (top 20 events out of a 19,000 daily event record) trend upward (R-correlation =0.980) in the last two decades for the Olympia area.

This presentation shares our quantitative program findings from the last decade on stream flow behavior and hydrologic response to rainfall patterns in an 800 square mile region known as Thurston County.

The Function of Localized Wetlands in Recharge of the Water Table in an Arid Environment

Mavis Kent, Plateau Geoscience Group LLC

Julie Anna Johnston, Plateau Geoscience Group LLC

Michelle Sanders, Plateau Geoscience Group LLC

Rone Brewer, Sound Ecological Endeavors

Wetlands in arid environments play an important role in recharge of the water table because they typically serve as a focal point for accumulation of surface water from various sources and a pathway for infiltration to the subsurface. Subsurface infiltration and flow reduces water losses through evapotranspiration, and may be critical to local and regional drinking water and to maintenance of downgradient wetlands and stream flow. The processes and magnitude of wetland water accumulation, retention, infiltration to the subsurface, and release back to the surface are dependent on water availability, local geology, soil permeability, depth to the water table, and climate. Also, wetlands in arid environments provide habitat and most importantly, water, that is crucial to the associated ecosystem.

The wetlands for this study have been delineated as Category III palustrine emergent and scrub/shrub, as part of the remedial investigation for the former Goldendale Aluminum Smelter in Washington, located along the Columbia River near the John Day Dam. The wetlands are situated on a geographical bench underlain by flows of Columbia River Basalt and capped by younger glacial-fluvial and possibly eolian sediments. We hypothesize that these wetlands likely provide shallow groundwater recharge, flood flow attenuation, and surface water recharge functions, in addition to their provision of wildlife habitat. Field investigations for this study consist of mapping soil types and geology, mapping and characterizing the wetlands, a subsurface geophysical survey, and measuring horizontal and vertical shallow groundwater gradients near the wetlands. Field data is used to calculate the water balance for the wetlands and assess the mechanism and rate of recharge to the water table. The results of this study will contribute to the understanding of wetland physical parameters that influence the water table at this locality and in arid environments in general.

Establishing Site-Specific Background and Baseline Conditions for Abandoned Mined Lands on a Watershed Scale

Michelle Havey, Hart Crowser, Inc.

Jason Shira, Washington Department of Ecology

Mary Monahan, Washington Department of Ecology

Mike Bailey, Hart Crowser, Inc.

This poster describes the work completed and planned in the Monte Cristo Mining Area (MCMA), a predominantly gold mining district in the Cascade Mountains, northeast of Seattle, Washington. The area was mined extensively in the 1890s and smaller scale mining continued into the twentieth century. Today there are more than 50 reported abandoned mines and prospects scattered across three watersheds (Weden Creek, Glacier Creek, and Seventysix Gulch) that together make up the headwaters of the South Fork Sauk River (SFSR).

Abandoned mine lands (AMLS) typically contain by-products of mining and milling operations that present potential risks to human health and ecological receptors. In the case of metal mine sites, risk assessment is often complicated by the presence of naturally elevated background concentrations and uncertainty of metal bioavailability in soils, sediment and surface water. Since it is not practical to cleanup to below background levels or when a contaminant of concern is not bioavailable, different approaches have been formulated to address these issues.

The MCMA is rugged, remote and currently has no road access. This dramatically increases the potential cleanup costs. Washington's Model Toxics Control Act (MTCA) regulations prescribe a means of rigorously calculating natural background concentrations. The U.S. EPA has developed technical guidance (rapid bioassessment protocols [RBPs]) for assessing aquatic biota to inform water quality monitoring and management. Also, Washington has recently developed sediment management guidance based on bioassays. Collectively these protocols serve as a cost-effective approach to identify cleanup requirements using biological indicators.

Field Trips & Workshops

PLEASE NOTE: the Washington Hydrogeology Symposium holds no responsibility or liability for those participating in Symposium field trips. All field trip registrants must complete and sign a liability waiver form. The liability waiver form is available online and will be available at the start of the field trip.

Prolific Aquifers in South Puget Sound

Monday, April 22, 2013 8:00 AM to 4:30 PM

Thurston County has two prolific aquifers: one supplying water to the former Olympia Brewery, and now the cities of Olympia, Tumwater, and Lacey; and the McAllister Gravels on the upper Nisqually delta, source of the city of Olympia water supply at McAllister Springs and the city's new well field. Recent work by the Washington Department of Natural Resources and Golder Associates has done much to clarify the hydrogeologic and stratigraphic framework of these aquifer systems. This trip will focus on geologic evidence on the ground as well as subsurface data from drilling programs. Transportation will be by van.

Leaders and Contacts: Tim Walsh, Washington Department of Natural Resources, Division of Geology and Earth Resources, tim.walsh@dnr.wa.gov, (360) 902-1432; Chris Pitre, Golder Associates Inc., chris_pitre@golder.com, (206) 316-5646.

On the Trail of the Ice Age Floods (Eastern Washington)

Friday, April 26, 2013 8:00 AM to Sunday, April 28, 2013 6:00 PM

Ice Age cataclysms violently transformed the Pacific Northwest thousands of years ago, leaving behind scores of flood features, many found nowhere else on Earth. Join us on a three-day tour of an astonishing landscape scoured by outburst floods, including those from Glacial Lake Missoula, as recently as 14,000 years ago.

PNNL geologists Bruce Bjornstad, author of the "On the Trail of the Ice Age Floods" series of geologic guidebooks, and George Last will be your guides to some of the most dramatic and spectacular evidence for floods within the extraordinary Channeled Scabland and Lake Lewis regions of eastern Washington including:

- Frenchman and Potholes Coulees
- West Bar Giant Current Ripples
- Grand Coulee including Dry Falls and Steamboat Rock
- Odessa Craters
- Crab Creek Coulee
- Frenchman Hills Erratics
- Drumheller and Othello Channels
- Wallula Gap
- Coyote Canyon Mammoth Dig
- Cold Creek and Priest Rapids Flood Bars
- Sentinel Gap

Smithsonian Magazine recognized this area as one of "The 10 Most Spectacular Geologic Sites" in the continental United States and in 2009 Congress followed suit to establish the first-of-its-kind Ice Age Floods National Geologic Trail. Transportation will be via mid-sized van, stopping at least twice each day for short hikes and excursions into special places such as Frenchman Coulee, Lenore Caves, Odessa Craters, Drumheller Channels, and the Coyote Canyon mammoth dig. As time permits stops will be made to taste the unique terrior of the floods' region at some of the many fine wineries located along route.

Leaders and Contacts: Bruce Bjornstad , PNNL, bruce.bjornstad@pnnl.gov and George Last, PNNL, george.last@pnnl.gov

Well Drilling Workshop

Thursday, April 25, 2013, 8:00 AM - 4:00 PM | *Location: presentation and drilling demonstration at the USGS Warehouse, 8914 Lakeview Ave SW, Lakewood, Wa 98499*

Presentations will briefly discuss the state-specific laws governing the drilling of geotechnical holes, water wells and monitoring wells, including notices and reporting requirements for drillers, geologists, and engineers. The workshop will also include an off-site drilling demonstration. This workshop is authorized to provide 2.0 hours of continuing education units (CEUs) for Washington rules and 2.0 hours of continuing education credits (CECs) for Oregon rules.

Workshop Presenters: Bill Lum, WA Dept. of Ecology, blum461@ecy.wa.gov, (360) 407-6648
Contact: Angie Goodwin, angie.goodwin@hartcrowser.com, (206)324-9530

Bioremediation Fundamentals and Applications

Thursday, April 25, 2013, 8:00 AM - 12:00 PM | *Location: Venice 3*

This 4-hour classroom session will provide essential understanding of the complex processes involved in the bioremediation of environmental contamination. Major topics covered include microbial respiration, remedy design and implementation, on-going performance assessment, regulatory concerns, and cost. Discussion will primarily focus on the in situ and ex situ remediation of petroleum hydrocarbons, chlorinated solvents, and heavy metals. This Workshop offers the hand-on opportunity to practice designing bioremediation approaches for hypothetical case studies, as well as practice reviewing and assessing performance during real-world application examples.

Students will leave with a working knowledge of how to design, implement, and assess performance for both oxidative and reductive bioremediation approaches. Students will also receive a CD containing presentation slides and useful guidance documents.

This course is designed to complement the Chemical and Thermal Remediation Fundamentals and Applications short course.

Workshop Leader and Contact: Troy Fowler, troy.fowler@hartcrowser.com

Chemical and Thermal Remediation Fundamentals and Applications

Thursday, April 25, 2013, 1:00 - 5:00 PM | *Location: Venice 3*

This 4-hour classroom session will provide students with broad understanding of in situ thermal and chemical remediation of environmental contamination. Students will develop an understanding of the processes involved with these remediation techniques, as well as how to couple these approaches with other technologies for plume-wide remediation. Application examples will be presented outlining contaminants of concern, design considerations, and treatment outcomes from actual sites.

Continued on next page

Students will leave with a working knowledge of how to design, implement, and estimate costs associated with these remedial approaches. Each student will also receive a CD containing presentation slides and useful guidance documents

This course is designed to complement topics presented in the Bioremediation Fundamentals and Applications short course.

Workshop Leaders and Contacts: Greg Beyke, gbeyke@thermalrs.com; Stacey Telesz, stacey.telesz@fmc.com; Jim Mueller, jim.mueller@fmc.com; Troy Fowler, troy.fowler@hartcrowser.com

MLU: A new way to analyze aquifer tests in multi-layered systems – a hands-on workshop

Thursday, April 25, 2013, 8:00 AM – 12:00 PM | *Location: Venice 4*

MLU for Windows is a modern groundwater modeling tool to compute drawdowns, analyze aquifer test data, and design well fields. Unlike other aquifer test analysis software supporting a wide variety of different solution types for one and sometimes two aquifers, MLU is based on a single analytical solution technique for well flow that handles:

Layered aquifer systems, that is, multi-aquifer systems (aquifers and aquitards) and single layered (stratified) aquifers

- Confined, leaky, and delayed yield aquifer conditions
- Effects of aquifer and aquitard storativities
- Up to 300 pumping or injection wells
- Up to 50 pumping periods for each well
- Up to 100 observation wells with 500 measured drawdowns in each well
- Wellbore storage and skin effect for each pumping well and observation well
- Partial penetration

MLU can be used to analyze and simulate all sorts of tests, including variable discharge tests, recovery tests, step-drawdown tests, complex tests in multi-well well fields and slug tests. It also handles partially penetrating and large diameter wells, bounded aquifers, and double-porosity systems. In addition, MLU can also be used in forward prediction mode to:

Compute drawdowns at various times and locations in a well field—it is very easy to use multilayer aquifer simulator using known or assumed aquifer parameters

Assist in aquifer test design by “pre-simulating” tests to help determine which parameters can be measured given a fixed array of monitoring and pumping wells

This four-hour workshop will start with a review of fundamental aquifer test analysis concepts before moving on to an introduction to MLU including a step-by-step tour of the software and a guided example problem. Participants will then work on a series of example problems to increase familiarity with the mechanics of the software and it capabilities. Printed materials and electronic copies of the software and example datasets will be provided.

Workshop Leader: Jeff Randall, jrandall.hydro@gmail.com. Dr. Jeff Randall was a Principal Hydrologist at CH2MHILL for over 34 years (recently retired). His projects ranged from hazardous and solid waste to water supply and resource evaluation. He co-authored the MLU Tutorial and recently co-authored a Software Spotlight review of MLU in the journal Ground Water.

Aquifer Characterization Tests and Pressure Transducer Data Collection

Thursday, April 25, 2013, 1:30 – 4:30 PM | *Location: Venice 4*

This workshop will cover groundwater hydrology fundamentals and is designed for groundwater specialists, environmental professionals, and drill operators. Learn how to streamline aquifer tests, reduce field time, and deliver reliable data. Due to technological advances, aquifer tests can be conducted with greater speed and accuracy and at a lower cost. This workshop will review slug tests, step-drawdown tests, and constant-rate pump tests; equipment requirements; test duration; and techniques to improve efficiency in the field. Participants will learn:

- Definitions and goals of aquifer tests
- Equipment needs
- Design and operation of testing procedures
- Test duration
- How data is used to calculate hydrologic parameters
- Techniques to improve efficiency in the field.

This presentation will cover new software developments that improve efficiency and allow users to capture pump and recovery data on the same log without reprogramming. Additionally, software advancements allow operators to change aquifer test protocols in real-time, which saves money and improves results. Users can export time-synchronized data from all pressure transducers involved in the aquifer tests to one data file.

Workshop Leader and Contact: Bill Mann, bmann@in-situ.com.

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