Ground and Surface Water Contributions to Chemical Mass Discharge: Field to Basin Scales

Richelle Allen-King, the 2003 Darcy lecturer is an associate professor at Washington State University, has a Ph.D. from the Department of Earth Sciences, University of Waterloo, and a bachelor's degree from the Department of Chemistry at the University of California, San Diego. She has served on committees for the National Research Council and presently serves as a member of the Council's Water Science and Technology Board. She also serves as an associate editor for the journals *Ground Water* and *Water Resources Research*. Dr. Allen-King's research focuses on the geochemical processes that control the fate and transport of contaminants in ground and surface waters. She will offer the lecture: "Ground and Surface Water Contributions to Chemical Mass Discharge: Considering the Problem at Field and Basin Scales." The 2003 Darcy Lecture Series will take Richelle's presentation to dozens of places all over the world.

Anatomy of a Sinking Chlorinated Solvent Plume

Dan Matthews[1] and Chip Goodhue[2]

At a chlorinated solvent spill site in southwestern Washington, several factors have led to the formation of a sinking trichloroethene (TCE) plume in the absence of an apparent dense non-aqueous phase liquid (DNAPL). This talk will summarize the evidence for a sinking plume, identify the hydrogeologic conditions at the site that cause downward plume migration, and discuss the implications a sinking plume has on site assessment and monitoring approaches, and on evaluation of remedial alternatives.

During a two year remedial investigation completed in the fall of 2002, a TCE plume approximately 2,200 feet long was identified. Water quality measurements indicate that the highest TCE concentrations occur near the water table in the suspected source area and occur at progressively greater depths north of this area. The chlorinated ethene plume appears to reach the bottom of the roughly 40 foot thick saturated interval within a horizontal distance of approximately 100 feet from the source area. Throughout most of the plume, TCE impacts are present only in the lower third of the saturated interval in the aquifer. DNAPL accumulations have been ruled out based on the lack of TCE detections in saturated soil samples from the base of the aquifer, the relatively low levels (sub-part per million) of dissolved phase contaminants, and the absence of DNAPL accumulations in site monitoring wells.

Ground water elevation measurements at the site indicate a consistent downward vertical gradient and northerly horizontal gradient at the site. Evaluation of ground water flow, contaminant transport modeling, and assessment of chlorinated ethene degradation activity were performed to assess the relative importance of these factors on formation of the apparent sinking chlorinated ethene plume. Of these factors, a strong downward vertical gradient driven by high precipitation recharge appears to be the primary factor in driving development of the sinking plume.

Site assessment techniques that facilitated identification and characterization of the sinking plume included multi-level depth discrete water sampling during auger drilling, and installation of monitoring wells clusters completed at two or more depth intervals. Evaluation of remedial alternatives for the site required assessment of performance and restoration time frames using a site hydrogeological model that addresses the vertically heterogeneous contaminant distribution.

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Uranium Mobility in Groundwater at the 300 Area of the Hanford Site

Jonathan W. Lindberg[1] and R. Jeffrey Serne[2]

Recent laboratory studies of uranium geochemistry have shown that the primary factors affecting uranium adsorption are carbonate concentration and pH. Uranium forms complexes with carbonate and is less adsorptive in a groundwater environment (higher carbonate concentrations) than in a river water environment (lower carbonate concentrations). Therefore, predicted K_d values under groundwater conditions (2 to 4 ml/g) are lower than in the zone of interaction near the Columbia River ($4<K_d<100$ ml/g), where river water and groundwater mix.

The new information provides insight on the attenuation of the uranium plume in the 300 Area of the Hanford Site and how the plume reacts to river stage fluctuations of the nearby Columbia River. The current hypothesis is that during waste disposal operations, uranium was adsorbed to sediment throughout the vadose zone and the aquifer in the immediate vicinity of the source, i.e., process waste disposal trenches. The waste fluids were relatively low in alkalinity because wastewater included significant quantities of river water. Uranium held on sediment from early dilute waste fluid disposal operations was subsequently desorbed by higher alkalinity groundwater when waste disposal operations ceased in 1995. The decreased K_d caused a sudden increase in uranium concentrations, as revealed in groundwater samples. After 1997, groundwater concentrations of uranium decreased with time in wells downgradient of the process trenches, as the remaining uranium in the aquifer desorbed.

Uranium concentration in the aquifer is also affected by river stage fluctuations. At high river stages, there is a reversed gradient of the water table along the riverbank, river water enters the aquifer, and the water table rises. The distance from the river that the river water mixes with groundwater depends on the magnitude and duration of the increased river stage. Uranium trend plots for wells downgradient of the process trenches show an annual cycle, which is associated with high river stages in late spring and early summer, and low-to-average river stages for the remainder of the year.

Depending on a given well's distance inland and the duration of the high river stage, the rising water table can result in either a decrease or increase in uranium concentration. There is a decrease along a zone near the river where groundwater-river water mixing occurs, thus lowering the carbonate level and favoring adsorption. An increase in uranium concentration occurs farther inland as full-strength groundwater with higher carbonate levels causes desorption of uranium in the lower vadose zone.

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Investigation of Contaminant Fate and Transport Beneath Leaked Hanford High-Level Waste Tank

Mark D. Freshley[1]

The U.S. Department of Energy (DOE) established the Groundwater/Vadose Zone Integration Project (Integration Project) in late 1997 to provide an innovative, new approach at DOE's Hanford Site for protecting the Columbia River. The Integration Project, now the Groundwater Protection Program, uses a roadmap to identify science and technology needs and to define activities to fill the gaps. The roadmap is the primary guide for planning science and technology research needed to address subsurface problems at the Hanford Site and to develop scientific understanding, information, and models needed to support Site milestones. The scheduling/sequencing of these activities in the roadmap, in turn, are coordinated with site milestones and decision points so that required new knowledge and information is available in time to be influential. One of the areas of recent success is in contributions to characterization of vadose zone contamination from several leaked high-level waste tanks.

Work scope identified in the roadmap is addressed by focused site-specific investigations funded through the Groundwater Protection Program and other basic research programs within DOE. The project has addressed a number of key scientific issues associated with the inventory of soil wastes at Hanford: tank waste source terms, the chemical speciation of tank wastes, water and contaminant fluxes through the vadose zone, and geochemical behavior of cesium-137, chromium, strontium-90, and uranium. The Groundwater Protection Program and its predecessor, the Integration Project, has been one of several recent activities at the Hanford Site that has created important, positive cultural changes among those involved in Hanford Site cleanup.

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Hydrology and MTCA Investigation of a Commercial Low-level Radioactive Waste Site

Zelma Jackson[1] and Tina Heggen[2]

US Ecology, Inc. operates a 100 acre Commercial Low-Level Radioactive Waste (LLRW) disposal facility within the United States Department of Energy (USDOE) Hanford site in southeastern Washington. Bordered by the Columbia River upstream of the confluence of the Yakima and Snake Rivers, its unlined trenches store waste in approximately 45 feet of the vadose zone. The LLRW disposal facility was sited within the central plateau separation areas of the DOE's 200 East and 200 West. The facility began operating in 1965. It remains as one of two commercial shallow-land disposal facilities currently operating in the United States.

Pasco Basin late Cenozoic stratigraphic units of concern at the site are the Ringold Formation (fluvial and lacustrine sediments), Hanford Formation (glaciofluvial sediments) and the Plio-Pleistocene (eolian sands and paleosols). The Hanford Formation serves as the host material for the disposal trenches. The water table is positioned in the Ringold Formation with groundwater moving easterly across the plateau to the Columbia River. During the Pleistocene, the Pasco Basin was repeatedly flooded from the fast runoff of water in the channel scabland to the east and northeast which is thought to contribute surface loading of sediments. Clastic dikes are a major feature of the dispositional environment of the basin and may serve as a preferential pathway for transport of waste constituents through the vadose zone.

In 1998, a site investigation looked at possible releases below the Chemical Trench and Trench five. Angle borings penetrated to the estimated midline of the trenches. At each location, soil gas monitoring wells and geophysical wells were constructed, and seven onsite groundwater monitoring wells were sampled. High concentrations of volatile organic compounds and halogenated hydrocarbons were detected in the soil gas beneath the trenches. Trichloroethene and chloroform have reached ground water. Transport of non-radiological chemicals through the vadose zone can be inferred as predominantly in the gas and dense nonaqueous liquid phases.

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Streamflow Variability, Water Use Impacts and Fish Habitat Requirements, Lower Skagit River Watershed

John Koreny[1], Charles Lindsay[1], Joanne Greenberg[2], Karen Welch[2], Kathi Peacock[3] and Norm Crawford[4]

A study was completed to evaluate the potential streamflow depletion from water use in the Samish River watershed, a 120 mile^2 sub-basin within the lower Skagit River system. The two major streams within the sub-basin, Friday Creek and the Samish River, have been closed to further appropriation due to concerns that insufficient streamflow is available for fish habitat. The natural climatic variability in streamflow and streamflow depletion were compared to the streamflow targets for fish species as determined by instream flow incremental methodology (IFIM). The historic streamflow variability for the watershed was determined using a continuous runoff-routing simulation model (HFAM) calibrated to 30 years of streamflow gage records. Field surveys were completed to determine domestic, irrigation, municipal and industrial uses of surface water and ground water. The calibrated HFAM model was used in combination with a calibrated ground water flow model (MODFLOW) to estimate the variation in streamflow recurrence associated with current and future development water use scenario. The mainstem Samish River depletion for current water use and land use ranged up to a maximum of 13 percent with the largest depletion occurring during August. Full development of the basin to the extent allowed by current zoning and water rights entitlement is estimated to result in a maximum of 31 to 36 percent depletion. Optimal streamflow targets established from IFIM results were all above the 50 and 80 percent recurrence for natural streamflow. The hydrologic simulations and IFIM studies show that the variation between natural streamflow and potential streamflow depletion from water use is much lower than the variation between the natural streamflow and optimal streamflow targets for fish species. The results suggest that maintaining natural streamflow is probably the most realistic long-term management goal for the watershed rather than attempting to meet fish habitat streamflow targets. The study shows the importance of incorporating detailed analysis of natural climatic streamflow variability into the IFIM process.

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Long-Term Ground-water Hydrograph Analysis for the Palouse Basin Aquifer

Farida Leek[1], Joan Q. Wu[2], and C. Kent Keller[3]

The Pullman-Moscow communities in southeastern Washington and northern Idaho depend entirely on ground water from two basalt aquifers for their water resources. These two aquifers are the shallower Wanapum and the deeper Grande Ronde aquifers which are part of the Palouse Basin Aquifer (PBA) system. Presently, the Grande Ronde aquifer is producing more than 90% of the total water supply in this area. The water levels in this aquifer, however, have been declining at a rate of about one foot per year for decades. An intriguing question motivating ground-water studies in this region is therefore whether the ongoing water-level declines in the deeper aquifer reflect ground-water "mining" or, alternatively, a transient response to growth-related increases in pumpage.

The main purposes of this study are: (1) to archive the long-term hydrogeologic data pertaining to PBA in a GIS database for easy data accessing, processing, and updating; and (2) to perform analyses of the spatially distributed, long-term hydrographic data for PBA by (i) examining ground-water level time series for evidence of pre-development conditions and (ii) performing statistical analysis of hydrographic, precipitation, and pumpage data to determine their interrelationships. Preliminary analysis of long-term climate data shows that, for both Moscow and Pullman, average annual precipitation displays no evident trend, excluding the possibility that decreasing precipitation has caused the decline of ground-water level. In addition, the pattern of seasonal water-level fluctuations in each aquifer do not notably correspond to precipitation in the basins. Hence, the most significant factor causing the continuous decline of ground-water levels would appear to be excessive pumpage or overdrafting.

This study focuses on developing a comprehensive GIS hydrogeologic database and thus a foundation for future regional ground-water modeling, monitoring, and management planning efforts. The results and findings from this study will enhance our understanding of the PBA system and will provide key information in managing the ground-water resources in the Pullman-Moscow area.

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Methods to Estimate Unmetered Ground-Water Withdrawals in the Yakima River Basin, Washington

Marcella A. Ripich

Increases in the demand for water for agricultural, industrial, municipal, fisheries and recreational uses in the Yakima River Basin, Washington, will most likely be met through additional ground-water withdrawals or changes in current water allocation and use. The U.S. Geological Survey, in cooperation with the U.S. Bureau of Reclamation, the Yakama Nation, and the Washington State Department of Ecology, is conducting a study to estimate current and historical ground-water withdrawals, how withdrawals affect the ground-water and surface-water systems, and the potential effects of increased withdrawals on streamflow and the ground-water system.

Electrical power-consumption data were used to estimate agricultural ground-water withdrawals in the Yakima River Basin. A power-consumption coefficient (PCC), which represents the amount of energy consumed, in kilowatt-hours, per acre-foot of water pumped, was calculated for each well according to the equation

$$PCC = P \times 5{,}433 / Q \,,$$

where

P = power demand of a running pump, in kilowatts;
5,433 = conversion factor (gallon-hours per acre-feet minutes); and
Q = pumping rate of withdrawal, in gallons per minute.

The pumping rate and the corresponding power demand were measured simultaneously. Assuming a linear relationship between these two quantities, the total volume of water pumped can be calculated for any period in which the total power consumption is known. The pumping rate was measured using a portable ultrasonic flow meter, and the power demand was recorded from the electrical-energy meter for each pump. The well owner provided the total power consumed during an irrigation season.

Previously, ground-water withdrawals in the basin were estimated from water right permits because pumping volumes are rarely recorded. Differences between the actual and permitted ground-water withdrawals however, are likely large. As an alternative to continuous inline-flow metering, the use of PCC values provides a cost-effective method to quantify ground-water withdrawals.

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Interpretive Hydrogeology of the Middle Wind River Basin, Skamania County, Washington

Said Amali[1], Steve D. Misner[1], Kevin A. Lindsey[2], Charly Boyd[3], Habib Matin[4], and Ronan Igloria[5]

The middle portion of the Wind River basin in Skamania County, Washington is unincorporated county land bordering the Gifford Pinchot National Forest. The Wind River and its main tributaries, Trout Creek and Panther Creek, flow through the area. These streams provide important habitat for steelhead which have been declared as threatened in the Wind River basin by the NOAA Fisheries. The current land use plan for the area predominantly includes clusters of rural residential development.

It is expected that the bulk of the future residential development will rely on private wells for water supply. These wells will likely be exempt from water right permitting due to their intended use and yield. Changes in water availability and water quality associated with current and future development are of primary concern in the area and will play a critical role in future decisions regarding land use, population density, natural resources, and fish and wildlife management.

The authors are working with County planning agencies to interpret the hydrology of the middle Win River basin to provide planning information and tools. In this ongoing project, a significant amount of existing information, data, and historical analyses results have been reviewed. This information includes characteristics of area geology; groundwater and surface water occurrence, flow, and quality; and land use. Additionally, limited water level and water quality data will collected during this project. The data will form an initial baseline of area characteristics for the County.

The early findings of this project indicate that separate hydrogeologic features exist within the basin. Accurately defining these features is important to our understanding of hydraulic continuity between streams and aquifers and their resultant vulnerability to water quality degradation, as associated with land use activities. The project findings also explain the general patterns of groundwater recharge and discharge in the area. A main goal of this project is to illustrate the magnitude of projected groundwater withdrawal relative to the volumes of water that pass through the streams as well as in the area aquifers.

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The Challenges of Water Rights Purchases and Transfers Panel

Scott Bender, Bender Consulting,, Moderator

The majority of water right activity in Washington State is currently in water right purchases and transfers. In-stream flow and biological restrictions has almost eliminated new water right permitting except for limited areas and circumstances. This panel discussion will present a brief understanding of the state of the practice in water law in Washington State, and will discuss the current technical, regulatory, and process requirements of purchases and transfers. The panel will allow policy makers and practitioners an opportunity to express their opinions on the state of the practice and what the future may hold in water rights within Washington State.

Panel members:

Karen Allston – The Center for Environmental Law & Policy
Adam Gravley – Preston Gates Ellis, LLP
Steve Hirschey – Washington State Department of Ecology
Clay Landry – WestWater Research, LLC
Yolanka Wulff – Washington Water Trust

The Contemporary Hydrogeologist Panel

Llyn Doremus, Nooksack Tribe, Modernator

At times, the role of a hydrogeologist is broadened beyond simply conducting good scientific studies and providing technical expertise (as if this were simple) to one of applying this expertise to the expanded spheres in which technical information is used. To utilize our expertise and understandings outside technical forums allows the introduction of a perspective to the information that is not constrained by strictly scientific method. However, the value of our experience and information to the society, which has bestowed it upon us, is in ensuring the information is put to the best use. This disconnect between the need for the information outside the scientific community, and the constraint that objective science imposes on the use of scientific information, limits open discussion on this conflict. A dialogue on how best to use the vast information resources that are retained in the hydrogeologic sciences, and the considerations in making use of information outside the context of scientific inquiry, will be taken up by this panel.

Panel members have each adopted an expanded "technical" role in forums outside the technical environment, and will share the specifics of the specific situation and the factors considered in their decision to step beyond the traditional hydrogeologists' role.

Panel members

Nadene Romero – Groundwater Science Services
John Vacarro – USGS
Ginny Stern – Washington Dept of Health
Mike Krautkramer – Robinson and Noble

Heterogeneous Physical and Chemical Aquifer Properties and the Role of Lithofacies in Contaminant Transport

D.P. Divine[1], R.M. Allen-King[2], D.R. Gaylord[3], and J.R. Alldredge[4]

The spatial distributions of permeability (k) and sorption (represented by the distribution coefficient, K_d) control contaminant transport in groundwater, making reliable and inexpensive estimation of their values necessary for accurate prediction of dissolved plume movement. In this work, we test the hypothesis that k and PCE K_d are correlated to sedimentary facies with the goal to better understand the spatial distributions of and correlation between the two properties. Samples were collected from eleven 1.5 m long cores spaced one meter apart parallel to groundwater flow from the well-studied Borden ground water research site. The scale of aquifer heterogeneity examined in this study is determined by the spacing of the second order bounding surfaces. These are typically weakly erosional and separate lithofacies.

The air permeability values (855 samples) fit a log-normal distribution (mean of –14.9 [(ln(cm^2)]) and standard deviation 0.61 [ln(cm^2)]. The K_d observations (374 samples) match no commonly used distribution function, have a mean of –1.05 [ln(ml/g)] and standard deviation 0.61 [ln(ml/g)]. Cumulative distribution functions of k and K_d by facies (analyzed via Kolmogorov-Smirnov tests) indicate that both permeability and sorption vary with lithofacies. Thus, lithofacies are significant in explaining the spatial distributions of each of the properties. Additionally, k and K_d distributions may be similar to each other in one facies, but dissimilar in another facies. This lack of consistent symmetry indicates that the two parameters are not simply correlated to each other. Study of the aquifer properties associated with lithofacies can shed light on the underlying sedimentary properties that control the distribution of aquifer properties. Improved contaminant transport predictions that arise from such understanding have the potential to enhance remediation designs.

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Occurrence and Distribution of Trace Elements in Lake Roosevelt Beach and Bed Sediments, and Air

Michael S. Majewski[1] and Sue C. Kahle[2]

Lake Roosevelt is a large reservoir on the Upper Columbia River in north-central Washington. It extends for 217 kilometers from the Grand Coulee Dam to within 24 kilometers of the Canadian border. The bed sediments are heavily contaminated with trace metals from active and abandoned mining operations, but the major source of this contamination is the discharges of slag material from a smelter in Canada. High concentrations of trace elements have also been found in the water, fish, and benthic invertebrate communities of Lake Roosevelt.

During various operational modes of the Grand Coulee Dam the reservoir pool depth can be drawn down more than 20 meters exposing many thousands of hectares of contaminated beach and bed sediments for several months during the spring and early summer and, to a lesser extent, during the fall. Once dry, the bed sediment materials have a high potential for entrainment into the lower atmosphere by wind gusts. Airborne dust particles can be carried downwind various distances, depending on their size and the magnitude and duration of the prevailing winds throughout the Lake Roosevelt airshed, exposing humans, both dermally and from inhalation, to potentially high levels of trace metals.

A study was conducted to (1) determine the occurrence, concentrations, and distribution of trace elements in the fine-grained fraction of exposed beach, bed, and bank sediments along Lake Roosevelt, and (2) determine the occurrence, concentrations, distribution, and seasonal variability of select airborne trace elements of mean particle diameter of 10 microns or less at three locations along Lake Roosevelt.

The trace element concentrations in the surficial bed sediments varied, but the major slag components, arsenic, cadmium, copper, lead, and zinc, showed generally pronounced concentration gradients from the International Border to Grand Coulee Dam. Concentrations of copper, lead, and zinc exceeded the Canadian severe-effect level guidelines for trace metals at several sites in the upper reach of the reservoir. The major components of slag showed a concentration trend with Zn>Pb>Cu>As>Cd.

The air sample results showed the same trace elements present at nanogram per square meter concentrations. The major slag components, however, showed a different concentration trend with Cu>Zn>Pb>As>Cd.

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Natural Hydrogeochemical Controls on Groundwater in the Union River Watershed, Kitsap County, Washington

S. D. Warner[1], M. Verwiel[2], T. Delfino[1], J. Tull[3], and J. Altman[4]

We studied the hydrogeologic and geochemical conditions underlying a site along the east bank of the Union River in south central Kitsap County, Washington. The inorganic composition of shallow groundwater is strongly affected by the transition of regional groundwater flow between recharge and discharge areas. The transition in the subsurface hydrology manifests itself as a change in vertical hydraulic gradient values from downward in the east, to neutral in the central portion of the area, to upwards near the Union River. The hydrostratigraphic system, including the presence of the Vashon Till and anisotropy, also contributes to the overall flow conditions.

The transition between recharge and discharge areas strongly effects the distribution and mobility of certain inorganic components of the groundwater, including iron, manganese, and arsenic. Shallow groundwater in the eastern recharge is mildly to strongly oxidizing due to the percolation of aerobic rainwater. The depletion of oxygen by microorganisms begins as the infiltrating water percolates through native organic matter in the shallow soil and continues until oxygen is nearly completely consumed. Microorganisms capable of utilizing other inorganic electron acceptors, including ferric iron then metabolize organic matter in the groundwater according to the representative net reaction:

$$(CH_2O)_x + 4xFeOOH + xH_2O \rightarrow 4xFe^{+2} + xCO_2 + 8xOH^- .$$

Oxygen essentially is depleted by the time the groundwater reaches the central portion of the site. From the central portion westward, highly soluble ferrous iron is found at high concentrations in groundwater, which is consistent with the iron stability diagrams (i.e., Pourbaix diagrams) developed for groundwater samples collected in the area. Where the groundwater discharges to the surface near the Union River and its wetlands, strongly reducing conditions are present due to the decay of natural organic matter. These conditions cause further increases in the concentrations of dissolved iron and related constituents. As this groundwater contacts atmospheric oxygen in the discharge area, amorphous iron hydroxide precipitates and forms thick deposits. Natural fluctuations in water levels in the wetland environment cause re-reduction of ferric hydroxides producing high concentrations of soluble inorganic constituents. This reduction-oxidation cycle is a natural condition as evidenced by the wetland areas within the Union River system, which indicate that these conditions commonly occur and contribute to its character. The strongly reducing conditions toward the Union River also promote natural degradation of some anthropogenic organic compounds in groundwater beneath areas of the watershed.

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Age of Ground Water in the Puget Sound Area

Steve Cox

Estimates of ground-water residence time for 33 ground-water samples from wells tapping a glacial aquifer system located near Submarine Base Bangor on the Kitsap Peninsula ranged from less than 50 to 4,600 years, based on the environmental tracers tritium, chlorofluorocarbon (CFCs), and carbon-14 and on detailed chemical analyses. Analysis of the spatial variations observed in the water-quality data was used to develop a conceptual model of the chemical evolution of ground water near the Base. The conceptual model was incorporated into geochemical models used to estimate ground-water residence time based on the concentration of carbon-14 in dissolved inorganic carbon in ground water. Similar patterns of spatial variation in water quality in other ground-water systems in the Puget Sound Lowland may indicate analogous processes and similar residence times.

In the Bangor area, ground-water samples were obtained from two extensive aquifers and from permeable interbeds within the thick confining unit that separates them. All ground-water samples from the shallow aquifer, composed of Vashon advance outwash, contained tritium or CFCs, indicating that they were recharged within the last 50 years, and they were considered to be modern ground water. Ground-water samples that lacked tritium or CFCs were classified as pre-modern. Ground-water samples from the confining unit below the shallow aquifer were classified as both modern and pre-modern, and ground water from the aquifer beneath the confining unit was predominantly pre-modern. The occurrence of modern environmental tracers in several deep aquifer wells indicates the relatively rapid movement of ground water into deeper hydrogeologic units. Ground water with the largest residence times typically occurred near areas of regional ground-water discharge.

Oxidation of organic matter and mineral dissolution increased the concentrations of dissolved inorganic carbon and common ions in downgradient ground water. The most chemically evolved ground waters were not necessarily the ground waters with the largest residence times. In some instances where organic carbon was present within the aquifer, microbial methanogenesis substantially altered water quality and carbon-14 concentrations. In ground waters from the Bangor area and other Puget Sound Lowland locations, pre-modern ground water typically was more depleted in the heavier stable isotopes of water (^{18}O and ^{2}H) than was recently recharged ground water. The occurrence of more depleted stable isotopes in pre-modern ground waters may be related to the efflux of ground water from the confining unit, which may have been recharged during cooler climatic periods of Pleistocene glaciation.

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Glacier Mass Balance and Hydrology in the North Cascades

Edward G. Josberger[1] and William R. Bidlake[2]

The temperate glaciers of the North Cascades are both indicators of climate change and an integral part of the regional hydrologic cycle. To understand the response of glacier mass balance to fluctuations in atmospheric circulation, the U.S. Geological Survey (USGS) has measured the winter, summer, and net mass balances of South Cascade glacier, located in the northern part of the Cascade Range, for the past 44 years. This record, one of the longest such records in the world, shows a dramatic reduction of glacier extent and volume as the mass balance responds to short-term climate fluctuations. From 1959 to 1976, the average annual net balance was -0.15 mweq (meters of water equivalent), with positive and negative balance years. The two-decade period, 1976 to 1995, was one of rapid ice loss, averaging -0.90 mweq per year, with most years having negative mass balances. Recently, 1995 to present, the glacial recession has slowed to -0.28 mweq. This long-term trend correlates with the changes in the Pacific Decadal Oscillation, as it shifts from a cool phase into a warm phase and back into a cool phase. Short-term climate fluctuations, such as droughts and El Nino/La Nina events, as characterized by the Southern Oscillation Index, also correlate with the short-term variations observed in the mass balance record.

The contribution of glacial recession and melting of perennial snow fields to the annual discharge from glacierized basins in the North Cascades is an important factor in the regional hydrology. Interannually, glaciers store water during cool, wet periods and release water during warm, dry periods. Similarly, within the water year, glacier melting provides a significant contribution to base flows, long after the annual snow pack is gone. To estimate this effect, the USGS has developed a technique that combines the mass balance observations from the South Cascade Glacier with Landsat-7 satellite imagery and digital elevation models in a Geographic Information System (GIS) environment. First, application of a snow-and-ice classification scheme to the satellite imagery determines the extent of the perennial snow-fields and glaciers. In the GIS system, the snow-and-ice-covered area is combined with the digital elevation model and the basin boundary to yield the snow-and-ice-covered area as a function of altitude within the basin. Finally, integration of the vertically dependent balance curves from the field observations with the vertical distribution of snow and ice in the basin yields the melt contribution. Application of this technique to the North Fork of the Nooksack River Basin shows that snow and ice melting contributed approximately 5 percent of the total annual discharge for the drought year of 2001.

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Groundwater Management—Snohomish County's Story

Jalyn Cummings

Groundwater, often overlooked in watershed and land use planning, has been addressed in Snohomish County through a three-phased process of technical data collection, planning, and implementation. Essentially, groundwater management has been realized through the long term visions of a handful of grant writers in two departments. Grant writing began as early as 1989 in the Planning and Development Services Department to provide the framework for groundwater management in Snohomish County.

In 1991, Snohomish County entered into an agreement to provide funding for the technical data collection work for the study of groundwater resources in Snohomish County. A Phase I study by the USGS produced Water-Resource Investigations Report 96-4312, entitled The Ground-Water System and Ground-Water Quality in Western Snohomish County, Washington, and was the first step in a three-phase design to kick off groundwater work in the County. The project was funded largely by a Centennial Clean Water Fund grant.

With the technical analysis of the County's groundwater resources in hand, Phase II could begin for plan development. Once again, grant writing proceeded and in 1996 Snohomish County was awarded a second Centennial Clean Water Fund grant. Phase II monies produced the Snohomish County Ground Water Management Plan (GWMP), Geohydrology Memorandum, and consultant work associated with a groundwater advisory committee.

Fully armed with technical documentation and a certified groundwater management plan, the County set out for a third grant to pay for the implementation of several key recommendations from the GWMP. In August 2001, the third Centennial Clean Water Fund grant for Ground Water Management Plan implementation was awarded.

Just over a decade and roughly $1,300,866.00 later, Snohomish County now has a groundwater management program located in the Surface Water Management Division of Snohomish County Public Works. Accomplishments to date include the development of a web-based database to compile and centralize Snohomish County groundwater data, preparation of a sub-basin groundwater investigation addressing local issues, and the development and review of Snohomish County's Critical Areas Regulations, policies, and development standards as they effect groundwater.

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Impervious Surface Blocks Infiltration: Good Science or Urban Legend

Jeffrey A. Kirtland

Impervious surfaces have been observationally linked to a loss of groundwater recharge. After all, each of us has directly observed impervious surfaces blocking infiltration. Many watershed and groundwater management documents, publish over the last half-decade, directly link declining summer streamflow volumes to a loss of groundwater recharge following urbanization. In fact, Washington State's own Critical Aquifer Recharge Area Ordinance guidance document assumes a 1 to 1 relationship between the percentage of impervious coverage and the loss of groundwater recharge (Cook, 1998). It is hard to ignore the obvious role impervious surfaces play in disrupting the pre-development hydrologic regime, but can a loss of infiltration capacity be clearly linked to reduced groundwater recharge and by extension reduced streamflow?

Examination of water table elevation data from wells in King and Snohomish Counties complied over the last couple of decades can provide a partial answer. For example, data collected and analyzed for the Western Snohomish County Groundwater Investigation shows stable or rising water table elevations in eight of eleven groundwater systems, including the most heavily urbanized areas (Thomas et al., 1997). Detailed statistical analysis of water table elevations in both King and Snohomish Counties is unable to discriminate between inter-annual variation in rainfall and increases in impervious area.

Where does the above analysis lead? There is no doubt that streams are experiencing more lowflow days in developed basins than in undeveloped basins. Unfortunately, the definitive answer as to why streams are "drying up" is not easily found in the assumption that impervious surfaces blocks or impedes the rate of groundwater recharge. To date, studies have looked at the statistical link between development and streams but have not analyzed all components of the hydrologic cycle in detail. A more in-depth understanding of changes in evaporation rates, the loss of near surface storage, and changes in interflow pathways are necessary before the impervious surfaces can be linked directly to a loss of summer streamflow.

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Water Resources of the Ground-Water System in the Unconsolidated Deposits of the Colville River Watershed, Stevens County, Washington

Sue C. Kahle

A study of the water resources of the ground-water system in the unconsolidated deposits of the Colville River watershed provided the local watershed Planning Unit and the Stevens County Conservation District with an assessment of the hydrogeologic framework, preliminary determinations of how the shallow and deeper parts of the ground-water system interact with each other and the surface-water system, and descriptions of water-quantity characteristics including water-use estimates and estimated water budgets for the watershed. The 1,007-square-mile watershed, located in Stevens County in northeastern Washington, is closed to further surface-water appropriations. The information provided by this study will assist local watershed planners in assessing the status of water resources within the Colville River watershed (Water Resources Inventory Area 59) and determine if there is water available for further allocation.

The hydrogeologic framework consists of glacial deposits that overlie bedrock and exceed thicknesses of 700 feet in places. A map of the surficial geology was compiled and used with drillers' logs for more than 350 wells to construct 29 hydrogeologic sections. Seven hydrogeologic units were delineated: the Upper outwash aquifer, the Till confining unit, the Older outwash aquifer, the Colville Valley confining unit, the Lower aquifer, the Lower confining unit, and Bedrock. The study produced maps of the thickness of the Upper outwash aquifer and the Colville Valley confining unit, a description of surface- and ground-water interactions, and water-budget estimates.

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The Hydro-Potential (HP) Value: A Rock Classification Technique Used For Estimating Groundwater Seepage Into Rock Excavations

William C. B. Gates, Ph.D., P. E., C.H.G.

Estimating seepage potential for excavation sites in bedrock such as tunnels presents challenges to the design and dewatering engineers. In 1997 the author developed a technique for groundwater development in bedrock terrain referred to as the hydro-potential (HP) value. This technique may be adapted to estimating groundwater seepage assuming groundwater is present in the fractures. The hydro-potential (HP) value is a proven rock mass classification semi-quantitative technique employed to evaluate the potential for developing groundwater in bedrock terrain. It is the potential for a rock mass to hydraulically transmit groundwater. The method describes six fracture characteristics of the rock mass and assigns a numerical value from reference tables based on their fracture properties. The equation for the HP- value is as follows:

$$HP_{value} = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{(J_k)(J_{af})}\right)(J_w)$$

Where the fracture characteristics are as follows: rock quality designation (RQD), joint number (J_n), joint roughness (J_r), joint hydraulic conductivity (J_k), joint aperture factor (J_{af}), and joint water factor (J_w).

The investigation was conducted in various lithologic terrains throughout Washington and other western states. During the investigation HP-values were compared to the yields of 21 bedrock wells and 11 locations in the State of Washington including Rimrock Tunnel on SR12 and Tunnel #1 on SR20 that demonstrated groundwater seepage problems. Contrasting the HP-values to bedrock well yields and seepage discharge displayed a significant inverse exponential relationship with strong correlation coefficients (R) exceeding -0.92. The benefit of the HP-value provides a tool for the engineer to estimate groundwater seepage into tunnels, mines or other excavations in bedrock. Correlation curves generated from this investigation provide a useful tool to predict seepage potential based on measured HP-values. Rock masses that exhibit HP-values <3 are subject to potential seepage problems. Conversely, rock masses that exhibit HP-values >3 should exhibit little seepage problems.

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Natural Gas Storage in Basalt Aquifers of the Columbia Basin: Water Resource Considerations

Vernon G. Johnson[1], Charissa J. Chou[2], Stephen P. Reidel[3], and Frank A. Spane[4]

This paper is the second of a two-part presentation on the subject of natural gas storage in deep basalt aquifers in southeastern Washington State. Background information and hydrogeologic considerations are presented in Spane et al. (this symposium). A report dealing with issues and methods for exploring the feasibility of natural gas storage within basalt aquifers was recently published by Pacific Northwest National Laboratory (PNNL 13962[a])

Studies by the U.S. Department of Energy have provided a wide range of structural, hydrologic, and hydrochemical data relevant to gas storage in deep basalt aquifers. Two industry sponsored gas storage characterization studies were initiated in 1999 that included drilling two ~1,000 m deep boreholes near Patterson, Washington. This paper focuses on the hydrochemical characteristics of these deep basalt aquifers and related water use and disposal issues involved in developing a natural gas storage reservoir in the central Columbia Basin where deep basalt groundwater is an important water resource.

Basalt aquifers that are unsuitable for either domestic or agricultural use because of poor water quality (e.g., high fluoride, iron or sulfide) are good (potential) candidates for natural gas storage. However, disposal of any produced water from these aquifers for either hydrologic testing or pre-conditioning of a candidate gas storage reservoir is a potentially limiting factor. Likewise, intercommunication of the deeper, low quality water with overlying aquifers due to drilling related activities must be prevented. These and related issues will be addressed using data from Department of Energy sponsored studies of deep basalt aquifers in the Pasco Basin.

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[a]Reidel, S. P, V. G. Johnson, and F. A. Spane. 2002. Natural Gas Storage in Basalt Aquifers of the Columbia Basin, Pacific Northwest USA: a Guide to Site Characterization. PNNL-13962, Pacific Northwest National Laboratory, Richland, Washington.

Natural Gas Storage in Basalt Aquifers of the Columbia Basin: Hydrogeology Considerations

Frank A. Spane[1], and Vernon G. Johnson[2], Stephen P. Reidel[3]and Charissa Chou[4]

Natural gas is rapidly becoming an important source for energy generation within the Pacific Northwest (PNW). One of the biggest obstacles facing the increased use of natural gas east of the Cascade Range is the lack of adequate storage capacity. Natural gas storage within deep geologic formations is an attractive option that has been used extensively worldwide to meet the need for adequate storage. Currently, there are over 500 operating subsurface natural gas storage facilities within the U.S. These subsurface storage facilities are developed within depleted hydrocarbon reservoirs and mined salt formations, or utilize aquifer storage. Natural gas storage within deep, non-potable, aquifers of the Columbia River Basalt Group (CRBG) has been proposed to meet storage/supply needs within the region, provided certain conditions can be met. These conditions include favorable site/locations near existing gas transmission lines, adequate storage capacity at suitable depths, containment, and the ability to economically store and retrieve the gas. Of particular importance is the issue pertaining to containment or intercommunication between individual basalt aquifers.

The CRBG flood-basalt province covers 200,000 km^2 within the PNW, and at its deepest location, reaches a thickness of >4,000 meters. Interior sections within individual basalt flows (some approaching 100 meters in thickness) form relatively impermeable/caprock horizons, separating higher permeability interflow contact zones. The higher permeability, interflow contacts (i.e., composite brecciated basalt flow top and overlying basalt flow bottom) are candidate horizons for natural gas storage. The Rattlesnake Hills Gas Field in the central Columbia Basin that was exploited commercially during the early 1900s suggests that natural gas storage and containment is feasible within the Columbia River basalt. Technical investigations by the U.S. Department of Energy also have provided a wide-range of detailed geologic, hydrologic, and hydrochemical data relevant to natural gas storage in deep basalt aquifers. This paper focuses on the hydrogeologic considerations for developing a natural gas storage reservoir in deep basalt aquifers of the Columbia Basin. Information that addresses feasibility issues, and methods for selecting and characterizing suitable locations for exploring the feasibility of natural gas storage within basalt aquifers was recently published by Pacific Northwest National Laboratory (PNNL 13962[a]).

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[a] Reidel, S. P, V. G. Johnson, and F. A. Spane. 2002. Natural Gas Storage in Basalt Aquifers of the Columbia Basin, Pacific Northwest USA: a Guide to Site Characterization. PNNL-13962

Hydrogeological Characterization of Groundwater Flow in the Columbia River Basalt Group using an Integrated Tool Box: Stratigraphic Mapping, Pressure Derivative Pumping Test Analysis and Geophysical Logging

David Banton[1], Doug Geller[2]

The Portland Bureau of Water Works (Bureau) plans to develop a well field in the Bull Run watershed. The proposed well field would have a nominal capacity of 10 million gallons per day (mgd) and be situated immediately to the west of Bull Run Reservoir No. 2 and produce groundwater from a deep aquifer confined within the underlying Columbia Basalt River Group (CRBG). The deep aquifer would be used for additional backup (emergency) supply, peak season supply, and Aquifer Storage and Recovery (ASR).

Since 1998, the Bureau has drilled and tested five exploratory wells at the site. These include a 4 inch diameter cored observation well, an 8 inch diameter test well, a 16 inch diameter test production well and most recently, two additional 6 inch diameter pilot wells. This work has identified the principal water – bearing units as interflow zones within the Ortley and Winter Water units of the Grande Ronde Basalt. Additional features of the system include: high-pressure flowing artesian conditions (up to 85 pounds per square inch shut-in pressure) and varying well production (flow rates from less than 100 gpm to as much as 2000 gpm). Four of the five wells drilled have moderate to high yields.

To better understand the small and large scale features of the basalt aquifer, an integrated approach has been applied in order to develop and build upon a conceptual hydrogeologic model. The main elements of this approach are: stratigraphic mapping, geophysical surveys, and well test analysis using pressure derivatives and composite analytical models. Stratigraphic and structural mapping positively identified CRBG units based on mapping and borehole sample visual and geochemical characterization. These data were supplemented with surface and borehole geophysical surveys, which allowed for further refinement in the structural features most notably faults and folding. Well test analysis focused on evaluating near-well and far-field aquifer properties, including transmissivity (permeability) distribution, distance to aquifer property changes, aquifer extent and boundaries, and associated effects of well extraction on aquifer pressure (depletion).

The analysis indicated that the core-hole and 16 inch well penetrate a laterally extensive, high transmissivity (40,000 gpd/ft to 170,000 gpd/ft), relatively high storativity (3E-04) confined aquifer that is bounded by multiple low permeability (‘no flow’) boundaries at significant distance from the proposed well field site. Groundwater flow within the bounded region conforms to the Theis assumptions (i.e. infinitely-acting radial flow) and occurs both within and between the individual interflow zones. The analysis also showed that the transmissivity of the aquifer increases in areas to the north and east of the site and that the low yield from the 8 inch well most likely reflects either localized stratigraphic or structural controls – or possibly drilling related permeability reduction in the immediate vicinity of that well.

A controlled 17-day artesian flow test recently completed on one of the two new pilot wells included monitoring drawdown and recovery response in the other four deep basalt wells. These test data confirmed the regional extent of the aquifer, aquifer properties and their distribution , enabled refined estimates to be made of the nature of distant aquifer boundaries, and the associated depletion effects.

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A Total Maximum Daily Load (TMDL) Study of the Quality of the Groundwater Discharge to Moses Lake, Washington

Charles F. Pitz

Moses Lake, located in central Washington, has exhibited eutrophic or hypereutrophic conditions over the past several decades. The lake was included on the 1996 federal Clean Water Act 303(d) list as an impaired waterbody. Phosphorus has been identified as the limiting nutrient for the lake. Based on characteristic uses of the lake, an in-lake total phosphorus concentration target of 0.050 mg/L has been proposed to manage water quality concerns. In order to develop an allocation strategy for phosphorus loading to the lake, a comprehensive Total Maximum Daily Load (TMDL) study was conducted by the Washington State Department of Ecology Environmental Assessment Program during 2001.

In support of the TMDL study, the role of groundwater input in the lake's water quality was investigated. To better characterize the nutrient content of groundwater directly discharging to the lake, and to evaluate possible nutrient sources, 12 lake-bed piezometers were installed in the littoral zone of the lake along portions of the shoreline judged from regional data to be receiving groundwater discharge. Water quality samples were collected from the piezometers, as well as from one near-shore domestic well and two surface springs, during May, July, and October of 2001. Samples were analyzed for orthophosphate (OP), total dissolved phosphorus, nitrate-N, ammonia-N, total persulfate nitrogen, chloride, total dissolved solids, and dissolved iron and manganese.

The majority of stations (75%) exhibited OP concentrations above the 0.050 mg/L target criteria. Concentrations of OP in groundwater generally increased from north to south, and parallel increases in concentrations of parameters indicating anthropogenic impact to water quality. A statistically significant relationship was established between OP concentration and the relative percentage of urban development upgradient of each station. These findings suggest that urban releases of wastewater to the aquifer are likely the primary origin of phosphorus entering the lake via groundwater discharge.

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Radiological and Chemical Contaminants Entering the Near-Shore Environment of the Columbia River at the Hanford Site's 300 Area

G.W. Patton[1,a], S.P. Van Verst[2], B.L. Tiller[1], E.J. Antonio[1], and T.M. Poston[1]

Past operations at the Hanford Site have resulted in the release of radiological and chemical contaminants to the soil column, groundwater, and ultimately to the near-shore environment along the Columbia River. This study characterized the contaminants at the Hanford Site's 300 Area near-shore environment through the collection and analysis of shallow groundwater, riverbank spring water, river water, biota, and sediment samples. Samples were collected at a time when the concentrations of contaminants entering the river via riverbank spring discharges and groundwater upwelling were maximized. This study was able to monitor the progression of contaminants from shallow groundwater, to riverbank springs, and ultimately to river water, sediment, and biota. Discharges of contaminants from riverbank springs had a larger influence on near-shore river water concentrations than discharges from groundwater upwelling.

Gross alpha and uranium were the only contaminants that exceeded Washington State ambient water quality criteria in samples of shallow groundwater, riverbank spring water, and near-shore river water. Other contaminants in the 300 Area water samples that were elevated compared to the background location (Vernita Bridge) were As, Ba, Cs-137, Cr, I-129, Se, Tc-99, Tl, and Zn. However, they were all below state water quality criteria. Contaminants in Columbia River sediment samples that were elevated compared to the background location were Sr-90, Cs-137, and U. The human doses calculated from likely current-use exposures (fishing and boating) were low and not harmful to the public.

Biota samples in the aquatic community had elevated concentrations of As, Be, Cr, Se, Tc-99, U, and Zn compared to background samples. Individual clam samples from the 300 Area were collected over a well-defined spatial range and this allowed an estimate of the habitat area with elevated concentrations of Cr, Se, and U to be made. Similar spatial profiles were observed for U levels in both near-shore river water and soft tissues of clams. Dose rates for terrestrial and aquatic organisms were well below the respective guidelines of 0.1 and 1 rad/day.

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Tidal Filtering of Pumping Test Data in the Downtown Seattle and Elliott Bay Area

Pearl J. Pereira[1], Dan P. McHale[2] and Richard J. Martin [3]

Data collected during two pumping tests performed as part of the Alaskan Way Viaduct Replacement Project were corrected for tidal influence. Based on tidal analyses performed prior to the pumping tests up to 2 feet of tidal fluctuation was observed in the upper unconfined aquifer system, and 3 to 5 feet of tidal fluctuation was observed in the lower confined aquifer system. This magnitude of tidal fluctuation masked the drawdown due to pumping as observed in nearby monitoring wells, therefore tidal corrections were necessary for an accurate estimation of aquifer parameters.

Tidal filtration of pumping test drawdown data was accomplished by: 1) collecting tide data and groundwater levels for a one-week period prior to the pumping test; 2) identifying the low and high points in the tide and groundwater level data, and dividing the data into monotonic segments; 3) calculating the tidal efficiency and time lag for each of the monotonic segments; and 4) applying time lag and tidal efficiency to tide data collected during the pumping test period and subtracting these effects from the drawdown data. The tidal fluctuations imposed on the drawdown data could not be completely filtered using this method; however, the correction to the data was sufficient to allow for analysis using standard methods.

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Hillside Infiltration Systems – Plain Stupid, or Possible?

Randal C. Dyer[1] and Brian E. Hall[2]

Present guidelines (e.g. Ecology Stormwater Management Manual for Western Washington Manual) discourages siting stormwater infiltration systems on steeply sloping ground. Why? Apparently, because common wisdom points to the risk of slope instability, and previous catastrophic failures caused by excess water in slopes. We don't agree. We believe that steeply sloping ground offers a new journey and new solution to the problem of finding economic sites for stormwater infiltration facilities.

Our proposed paper addresses the concerns of infiltrating stormwater on slopes, and indicates that under certain conditions (which are frequently encountered in the Pacific Northwest), hillslope infiltration is feasible and desirable. This is illustrated with reference to a case history for a 6-CFS infiltration facility we have recently investigated in Issaquah, Washington. At Issaquah, the cost of suitable land for housing is expensive, that locating an infiltration facility on a sloping site, resulted in major cost savings.

Our paper will describe the case history, and especially the detailed, stepwise investigation required to prove the suitability of the site. Part of the investigation included a 24 hour full-scale pumping test in which 5 million gallons of water was pumped onto the slope to observe the infiltration characteristics.

The paper will also address concerns such as the reduction of infiltration capacity with time due to sediment, concerns of ground pollution resulting from the large volume of infiltration, and facility operating requirements to prevent down slope mounding of the water table and slope breakout.

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Estimating Time of Remediation Associated with Monitored Natural Attenuation

Francis H. Chapelle received B.A. (Music) and B.S. (Geology) degrees from the University of Maryland, and M.S. and Ph.D. degrees from the George Washington University. He has been a hydrologist for the U.S. Geological Survey since 1979. His research interests center on how microbial processes affect the chemical quality of ground water in both contaminated and pristine environments. He has authored more than 80 scientific papers and a textbook ("Ground Water Microbiology and Geochemistry," John Wiley & Sons, 2000) on these subjects. In addition, he has written a book for the non-specialist "The Hidden Sea" (National Ground Water Association, 2000) describing the history of various mystic and rational approaches to understanding ground-water systems, and how the idiosyncrasies of aquifers often complicate efforts to assess and clean up environmental contamination.

Ambient Groundwater Monitoring in King County, Washington

Ken Johnson[1]

In 2001 – 2002, as part of King County's Groundwater Protection Program, the Dept. of Natural Resources and Parks has been conducting semi-annual water quality monitoring in more than 60 wells. Locations and parameters are consistent with previous (1989 – 1993) monitoring performed to characterize groundwater conditions for Groundwater Management Plans under WAC 173-100. The use of previously sampled wells allows estimation of water quality trends over an approximately ten-year interval.

Wells are located in four of the Groundwater Management Areas in the County and are mostly owned by individual households and public water systems. The sampling locations, as originally chosen, are representative of the aquifers in the Area, both by depth as well as geographically. They are also generally away from known releases of hazardous substances.

Chemical parameters for analysis are comprised of inorganic and conventional parameters on a total (non-filtered) basis, chosen on the basis of health concerns, likelihood of detection, and simplicity of analysis. Detection limits are similar to previous analyses and well below MCLs. One round includes analysis for organic chemicals, including volatiles (VOCs), semi-volatiles (BNAs, including tentatively identified compounds), and some herbicides / pesticides.

Interpretation of the data includes statistical comparison of the mean concentration of each parameter, old vs new, with the particular statistical method chosen according to the distribution of the data. Generally present-day concentrations are lower than those of a decade ago, indicating an overall improvement in ambient groundwater quality. Concentrations are also compared to MCLs – the most common exceedances are of arsenic (new MCL of 10 ppb), total and fecal coliform bacteria, nitrate, and lead. Many wells show exceedances of the secondary MCLs for iron and manganese.

The resulting data characterize general background conditions. They may also be used for early detection of effects from various landuse or other policy changes. The specific data are being mined for intra- and inter-sampling round variability, outliers, and special areas (based on geography, aquifer / depth, or geochemical water type).

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Risk Assessment for Potential Stormwater Infiltration Impacts on Groundwater Quality at Proposed Wellfield

David Banton[1] and Travis McGrath[1]

The new wellfield is being proposed by a northwest utility. The proposed wellfield consists of multiple wells producing between 1,000 and 2,500 gpm each, for a total capacity of 10 to 30 MGD. Multiple land-use types exist within the wellfield's capture zone, including agricultural, commercial, and residential. Future development is anticipated throughout the area.

The utility is concerned with potential water-quality impacts from infiltrating stormwater, particularly in areas where stormwater is not captured by a sewer system. The utility therefore commissioned a risk assessment to evaluate the likelihood of infiltration-related water-quality impacts. The risk assessment was based on a relatively simple hydrogeologic representation and on abstracted hydrologic and contaminant-transport processes. This approach allowed a reasonable assessment of the likelihood for adverse water-quality impacts and for an evaluation of the sensitivity of the results to key factors (e.g., well production rate). The resulting conceptual model was implemented within GoldSim®, a graphical, probabilistic simulation software package. Uncertainty in each of the major factors governing the concentration of contaminants in well water were represented explicitly within GoldSim.

The risk assessment was conducted in two phases. The first phase evaluated the probability of water-quality impacts for a single well located adjacent to a proposed stormwater-infiltration facility. Results indicate that the probability of a stormwater-related fecal coliform impact to this proposed well was less than 10%. For other constituents considered (primarily metals), the probability of an impact to water quality was less than 0.1%. The second phase evaluated risk to the entire wellfield when flows from all wells were mixed together. For this scenario, the probability of a water-quality impact from stormwater infiltration was less than 0.1%.

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The Effects of Three Residential On-Site Sewage Systems on Ground Water Quality

Melanie B. Kimsey[1] and Barbara Carey[2]

The purpose of this study is to evaluate the degree to which on-site sewage systems contribute to ground water quality degradation in various hydrogeologic environments. Three residential on-site sewage systems were monitored to evaluate the effects on ground water quality and to determine the degree of contaminant treatment and assimilation that occurs in the subsurface. The extent of ground water degradation is estimated by measuring the effectiveness of the treatment and attenuation of nitrogen, fecal coliform bacteria, metals, cations and anions, and volatile organics in different aquifer materials. Ground water tracers were also used to verify the source of the impacts. Ground water, vadose zone water (under the drainfield), and effluent were monitored at these locations on a quarterly basis for two years.

The main variable between the sites is the aquifer material. Two of the on-site sewage systems are located in a coarse sand and gravel aquifer in the Lake Sawyer area. The third system is located in a fine sand aquifer in Thurston County. The constants at all three sites include shallow depth to water, vadose zone materials similar to the aquifer materials, similar precipitation, septic systems in compliance with the on-site sewage system regulations, similar types of gravity systems, and systems of common age and wastewater loading.

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Evaluation of Aquifer Storage and Recovery in the Ahtanum-Moxee Subbasin using a Groundwater Flow Model

Michael P. Klisch[1] and Christian V. Pitre[1]

Aquifer Storage and Recovery (ASR) is a water management method in which water is recharged into an aquifer during periods of availability, and stored for a period of months to years. Water is later withdrawn during periods of drought, high demand, or for emergency use. The City of Yakima conducted an ASR pilot test in 1999 and 200 that demonstrated the short-term feasibility of ASR. There is considerable interest in using ASR as a water resource management tool in the Yakima basin.

To evaluate the feasibility of long-term water storage using ASR, a three-dimensional groundwater flow model of the Ahtanum-Moxee subbasin was constructed using MODFLOW. The model was designed to evaluate storage of water within the Lower Member of the Upper Ellensburg Formation, a confined sand and gravel aquifer. The model was calibrated to the observed aquifer response during the previous ASR pilot testing.

Realistic recharge rates of 1,000 gallons per minute in each of three wells over 180 days was simulated (i.e., a total recharge of 0.8 billion gallons). Storage of the water within the aquifer system was simulated for ten years. Preliminary results show that almost all of the recharged water is retained within the aquifer system over this time period.

During the ten-year period of storage, water was redistributed from the aquifer that was directly recharged to adjacent strata. The natural storage capacity of the adjacent geological layers proved to store a significant amount of the water. The greatest changes in storage of the aquifer directly recharged occur within the first two years of storage, and remained relatively constant for the remainder of the storage period. Changes in other strata of the aquifer system continued to respond at a higher relative rate for longer periods of time.

The results of the ASR pilot test proved the feasibility of this resource management tool in the Ahtanum-Moxee Basin. Modeling results prove the long-term feasibility of a full ASR program.

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Getting Together in the Des Moines Creek Basin

Susan Everett, P.E.[1], Alan D. Black, P.E[2]

Over the summer of 2002, the Washington Department of Transportation (WSDOT) advanced a transportation project with complex and conflicting water resource and environmental issues. This presentation highlights the value engineering process and how it could realize savings of a third of the estimated $46-million stormwater management cost for the SR-509 corridor. The effort also created a win-win scenario that would provide cost savings while enhancing the project's water resource benefits within the Des Moines Creek Basin.

Value engineering studies have a long tradition for identifying optimum design and scheduling concepts for our transportation improvements. This is the first case where WSDOT has applied them to water resource issues. The presentation will provide an overview of the value engineering process, what creative ideas where developed before and during the study, and how it served the interests of many with a small, manageable study group.

The presentation will conclude with lessons learned from this study and how WSDOT will continue to look for these win-win opportunities throughout the Puget Sound region.

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Living with Uncertainty in Resource Management Science

Sandy (Alex K.) Williamson

Science-based management seems to have become an accepted buzzword. But what does it really mean in the important resource management decisions facing us today? Decisions are usually complex, resulting in answers with hopefully an estimate of the confidence level. Most scientists were trained that the allowable level for a valid result was either 95-percent or 99-percent confidence. We were trained not to publish results only certain at the 80- or 90-percent confidence level.

So what happens in this common situation? The scientists, uncomfortable with presenting results at those lower confidence levels, tell the managers that those questions cannot be answered. Then the scientists search for a simpler question that is answerable with 95-percent confidence. Scientists are generally very adverse to risk taking, especially when the risk in question is the risk of being wrong. However, the difficult question MUST STILL be answered by the resource manager, or even in some cases by the public through a referendum. So people who are generally not trained in the scientific disciplines relevant to the question are forced to translate the scientifically confident answer of a simple question to the more complex, but relevant question needed. Is this what science-based decisions should look like?

I suggest that we scientists attempt to answer the relevant, although complex questions, even if the uncertainty is only 80-percent confidence. Eighty-percent confidence may not be enough for some questions where lives are at stake, but it may be the best we can do. We usually do not consider the uncertainty associated with the do-nothing alternative, which is probably what happens when we reject an answer because it is not certain enough. Most people accept uncertainty in some areas of life. Many weather forecasts are probably no more confident than 60-70 percent, yet we appreciate getting them.

Some business people say they want nearly complete certainty in the outcome before they are asked to make changes that would cost them money or time. This makes sense except that often the do-nothing alternative has uncertain [and often costly] outcomes as well. And if the science-based decision included economic factors, it could maximize the benefit for all.

<u>Examples where the complex question is avoided in favor of the easier, but less relevant question</u>:

- In the Northwest today, many resource questions revolve around salmon. A relevant question would be how many salmon are likely to be saved by taking this action [dam removal, banning fishing, etc.]. If we could answer some of those questions, then we could compare alternatives in a much more sensible manner. In the dam removal case, the scientists have translated that question to a simpler one like, “sediment loading in the stream will increase or decrease,” or dam removal will increase the velocity of water movement in the downstream reservoir, which should help salmon smolt survival.
- Choosing best management practices (BMPs) that are most beneficial. Most often this decision is based on judgment alone. If this decision were aided with a statistical approach, it would usually involve some kind of multiple regression where many factors are correlated against a result.
  Comparing several factors may result in only 80% confidence. This known uncertainty might make some people uncomfortable, yet the judgment decision might have had even less confidence, though it was not known.

We must clearly communicate our findings and our estimate of the confidence level, as well as our judgments about how certain we are about both. We must help people understand all the uncertainties so that they can properly make their own conclusions about our results.

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Groundwater Management—Progress in California?

Carl Hauge

Demographers estimate that California's population will grow from 32 million in 1995 to about 48 million in 2020, an increase of 16 million that will create a demand for additional water. Part of that demand will be met by recycled water, desalination, a shift from agricultural to urban use, and conservation. More effective management of groundwater basins could also provide additional water. Although surface water is regulated under the Water Code, groundwater is not. Groundwater is regulated by court decisions stating that landowners have a correlative right to extract groundwater. That right has only been quantified for qualified pumpers in 19 adjudicated basins.

Because there is no state law regulating groundwater, the Legislature in 1992 amended the Water Code to allow local agencies in unadjudicated basins to develop groundwater management plans to improve groundwater management. Over 200 agencies developed such plans, and 60 agencies adopted plans under other statutory authority. But the question remains, "What is a good groundwater management plan?" The Legislature directed the Department of Water Resources to develop criteria to evaluate groundwater management plans and to develop a model ordinance for groundwater management that could be adopted by California's 58 counties.

A good plan will address 9 topics. A 2002 amendment to the Water Code requires the first 6 topics before state funding can be awarded. First, the management entity must publish a procedure for ensuring public participation and stake holder involvement in the planning and implementation processes to ensure that the process will be driven from the bottom up and not by bureaucracies from the top down. Second, the plan must lead to a reliable and sustainable water supply for beneficial uses by adopting management objectives (MOs) that provide threshold values for surface and groundwater levels and quality, and land subsidence. When a threshold value is exceeded, action by the management entity may be necessary. Third, the plan must include collection and evaluation of data to monitor, and provide feedback to ensure that MOs are met. Fourth, planning must include inter-agency coordination of regional issues that affect, or can be affected by, the management entity. Fifth, there must be a map showing the boundaries of all water-related entities within the basin. Sixth, hard rock areas outside of defined groundwater basins must use appropriate technology.

Seventh, there should be a description of the aquifer characteristics and properties. Eighth, there should be periodic reporting of the program, results, and actions by the entity. Ninth, the plan should be re-evaluated periodically to ensure that the MOs are providing a reliable groundwater supply.

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Critical Aquifer Recharge Areas

Laurie K. Morgan

The 1990 Growth Management Act requires local jurisdictions to designate and classify Critical Areas. Critical Areas include wetlands, frequently flooded areas, critical aquifer recharge areas, geologically hazardous areas, and fish and wildlife habitat conservation areas. Critical Aquifer Recharge Areas (CARAs) are areas where drinking water supply aquifers are susceptible to contamination, and where limiting recharge availability would cause a problematic decline in water availability.

CARA ordinances typically involve designation and classification of groundwater resources, an analysis of aquifer susceptibility, and control of potential contamination sources. To help local jurisdictions with GMA CARA requirements, the Washington State Department of Ecology has published the "Guidance Document for the Establishment of Critical Aquifer Recharge Area Ordinances." The guidance is available on-line at http://www.ecy.wa.gov/biblio/97030.html.

Using CARA ordinances, a community can protect its water supply and avoid the monumental expense associated with groundwater cleanup. Examples of the cost of groundwater contamination include:

- City of Tumwater Palermo well field: Total cost for dealing with solvent contamination was $3.9 million dollars, the cleanup took more than six years, and three of six city wells were closed for five years.
- Boomsnub Corporation, electroplating facility, Vancouver, Washington: According to one report, an estimated $10 million will be spent in an attempt to save the City of Vancouver's water supply from contamination with hexavalent chrome.

EPA studies have shown that funds expended for groundwater prevention are cost-effective compared to groundwater cleanup at a ratio that runs anywhere from 1:5 to 1:200 (U.S. EPA, 1995. Benefits and Costs of Prevention: Case Studies of Community Wellhead Protection, EPA 813-B-95-005). Critical Aquifer Recharge Area ordinances are an effective way of preventing loss and degradation of critical community drinking water supplies.

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Global Water Resources and the Rate of Science in Public Policy

Nadine Romero was the originator and chair of the first Symposium on the Hydrogeology of Washington State. She states, "*But, ideas are worth nothing without the energy and know-how of the hydrogeologists at the Washington Department of Ecology, the USGS and consulting firms state-wide -- this event was undoubtedly their doing and it was based on a single core belief that we needed a formal space to have dialogue and share information on the hydrology and hydrogeology of the Pacific Northwest."* Nadine worked as a hydrogeologist with the Washington Department of Ecology from 1991 until 1997. In 1998 she formed Ground Water Science Services, LLC in Olympia, Washington and worked as a consultant for 3 years before applying to Harvard University to gain experience in public policy and analyses. She believes more scientists need to formally dip into public policy, "*I think all scientists need to deepen their policy and analytical skills. At the Kennedy School of Government, only a handful of natural resource scientists are studying public policy. Yet, there is so much to be done on the planet. Some 1.3 billion people lack clean water and are below basic human subsistence levels. Broadening our understanding of how governance, political and economic systems work globally is paramount to our scientific performance, and the functioning of a rapidly changing globe."* Her core courses at Harvard's John F. Kennedy School of Government are in energy, environment, economics and technologic innovation. Nadine received her *A.B*. from Mount Holyoke College, an *M.S.* from Michigan State University and will graduate in Spring of 2002 with a Master's in Public Administration, *M.P.A* from Harvard University.

Subsurface Geologic Mapping of the Columbia Basin Groundwater Management Area: Results and Applications

Terry Tolan[1] and Kevin Lindsey[2]

A series of isopach and structure-contour maps covering the entire Columbia Basin Groundwater Management Area (GWMA) area (approximately 6,000 square miles in Adams, Grant, and Franklin Counties of east-central Washington), portray the distribution of many of the geologic units that host groundwater in this region. These geologic units include Columbia River Basalt Group (CRBG) members, Ellensburg Formation interbeds in the CRBG, and suprabasalt sediment units.

CRBG units mapped include the Ice Harbor, Elephant Mountain, Pomona, Esquatzel, Asotin, Wilbur Creek, and Umatilla Members of the Saddle Mountains Basalt; the Priest Rapids, Roza, and Frenchman Springs Members of the Wanapum Basalt; and the top of the Grande Ronde Basalt. Structure-contour maps of unit tops provide a tool for delineating the distribution of selected interflow zones. It is the interflow zones within the CRBG that host the most productive aquifers.

Sediment unit maps focused primarily on Ellensburg Formation interbeds and suprabasalt units including the Ringold Formation and Quaternary sand and gravel largely deposited by the Pleistocene Cataclysmic Floods. Ellensburg Formation and Ringold Formation maps show the thickness and distribution of these units. Depending on sediment facies and lithology these units can either (1) host significant groundwater and provide pathways for groundwater movement and (2) contain little groundwater and block groundwater movement. Maps of coarse Quaternary clastic deposits, most notably Cataclysmic Flood deposits, provide a basis for delineating areas where shallow groundwater can move relatively rapidly.

Results of this work will allow GWMA to identify specific geologic units from which wells are drawing water that are being used as part of GWMA's long-term monitoring of nitrate-N in groundwater. Other uses of this mapping include: (1) delineating erosional windows which provide pathways for vertical groundwater movement within basalt units and between basalt units and suprabasalt sediments, (2) determining lateral continuity of water-bearing zones, and 3) identifying potential points of recharge for deeper aquifers.

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Why Are The Location Datums For Your Sampling Station Important?

Russ Darr[1]

It is becoming more and more common for environmental data to be plotted on a map using a GIS system. The GIS system needs to know the horizontal and vertical datums for the coordinates you provide. Most professionals collecting data are not aware of the implications when the wrong datums are used. If the wrong datums are used the location and elevation will be incorrectly plotted.

All USGS maps have the vertical and horizontal datums printed at the bottom of the map. Thus if the location data were collected from a USGS 7½ minute quadrangle map and you stated the horizontal datum was NAD 83, your location would not be correctly positioned because the correct datum is NAD 27.

Most GPS units allow the user to select the datums. This may be a problem with shared GPS units. Always check to be sure the datums are the ones you report before collecting new locations or elevations. Another user may have changed them datums, since you last use that GPS unit.

The cost of providing the wrong datums may render your data unusable or result in a wrong interpretation of your data. For example station A may is west of station B. But because the wrong horizontal datum was reported for station B, it plots on the map east of station A. The same kind of problem may also result for vertical data. This could result an apparent reversal of a ground water gradient.

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Hydrogeologic Characteristics of the Columbia River Basalts Near Goldendale, Washington

Steven J. Stresky[1] and Timothy J. Flynn[2]

Significant variations in hydrogeologic characteristics were observed during a ground water exploration program to develop new ground water supplies for the City of Goldendale. The hydrogeologic data obtained from the exploration wells, which penetrated the entire Wanapum Basalt sequence and the top of the underlying Grande Ronde Basalt, fills a data gap and improves the geologic understanding in an area of limited subsurface data in the Klickitat River basin. This presentation reviews the exploration program and discusses an interpretation of the geology within the Columbia River Basalts (CRB) and its influence on ground water conditions.

The first drilling site was approximately five miles south of Goldendale in Swale Creek Valley, a basin consisting of alluvial sediment overlying the Wanapum Basalt. Ample ground water yield was discovered at the top of each of six Wanapum Basalt flows and the top of the underlying Grande Ronde Basalt. The top of the Ginkgo Flow revealed the most prolific yield in the basalt sequence. Water quality throughout the Wanapum as well as the Grande Ronde basalts was generally excellent and suitable for municipal supply. More commonly, poor water quality has been observed elsewhere in the limited number of explorations into the Grande Ronde Basalt.

The second drilling site was about 10 miles north of Swale Creek Valley on the southern flank of the Simcoe Mountains. A variety of volcanic deposits was encountered above the CRB, including competent basalt flows, vent-facies deposits, and lahars. A fluvial interbed was penetrated twice, suggesting a faulted sequence of deposits.

Exploration below the volcanic deposits in the Wanapum and Grande Ronde basalts revealed conditions very unlike those encountered in Swale Creek Valley. Flows were unusually thick, had poorly-developed flow tops, and exhibited minimal yield. The Ginkgo Flow, thought to be regionally extensive, was absent. Ground water yield from the Grande Ronde Basalt was sufficient, but the water quality was very poor.

The exploration has contributed to the understanding of hydrogeologic conditions relative to the basalts and geologic structure in the Goldendale area. The considerable contrast in aquifer yield and water quality between the two exploration sites is likely due to structural deformation, causing significant hydrogeologic variation over a relatively short distance. This variation has important implications to water supply development, evaluation of water rights, and watershed planning in the region.

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Pesticide Occurrence and Ground Water Quality Protection Through the Development of Area-wide Pesticide Management Plans in Washington State

Kirk V. Cook, PHG

Since 1987, EPA has been working to develop a pesticides and ground water rule requiring pesticide management plans (PMPs) to be written for specific pesticides. On June 26, 1996, the EPA Office of Pesticide Programs (OPP) submitted their *Pesticides and Ground Water State Management Plan Regulation; Proposed Rule*. The draft rule would require pesticide-specific management plans to be written for pesticides of national concern (atrazine, simazine, alachlor, and metolachlor). As this national process has progressed, WSDA, the state lead agency for the PMP process, is now in the final stages of completing and planning for pesticide-specific management plans.

Pesticide occurrence in Washington State does not appear to be wide spread. Detections of pesticides has not reached levels detected in other areas of the county were agricultural activities are extensive. In most cases pesticide levels have not violated federal Maximum Contaminant Levels (MCLs); however, because state ground water quality regulations are more restrictive, there have been additional violations noted throughout the State.

In order to fully protect Washington's groundwater resource, the Washington State Department of Agriculture plans to use tools developed through the Aquifer Vulnerability Project, to assess the potential for groundwater contamination via pesticide use in all agricultural areas of the State. Once the assessment has been completed, monitoring and verification sampling will occur to determine the presence or absence of the pesticide(s) of concern. The vehicles for accomplishing these goals are the generic and pesticide management plans.

The *Washington State Generic Pesticide Management Plan: Ground Water Protection Strategy* outlines the government agencies involved in protecting ground water from pesticides. The document describes the roles of each agency, and how these authorities and programs will be coordinated. The involvement of pesticide applicators, dealers, and registrants is described as well. This document is viewed as a generic pesticide management plan and will be used to prevent and respond to any potential or actual pesticide threats to ground water, and to develop pesticide-specific management plans for the four targeted pesticides and other pesticides important to Washington State's agricultural industry if deemed necessary. Ground water and human health protection are the primary goals of this document and the PMP program.

The core aspects of the *Washington State Pesticide Management Plan* are:

- Ground water assessment and planning;
- Ground water monitoring and prevention actions; and
- Response to ground water contamination.

Other important components include enforcement mechanisms, public awareness and participation, information dissemination, and records and reporting progress. An emphasis will be placed on information and education, best management practices (BMPs), monitoring, and prevention. If the concentration of a pesticide in ground water, resulting from current legal use, is equal to or greater than the state ground water quality standards, then more serious measures such as a use prohibition will be taken to protect the resource. The response and regulatory framework outlines the processes WSDA will use to define and respond to contamination situations.

This generic pesticide management plan will provide general guidance, and allow the flexibility needed to develop pesticide-specific management plans that are both environmentally responsible and economically and socially realistic.

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Distribution of hyporheic invertebrates in Puget Sound Lowland Streams

Anne A. Weekes[1]

The presence of invertebrates deep in the substratum of streams has been well documented for many systems. However, there is a paucity of data not only for streams in the Pacific Northwest, but also for streams in urban areas. To improve our understanding of the distribution of hyperheic invertebrates, diversity and abundance in this region was determined by collected samples from shallow (30 cm) and deeper (60-72 cm) wells from Puget Sound Lowland Streams in the Seattle Metropolitan area. Invertebrate community distribution was compared among five streams that all had similar geomorphological parameters.

Cyclopoid copepods, harpacticoid copepods, nematodes, oligochaetes and water mites (hydrachnidia) were present in all the streams. For a similar sample size, almost twice as many individual invertebrates (1,535) were found in Covington Creek, compared to Leech Creek (835). However, dominant taxa and abundance varied greatly between streams, as did distribution of invertebrate groups within streams. Fifty-four percent of the invertebrates in the Leech Creek sample were cyclopoids. In Covington Creek, individuals were more evenly distributed among archiannelids, cyclopoids, harpacticoids and water mites. Vertical differences were also found between well depths; 80% of the Leach Creek cyclopoids were found in one of the deep wells. Some groundwater associated fauna, such as amphipods, were found in very small numbers, even though deeper wells were included in all the sampled streams. Archiannelids were relatively abundant.

Variations in distribution and abundance appeared related to physical parameters. These included stream and hyporheic zone temperature at the well location, reach slope, suspended sediment concentrations within each hyporheic zone, channel and well sediment composition, the average slope for the well reach, and the low flow surface and hyporheic zone velocity. While the study variables were observed on a reach scale, upstream headwater catchment characteristics could also be important to invertebrate abundance and diversity, and were also broadly characterized in the study. Conclusion: what are the most important physical factors affecting invertebrate distribution.

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Impact of Sediment Temperature Gauge Used to Estimate Stream Seepage

Bryce E. Cole[1]

Many methods for determining hydrologic budget components require use of intrusive instruments. Many practitioners use temperature for estimating groundwater flow or infiltration. However, there is little published material on the impact of temperature gauges placed in the sediments, particularly addressing how long a gauge placed in the sediments requires before the perturbation of the natural temperature dissipates.

Successive temperature loggers were placed in stream sediments at two locations to find the length of time required before adjacent temperature gauges recorded similar temperatures. The stream sediment at the first site near Walla Walla was hard clayey gravel that required a one-inch hand auger to insert the temperature gauge six inches. The softer sediments at the second site south of Spokane allowed direct insertion of the temperature probe. Temperature gauges were installed approximately one-month after another and data for 100-200 days were compared for similarity.

"Similar" temperature readings between gauges were identified two ways. The first compared temperature time series graphically, noting whether gauges had a linear offset between their signals, or had wider temperature fluctuations. This comparison method was useful for determining differences in temperature gauges - either an intrinsic difference for the devices such as a linear offset, or a difference in the depth of the placement of the gauge in sediments. This method seemed appropriate for an initial estimate of the times for gauges to coincide in terms of temperature time series for the harder sediments at the Walla Walla site. Temperature signatures appeared to coincide 60-75 days after gauge deployment. For the soft sediments at the Spokane site it appeared that gauges corresponded to each other within hours of deployment.

The second method fit the data to a vertical one-dimensional model with the stream temperature as the upper boundary and a "constant" groundwater temperature at a known depth. Both settings were gaining streams, so the "constant" groundwater temperature varied with time, thus, seepage velocities were determined in twenty-day increments, varying two parameters in the model: the "constant" groundwater temperature, and the seepage velocity. Seepage velocities from the gauges in the hard sediments initially increased in value, but then decreased which would seem a necessity for the sediments to collapse around the temperature gauge. The "constant" groundwater temperature started to register similar values after a 75 day period.

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Groundwater Influence on River Water Temperature

Llyn Doremus[1], Treva Coe[1] and Russ Faux[2]

The South Fork of the Nooksack River routinely exceeds Washington State criteria for water temperature during months of July and August. An extensive dataset has been assembled characterizing the river hydrology and water temperature; including hourly temperature measurements over summer months at up to 20 locations along the 35-mile river length, simultaneous discharge measurements over the river length and aerial recording of infrared radiation (referred to as Forward Looking Infrared Radiation or FLIR measurements) over the entire river in a 6 hour period.

The river drains a watershed of approximately 187 square miles, flows over a length of about 39 miles and has an average annual flow of 746 cubic feet per second (as measured at river mile 14.8) for the 48-year period of record. River flow is sustained by groundwater discharge, rainfall runoff, snowmelt and glacial runoff (in order of decreasing magnitude). Discharge in 2001 ranged from 5,230 to 103 cubic feet per second (the minimum value was recorded on the day before the FLIR measurement). The watershed ranges in elevation ranges from 7,000 to 200 feet. River mile 13 represents a transition from the lower-elevation, wide, flat valley bottom, to the steeper sloped, forested higher elevation watershed.

High water temperatures, although well correlated with air temperature, are also influenced by the riparian areas on the river shore, the geomorphology of the river channel, and the groundwater contribution to surface water flow.

Discharge measurements during extremely low flows indicate a hydrologic system dominated by groundwater discharge. Hyporheic zone temperature measurements in the lower watershed indicate that sympathetic flow in the shallow subsurface surrounding the river supports a significant thermal reservoir. High temperatures routinely recorded in the upper watershed suggest that water temperatures do not simply increase with increased exposure to higher temperature air along the length of the river course. Instead, instream data records (hourly water temperatures) and the single event FLIR temperature measurements suggest that the water temperatures vary as a function of the groundwater contribution to surface water and the slope of the surrounding watershed that drives the rate of groundwater discharge, as well as the solar radiance that reaches the river surface and its overlying air mass.

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Thermal Transport Investigation Selah Lake Gravel Mine

David E. Brown, RG[1], Merideth Gibson[2] and Wayne Kalbfleisch[3]

David Brown & Associates, Inc. designed a methodology to compare thermal data to identify interactions between groundwater, mine ponds, and the Yakima River, through the Selah Reach. Nearly 500K data points were collected over a seven-month period each year of the on-going five-year study. Sensor locations initially included both banks of the river, monitoring wells, and in the four mine ponds. After year two, it was determined the sensors on both banks of the river were redundant, resulting in removal of right bank sensors. Data from April to November of each year were evaluated statistically in order to identify the interactions between the water bodies. The approach used during the first year was determined to be too complex. Analysis was utilized during the following years using standard deviation, two-sided T-test and confidence intervals.

Atmospheric data were also collected to allow comparison with water body thermal data. An automated weather station was established on-site, to collect data on a 30-minute interval. High correlations between average daily water temperatures and average daily air temperatures were discovered.

The river gradients were calculated between the adjacent sensors. Because all data transfers could not occur at exactly the same time, the temperature recordings were adjusted to common time scales. After calculating gradients over the different river flow periods, statistical analyses were performed on the thermal gradients.

Data collected from the mining ponds was imported into the thermal modeling software, VS2DI. Model outputs predicted when pond water could be entering the river. Calculations of thermal influence on the river have shown that seepage from ponds have minimal thermal impact on the Yakima River. The maximum calculated temperature increase from pond seepage 0.1°C.

An airborne thermal infrared survey was flown during 1999. The video identified one thermal plume originating from the edge of the southern-most pond through an artificial dike. No other connections between mine ponds and the river were identified in the infrared analysis.

The results of the study have indicated that the there is a potential for thermal impact to the groundwater south of the pond system. However, the extent and magnitude of any thermal impact were shown to be transient. Examination of thermal impact to the Yakima River from the mining ponds has been shown to be insignificant through statistical analysis coupled with field observations.

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Influence of Long Term Precipitation Trends on Landfill Post Closure Ground Water Monitoring Data

Arnie Sugar, P.G. HWA GeoSciences Inc.

Post closure ground water monitoring at a landfill in Pierce County exhibited marked downwards and upwards trends in inorganic parameter concentrations. The landfill was closed under MFS (173-304 WAC) in 1991, including consolidation of waste to a central area, a 60 mil membrane cap, drainage layers, topsoil, surface water control, and passive gas venting. Concentration trends for metals (arsenic, manganese, iron, zinc), chloride, sulfate, TOC, coliform, pH, and conductivity over a 12 year period exhibited a strong correlation with long term precipitation trends, with 0-1 year time lags, and soluble/mobile parameter concentrations exhibiting the greatest apparent sensitivity to precipitation.

Possible mechanisms for this relationship include 1) increased infiltration and leaching through undocumented or residual waste present outside the capped area, 2) leakage through the cap, or 3) rising ground water contacting waste, leachate, or sorbed compounds below the waste.

This relationship suggests that 1) long term precipitation trends may strongly influence ground water monitoring results, 2) performance and regulatory compliance evaluations should consider precipitation trends, and 3) long post closure periods (20 years) are appropriate.

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Reducing Groundwater Conditions at Forest-Products Industry Sites: 1. Aquifer Geochemistry

Glen M. Wyatt

Reducing conditions dominate in groundwater chemistry observed in the vicinity of landfills containing wood debris and wastewater treatment lagoons at pulp and paper mills, and in soils containing decaying organic matter. Groundwater downgradient from such sites frequently has high concentrations of dissolved organic carbon, alkalinity, iron, manganese, color, ammonia, and sulfide. Dissolved oxygen concentrations are typically less than 1 milligram per liter (mg/L) and negative oxidation-reduction potential (ORP). Acetone, methylphenols, and other VOCs have been observed in leachate from wood debris landfills. Similar geochemical conditions have been noted at hydrocarbon release sites; the driving mechanism for the geochemistry at both types of sites appears to be fermentation and respiration by anaerobic bacteria.

Organic compounds present in landfill leachate samples and groundwater samples from wells completed in and adjacent to wood-debris landfills may be generated by anaerobic bacteria. Acetone, 2-butanone (methyl ethyl ketone), 4-methylphenol, toluene, and benzoic, propanoic, and butanoic acids have been observed in these samples. These compounds do not appear to be laboratory contaminants and are locally or seasonally present. We have not attempted to determine the bacterial strains involved in the production of these compounds, but a literature review suggests *Clostridium* sp. and *Tolumonas auensis* as possible investigation targets.

Iron and manganese reduction by anaerobic bacteria results in elevated concentrations of iron and manganese in groundwater within and downgradient from wood-debris landfills, near wastewater impoundments at pulp mills, and in soils containing decaying organic matter. Dissolved ferrous iron [Fe(II)] concentrations of 10 to 60 milligrams per liter (mg/L) are not uncommon and may exceed 100 mg/L. Manganese concentrations up to about 10 mg/L are also typical, indicating the manganous [Mn(II)] form is present. Arsenic or chromium in aquifer materials may also be released to groundwater by anaerobic processes. Reduction of nitrate (to ammonia) and sulfate (to sulfide) have also been observed, and may show recharge-caused seasonality observable in time-series plots.

Surface seeps from landfill-impacted groundwater may be colored orange as reduced iron is oxidized and precipitates. Anaerobic bacteria, such as *Beggiatoa* sp. may also be observed in seeps from anaerobic groundwater.

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Reducing Groundwater Conditions at Forest-Products Industry Sites: 2. Field Water-Quality Parameter Measurements

Glen M. Wyatt

Reducing groundwater conditions may be investigated using field measurements because of the unstable nature of groundwater samples. Reduced groundwater samples are low in dissolved oxygen. Normal sample collection techniques will cause exposure of the sample to air, changing the sample's geochemistry. To obtain data representative of groundwater conditions for use in geochemical modeling, field measurements are necessary.

Dissolved oxygen may be determined in the field using a membrane-equipped probe or with a colorimetric method. The electrometric method is relatively easy, providing the membrane is correctly attached to the electrode. The method appears to fail at low DO concentrations, <1 milligram per liter (mg/L), or where sulfide is present. To avoid these problems, DO at 0-1 mg/L may be measured using the Rhodazine D method (CHEMetrics, Inc. test kit K-7501). The indigo carmine method may be used for DO concentrations from 1-12 mg/L (kit K-7512).

If the DO concentration is low, iron will be present as iron (II), which will oxidize to ferric iron on exposure to air. Iron (II) concentrations may be measured using CHEMetrics test kits. A filtered sample is analyzed using CHEMetrics' test kit K-6010D to determine Fe(II) for concentrations up to 250 mg/L. If the Fe(II) concentration is <10 mg/L, kit K-6210 is used. In highly colored water, a spectrophotometric method may be used (HACH Fe(II) method using a DR 2000 spectrophotometer), however, this is a more complex method that requires operator training. Sulfide may be measured using CHEMetrics kit K-9510.
Field alkalinity analyses are recommended for <1 mg/L DO and Fe(II) >1 mg/L. A filtered sample is titrated in the field using a HACH digital titrator, according to USGS methods. The alkalinity is determined from inflection-point data using the USGS on-line alkalinity titrator program (http://oregon.usgs.gov/alk/). Field titration avoids the potential changes in sample geochemistry caused by precipitation of iron oxides, which has been observed to occur about 2 hours following sample collection. Laboratory alkalinity measurements may be performed according to fixed endpoint titrations (e.g., pH 4.5 using Standard Methods 2320). Field alkalinity titrations to the inflection point indicate that Standard Methods technique may underestimate the sample alkalinity, as the inflection point may occur at a pH <4. This also implies that reduced species (and not just HCO_3^-, $CO_3^=$, or OH^-) are contributing to total alkalinity. Cation-anion balance calculations may also be impacted in reducing conditions.

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Design and Construction of an Inward Gradient Landfill

Kevin G. Lakey, PE, RG

The LRI Landfill is a municipal solid waste landfill located in Pierce County, Washington. This 168-acre facility is sited over a sole source aquifer. Under Washington State solid waste regulations (WAC 173-351), the facility applicant had to successfully demonstrate that the aquifer is not vulnerable to contamination. This demonstration was based on the natural groundwater protections at the site that include a 40 to 50 foot thick layer of low permeability glacial till that is present between the surface and the underlying aquifers. Further enhancing the natural protections at the site is the presence of a confined aquifer beneath the glacial till. This pressurized aquifer condition was utilized in the landfill design to create an inward hydraulic gradient beneath the landfill.

The landfill, which is being constructed in phases, will consist of eight contiguous disposal cells excavated into the glacial till at full build-out. The bottom excavation depth of each cell lies below the potentiometric surface of the aquifer. The bottom liner consists of a sloped composite liner of 60-mil high density polyethylene (HDPE) geomembrane and two feet of low permeability clayey soil. The geomembrane liner is overlain by a one foot layer of high permeability sand to promote leachate collection and an additional one foot operating layer to protect the geomembrane during the initial placement of refuse. Beneath the composite liner is a one foot thick layer of high permeability gravel to dewater the underlying till and provide early leak detection and collection capabilities. Pumping from this leak detection/collection system (LDCS) induces an upward gradient from the aquifer toward the landfill. As a result, in the unlikely event of a leak in the landfill liner, the leachate will be collected along with the groundwater, rather than migrate toward the aquifer.

The unique combination of engineered containment, naturally occurring very low permeability glacial till beneath and surrounding the landfill, and upward groundwater flow away from the confined aquifer and into the LDCS provide a state-of-the art waste disposal facility that is protective of the regions groundwater. The LRI Landfill began accepting waste in December 1999. To date the first two disposal cells have been constructed.

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Ecology's Environmental Information Management System – Sharing Environmental Data via the Word Wide Web

Christine M. Neumiller[1], John E. Tooley[2], William R. Kammin[3], Deborah Stewart[4], E.J. Julio[5], and Russell Darr[6]

In the mid 1990's, the Washington State Department of Ecology (Ecology) had a vision – build a comprehensive environmental database in order that data could be shared internally and eventually with the entire environmental community. That day has arrived. In November 2002, Ecology launched a searchable version of its Environmental Information Management (EIM) System database to the Internet.

The EIM System is home to over a million physical, chemical, and biological environmental result records and is constantly growing. With the EIM Internet Query System, users can look at chloride concentrations in wells in Island County or find all results for benzene in King County ground water. The EIM Query System searches the database via three primary categories – by study, by location, and by result parameter name, list, group, or CAS Registry number. Search criteria can be further broken down by county and Water Resource Inventory Area (WRIA). In each category, further conditions can be placed on search criteria, such as specifying sample matrix type for result parameters.

Search results are presented in a list that is sortable by column heading, such as sample matrix, parameter, parameter value, etc. Search results can be exported by study (study, location, and results details, and if applicable, well station and measuring point details), location (all results data for that location), or result parameter (i.e., all chromium ground water data in Clark County). Additionally, pre-built datasets can be exported by study, county, WRIA, and result parameter, primarily for those who want to load information into their own databases. Data is exported in csv format (comma-delimited ASCII text), suitable for loading into a spreadsheet or a relational database.

A more robust GIS-based interface is under development. This will add the ability to search for and view data spatially, along with other advanced features such as XML export capacity. Additionally, new datasets are added continuously. For example, the ground-water database from Ecology's southwest region is currently being migrated into the EIM system. It includes over 1000 well stations and 35,000 result records for water level alone.

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Conceptual Model Development for the Sitewide Impact Assessment of the Hanford Site Contamination Using a Holistic System Approach

Dibakar (Dib) Goswami, Ph.D

The Hanford Site environmental legacy represents one of the U.S. Department of Energy's (USDOE's) most complex technical, regulatory, and public policy challenges. Past Hanford Site operations resulted in radiological and chemical contamination of the vadose zone, groundwater and the Columbia River. Approximately 90 square miles of groundwater are contaminated above federal and state drinking water standards. More than one thousand possible contaminant sources exist within the Hanford Site. While cleanup of these sites is now currently managed mostly on an operable unit by unit basis and contaminant specific basis, a holistic approach is essential to determine the cumulative impact and risk guiding cleanup action, prioritization, developing site use scenarios and finally meeting regulatory requirements.

A simple conceptual model for the holistic assessment is developed starting with the inventory of sources that is released through different mechanisms. The sources release directly to the vadose zone and can infiltrate to groundwater which eventually feeds the Columbia River. There is a river-groundwater interface technical element followed by river transport and biological transport elements. Each of these technical elements is based initially on a deterministic understanding. Multiple realizations simulate various technical element conceptual models and model parameter variations. The overall simulation can be viewed as two largely independent events. First, there is the combination of technical elements that yields a representation of the contaminant distribution in space and time, resulting from a suite of environmental remediation, geological and hydrogeological conceptual models, and various model parameter scenarios. Second, there are the individual risk and impact assessments that use the contaminant distribution in space and time as plausible future environments to which we expose humans, the ecosystems and cultures according to a number of site use scenarios for exposure and impact. Because resource requirements propagate uncertainty through the overall simulation involving each of the technical elements, fewer simulations are proposed to achieve a general indication of the variability in performance of the entire system.

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Using Microsoft Access to Create a Groundwater Pseudo-GIS

Douglas Kelly[1] and Gordon Eaton[2]

It is possible, with a few basic-programming skills, to create a groundwater database that is highly customized to the needs of users. Well logs, graphical analyses, tabular data and various maps can be saved as digital documents for electronic distribution.

Databases have been developed for storing many kinds of groundwater data including stratigraphy, chemistry, water level, well construction, location, ownership, well capacity, and water use. Less common data have also been integrated into the system, for example, digital elevation models, bathymetric data, assessors tax parcel information, spatial / temporal precipitation distributions, and tidal stage. Stratigraphic data are encoded using the Unified Soil Classification System. Automated import routines have been developed for loading laboratory results.

Well log data can be searched within a user-specified geographic area, and filtered to view wells that meet selected physical or water quality parameters. The results of a search are displayed as a tabular summary and can be printed or saved digitally. Through ActiveX automation, maps of the search area can be generated automatically in AutoCAD, displaying well locations and user selected parameters pertaining to each well. In addition to standard maps, “stick diagrams” can be generated that display the stratigraphic information for all wells in the search area. The stratigraphy from each well log is color-coded based on the USCS designations for each stratigraphic description.

Time series plots of any analyses can be generated. Other parameters such as precipitation, tidal stage, water levels and well production, can be plotted on the same graph. Stiff and Piper diagrams can be generated for any well that has the necessary sampling results. Other analysis tools specific to seawater intrusion analysis have likewise been integrated into the database. Many of these analyses can also be utilized in the regional search tools; for example, a Piper diagram can be generated to view chemical analyses from all wells in a search area. Spatially distributed Stiff diagrams can be generated in the maps discussed in the previous paragraph.

Stratigraphic data can be utilized for the generation of groundwater flow models. Tools have been developed for relating stratigraphic information in well logs to regional aquifers and aquitards. ActiveX automation of geostatistical software has been utilized for generating gridded elevations through well log ‘picks’ for tops and bottoms of aquifers. Spatially distributed aquifer parameters are also calculated, based on well log stratigraphy. Generation of rendered three-dimensional images (CAD Drawings) for visualization of model parameter distribution is also automated.

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A Decision Support System for the Yakima River Basin

Mark Mastin[1], John Vaccaro[2], Chris Lynch[3], and Warren Sharp[4]

A database-centered Decision Support System (DSS) has been constructed for the Yakima River Basin as part of a joint U.S. Geological Survey and U.S. Bureau of Reclamation program--the Watershed and River Management Program. The purpose of the program and DSS to improve short- and mid-term water-management operations of Reclamation projects in the western United States and long-term policy decisions.

The DSS consists of three major components: a river and reservoir management model (Riverware), a modular modeling system (MMS) that calculates runoff, and the central hydrologic database (HDB). The HDB contains metadata and historical and real-time hydrometeorological data. It allows for easy data query and display through graphical-user and data-management interfaces. The HDB acts as the bridge between Riverware and MMS by accepting model input and output.

Riverware is an interactive object-oriented model that can be operated at daily-to-monthly time steps. A basin-wide model has been constructed for the Yakima River Basin to simulate all major features at a daily time step, including reservoirs, streamflows, diversions, and returns. It includes operational rules for reservoir releases and river diversions. The model can be run using specified inflows and outflows, rule-based simulation, or optimization techniques. For optimization runs, downstream target fishery flows can be set as prioritized constraints.

The MMS calculates runoff by integrating a variety of modules that each simulate different hydrologic processes, such as snow accumulation and melt or evapotranspiration. A model-building tool allows a user to select the modules that are needed and combine them into a watershed model. Four watershed models have been constructed for the Yakima River Basin using MMS. These models were used to simulate unregulated daily streamflow for 52 years of record for 51 subbasins to provide the basis for long-term policy decisions using Riverware. The models are also being used for forecasting unregulated runoff volumes for mid-term operations.

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Quaternary Geology of the Puget Lowland

Join us Wednesday evening, April 9th, at 6:00 PM for an informal forum to discuss and display our collective understanding and recent advances in unraveling the Quaternary geology of the Puget Lowland. Current research efforts include stratigraphy and chronology, distribution and correlation, structure and tectonics, and new mapping and detailed site investigations. Stratigraphic and chronologic methods in use include tephrochronology, and radiocarbon, fission-track, and luminescence dating. Distribution and correlation methods, such as paleomagnetic determinations, bulk geochemistry, and pollen and diatom analyses, are enhancing our understanding of the Quaternary history. Integration of geophysical and geological data sets is producing a clearer picture of the tectonic setting of the Puget Lowland and the degree to which Quaternary deposits are deformed. The outcome of these investigations is a new generation of geologic maps and other products from academic, agency, and consulting geoscientists.

Sponsor: The Seattle Geologic Mapping Project, University of Washington
Cost: Free to Symposium registrants
When: Wednesday April 9, 2000, 6:00 pm
Where: Sheraton Convention Center Rotunda, Tacoma

Coordinators:

Kathy Troost
University of Washington
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Any scientist or investigator who would like to bring an informal poster, display, and/or speak at the forum should contact Kathy or Derek.

Hydrogeology of the Hanford Site Vadose Zone

Bruce N. Bjornstad [1], George V. Last[2], and Duane G. Horton[3]

The vadose zone at the Department of Energy's Hanford Site in the Pasco Basin, south-central Washington, consists of mostly Pleistocene-age cataclysmic flood deposits, informally referred to as the Hanford formation. Locally, pre-flood deposits of the Cold Creek unit (formerly the Plio-Pleistocene unit) and the Ringold Formation may lie between the Hanford formation and the water table (DOE 2002). A thin veneer of post-Hanford formation, eolian deposits occurs at the surface.

Based on observations of outcrops and a limited number of drill cores, the Hanford formation can be subdivided into 11 textural-structural lithofacies, which group into three facies associations (gravel-dominated [GD], sand-dominated [SD], and interbedded sand- and silt-dominated [ISSD]). GD flood deposits lie along flood channels through the central portion of the Pasco Basin, whereas ISSD flood deposits occur around the basin margins. SD is transitional between GD and ISSD, and is the principal unit beneath the 200 Area Waste-Management Units, whereas GD predominates beneath Hanford's 100 Areas. Flood deposits are inherently heterogeneous and anisotropic due to the highly complex interplay between channels and bars during multiple flood episodes.

Moisture in the vadose zone is typically concentrated along high-contrast bed interfaces, as well as on finer grained, relatively impermeable layers within the Hanford formation and Cold Creek unit. Natural and artificial recharge water may migrate downward along discordant clastic dikes or spread laterally, sometimes in a stair-step fashion, along overlapping series of discontinuous, fine-grained strata. Moisture-trapping bed interfaces occur in all strata, but low-permeability strata occur most frequently in ISSD and least frequently in GD flood deposits.

Studies are ongoing to evaluate the physical and chemical characteristics of vadose-zone strata and assign hydrologic properties to each sediment type for modeling purposes.

DOE, 2002, Standardized Stratigraphic Nomenclature for the Post-Ringold-Formation Sediments Within the Central Pasco Basin, DOE/RL-2002-39, Rev. 0, U.S. Department of Energy, Richland, Washington.

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Alternative Conceptual Models of Sediment Geometry at the Hanford Site, Southeast Washington

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Prior uncertainty analyses of Hanford groundwater model predictions have focused on uncertainties in model parameters (e.g., hydraulic conductivity) given an assumed conceptual model of hydrogeologic structure. In this study we evaluated predictive uncertainty related to the model structure. Our study focused on two major elements of the hydrogeologic structure of the Hanford Site: the geometry of mud units that occur within the aquifer, and the parameter zonation for hydrologic properties of the uppermost conductive portion of the aquifer.

A series of stochastic simulations of the presence/absence of the mud units were prepared using geostatistical methods. The stochastic simulations were numerically ranked and a subset of the best and worst simulations (as determined by connectedness of the aquifer given the simulated mud distributions) were used as inputs to an inverse model. Inverse modeling was performed using UCODE and a finite element flow and transport code (CFEST) and used to test the fit of over 69,000 observed potentiometric head data for several alternative models of the mud distribution. Those conceptual models included the existing base case (hydrogeologists' interpretation) and the median and the extremes of the set of stochastic realizations. We compared the overall inverse model fit and the range of estimated parameters for the four alternative conceptual models to identify the relative magnitude of parameter uncertainty versus conceptual model uncertainty (model error).

We used similar methods to study the spatial distribution of aquifer sediment (e.g., gravel, sand, or silt) in the uppermost aquifer unit. Geostatistical simulations of sediment type zonation were generated and ranked based on the relative amounts and geometry of zones of varying hydraulic conductivity. Selected simulations reflecting the range of conceptual models were used as the basis for additional inverse model runs (parameter estimation). The results of the inverse modeling (parameter estimates and model fits to observations) again were compared to identify relative contributions of parametric and conceptual model uncertainty to overall predictive uncertainty.

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Geology Architecture Mapping of the Abbotsford-Sumas Aquifer

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Mapping aquifer architecture and generating layers for numerical models of aquifers provides significant challenges to hydrogeologists. Limited and often poor quality data, as well as variable data formats are significant challenges that must be overcome to generate an accurate three-dimensional representation of the aquifer. This paper describes the methodology used to collect lithologic data, and subsequently, map the architecture of the Abbotsford-Sumas aquifer as part of ongoing research by Simon Fraser University and Environment Canada to develop a regional numerical groundwater flow and transport model for the aquifer. Because the aquifer straddles the Canadian-U.S. border between the province of British Columbia and Washington State, some unique challenges were met in acquiring and using data from different jurisdictions.

Aquifer architecture has been described using cross-sections constructed from well and bore lithology information, and the identification of aquifer layers was determined primarily from control points for which reliable data were available on both sides of the border. Aquifer layer topography was generated using filtered and classified well log information from the BC Water Well Database and supplemented with US well data where available. The unconfined sand and gravel aquifer is considered highly vulnerable to contamination that originates primarily from agricultural land use activities. High levels of nitrates have been measured in the aquifer, and consequently, efforts are being made to alter land use practices and to monitoring changes in nitrate levels. The model will be used to simulate flow and transport at a regional scale, thus providing a potentially valuable a management tool for tracking and predicting non-point source contaminant migration over a large scale. The model will also aid in the development of local smaller-scale models by defining larger-scale aquifer properties and boundary conditions. Ultimately, the model may be useful for predicting the potential effects of implementing land use scenarios on the groundwater quality.

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Groundwater Implications of the Sub-Vashon Unconformity and other Discontinuities in Quaternary Deposits of the Puget Lowland, Washington

Kathy Goetz Troost

The topographic relief on the base of the Vashon Drift (i.e. its basal unconformity) is likely greater than 1400 feet, with 800 feet of erosion lying below modern sea level. The nature of the unconformity, a combination of deposition on the Olympia-age topographic surface and Vashon erosional processes, varies over short lateral distances. Where depositional, it may be marked by paleosols developed on the pre-Vashon topography. Where erosional, it truncates older deposits of variable lithology and may be virtually impossible to detect at the site scale. Paleochannels are common in the subsurface and Vashon-age channels are common at or near the modern ground surface, some of which have been filled with fine-grained and some with coarse-grained deposits. The apparent absence of Olympia-age lahars and andesitic sand on the west side of Puget Sound suggest that Olympia-age equivalents of Colvos Passage and the Tacoma Narrows channels were present near their current locations during the Olympia nonglacial interval. The Vashon glacier and its associated outwash probably filled and then re-carved at least some pre-existing channels in Puget Sound. Within the Vashon Drift, the sub-till unconformity is likewise variable, truncating buried topography and extending to well below modern sea level.

This and many other such subsurface unconformities complicate efforts at identifying stratigraphic units and, more importantly, influence local and regional groundwater flow patterns. For example, deep coarse-grained channels commonly connect shallow and deep aquifers, providing contaminant pathways into otherwise protected aquifers. Other discontinuities, such as faults, folds, sand dikes, voids, and inclusions, provide ample sources for stratigraphic misinterpretation and interference on groundwater flow. Offsets in the subsurface may exceed 7 meters as a result of faulting, causing truncation of aquifer materials or fracturing of otherwise “aquitard” materials, rendering them relatively permeable. Detailed site studies as well as regional mapping are essential in characterizing the degree of complexity in the Quaternary deposits of the Puget Lowland.

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Near-Real-Time Simulation and Internet-Based Delivery of Forecast-Flood Inundation Maps Using Two-Dimensional Hydraulic Modeling: A Pilot Study for the Snoqualmie River, Washington

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A system of numerical hydraulic modeling, geographic information system processing, and Internet map serving, supported by new data sources and application automation, was developed that generates inundation maps for forecast floods in near real time and makes them available through the Internet. Forecasts for flooding are generated by the National Weather Service (NWS) River Forecast Center (RFC); these forecasts are retrieved automatically by the system and prepared for input to a hydraulic model. The model, TrimR2D, is a new, robust, two-dimensional model capable of simulating wide varieties of discharge hydrographs and relatively long stream reaches. TrimR2D was calibrated for a 23-kilometer reach of the Snoqualmie River in Washington State, and is used to estimate flood extent, depth, arrival time, and peak time for the RFC forecast. The results of the model are processed automatically by a Geographic Information System (GIS) into maps of flood extent, depth, and arrival and peak times. These maps subsequently are processed into formats acceptable by an Internet map server (IMS).

The IMS application is a user-friendly interface to access the maps over the Internet; it allows users to select what information they wish to see presented and allows the authors to define scale-dependent availability of map layers and their symbology (appearance of map features). For example, the IMS presents a background of a digital USGS 1:100,000-scale quadrangle at smaller scales, and automatically switches to an ortho-rectified aerial photograph (a digital photograph that has camera angle and tilt distortions removed) at larger scales so viewers can see ground features that help them identify their area of interest more effectively. For the user, the option exists to select either background at any scale. Similar options are provided for both the map creator and the viewer for the various flood maps.

This combination of a robust model, emerging IMS software, and application interface programming should allow the technology developed in the pilot study to be easily applied to other river systems where NWS forecasts are provided routinely.

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A New Method for Deepening Wells That Are Going Dry

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Water levels in monitoring wells in the 200 Areas and vicinity at the Hanford Site, have been declining for eight years or more due to the decreased amount of wastewater discharged to the ground. As a consequence, more than 30 stainless steel monitoring wells have gone dry. Many more wells in these areas are expected to go dry in the next 20 years. To continue monitoring of Hanford groundwater, these wells will have to either be abandoned and replaced, or deepened. Previous efforts to deepen Hanford stainless steel wells have not been successful or cost effective. Recent developments in cutting and drilling technologies make it possible to cost-effectively deepen existing stainless steel monitoring wells at Hanford and return many dry wells to use.

Deepening of stainless steel wells was not successful previously for two primary reasons: First, the stainless steel bottom cap thwarted conventional grinding and cutting techniques. Stainless steel galls and grabs standard drilling mills, bits or cutting tools. Second, the unconsolidated nature of Hanford sediments requires that drilling and setting of screens be accomplished inside temporary casing because the formation is susceptible to caving. Deepening a well of only 4 inches inside diameter requires the use of temporary casing and drilling tools that are 3 ½ inches and smaller, which was not practical several years ago.

These two primary problems have been solved recently by the use of abrasive jetting technology to cut through the bottom of the wells and by very small drilling and casing technologies. The abrasive jetting tool, a technology developed by the University of Missouri at Rolla, MO, uses a very high velocity, thin water jet with garnet abrasive to cut quickly through the stainless steel bottom cap. With the bottom cap cut away, a narrow-diameter drilling method with eccentric bit, reversed circulation, top-head drive, and a drill-through casing driver can drill and advance narrow, temporary casing beyond the bottom of the existing well screen. When the desired amount of additional hole is drilled and cased, a new, even smaller diameter well screen can be installed and the temporary casing removed. The inside diameter of the new screen is approximately 2 inches, which is large enough to accommodate several types of small-diameter sampling pumps.

This well deepening method is being demonstrated in three wells at Hanford. The method based on previous bench scale and field tests is both quick and cost effective. The projected cost of deepening a single well during these initial trial runs would be approximately half of the cost of a new well. The cost would decrease further as the method comes into common use.

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Comparison of Field and Laboratory Methods for Detecting Low to Moderate Levels of Arsenic in Soil

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Concern over the past use of lead-arsenate pesticides in orchards is gaining attention in Washington State. Historic orchards are increasingly being converted to residential and commercial properties. Residual arsenic concentrations remain in the upper several feet of soil at concentrations as high as 400 mg/kg and the estimated excess cancer risk exceeds 10^{-6}. Higher contaminant concentrations are possible at isolated "hot spots."

There are a variety of methods and technologies on the market today for determining the concentration of arsenic in soil. The Washington State Department of Ecology (Ecology) will compare the cost, ease, accuracy, and limitations of five different analytical methods used to determine arsenic concentration in soil samples taken at existing public schools in two prominent orchard communities in Central Washington. The analytical methods to be compared are: Arsenic Quick™ Test manufactured by ITS, Inc., the NITON XRF field method, the NITON XRF laboratory method (EPA Method 6200), Inductively Coupled Plasma (EPA Method 6010), and Graphite Furnace Atomic Absorption (EPA Method 7060). Results from the study will be used to help determine appropriate analytical methods to aid in characterization of arsenic, guide remediation activities, and confirm cleanup action completion.

Preliminary sample results indicate that when comparing Inductively Coupled Plasma (ICP) to Graphite Furnace Atomic Absorption (GFAA), NITON laboratory, and NITON field methods, there is a correlation of greater than 90% for each case. When comparing ICP to The Arsenic Quick™ Test, a colorimetric method, there is a correlation of less than 70% between the two methods.

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Well Deterioration and Rehabilitation – Extending a well's Efficiency and Effective life

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Expanding population, tightened state and federal regulations regarding drinking water standards, aquifer water rights issues, and the cost of new well construction place great pressure on water system purveyors to supply adequate potable water to meet current and projected demand. Well owners with adequate water well maintenance and rehabilitation programs are able to maintain a higher well efficiency for significantly longer periods, allowing the well owner to better manage water resources. The cost of new well construction along with regulatory and water right issues make well rehabilitation a cost-effective solution to increasing well efficiency.

An adequate aquifer yield evaluation and a proper well screen design is critical to maximizing the potential yield of a well. Well efficiency and yield begins to deteriorate shortly after it is constructed and placed into operation. Many factors both natural and operational contribute to this deterioration. Primary factors that stress a water well and contribute to its deterioration include poor well location, bacterial growth, mineralogical precipitation, over-pumping, and poor pump placement.

A consistent long term well monitoring program is the most cost effective way to track the health of a well. Some simple inexpensive monitoring approaches include keeping a record of specific capacity changes, water quality sampling, and occasional bacteriological testing.

With a basic well monitoring program, the well owner will know when it is time to rehabilitate. Well rehabilitation technologies are divided in three broad categories, mechanical, chemical and impulse generation. Mechanical techniques include brushing, surging, jetting, and freezing. Chemical techniques primarily consist of dispersants and hot or cold acids. Impulse generation technologies include high pressure gas and explosive charges. Selection of the most appropriate method depends on aquifer characteristics, well design, and reason for the reduction of well efficiency. It is important to realize that the longer rehabilitation is delayed in a well with declining yield, the less likely it is that the original yield is recoverable. Research and experience indicate that the optimum time to rehabilitate is when the well has lost about 20% of its original specific capacity.

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Numerical Modeling to Evaluate Streamflow Effects of a Wet-Pit Aggregate Mine

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A proposed wet pit, aggregate mine on a drift plain in Mason County was required to estimate baseflow effects in John's Creek, Mason County, because the creek is closed to further appropriation from September 15 to November 15. When mining is complete, several pit lakes totaling 24 acres will occupy the 124-acre site. The lakes are expected to reduce groundwater recharge, create higher permeability zones associated with lake excavation, and alter seasonal wetland stages near the lakes. Water use for aggregate washing and other mine activities will be limited to 5,000 gallons per day (0.008 cfs). Quasi-three-dimensional numerical modeling was used to estimate the baseflow effects and identify a mine build-out configuration that minimized the effects.

Recessional outwash will be mined below the water table in places. Groundwater in the outwash flows toward John's Creek, about 1,000 feet south of the mine, and also percolates slowly down through underlying till to an advance outwash aquifer. Groundwater in the advance outwash discharges to lower John's Creek and Oakland Bay. A set of streamflow seepage measurements revealed the approximate rate of outflow from both aquifers during August baseflow conditions.

Natural recharge occurs at approximately 44 in/yr, while open-water evaporation occurs at approximately 3 in/yr greater than evapotranspiration (ET) from native vegetation. Reduction in groundwater recharge from 24-acres of lake will reach a maximum of 0.12 cfs (52 gpm) during warm months. In comparison, baseflow in the nearest reach of Johns Creek ranges from 2 to 4 cfs.

Numerical modeling revealed that seasonal baseflow reduction due to the pit lakes is dampened with distance and lagged in time at the stream, depending on the position of the lakes. The resulting rate of baseflow depletion will be significantly less than the seasonal reduction in the rate of groundwater recharge. A variety of pit-lake configurations and locations were simulated to identify locations that minimized baseflow reduction and wetlands stage changes, while maximizing aggregate removal. Wetland locations and hydrogeologic factors, however, restricted the possible lake locations. Simulation of the most favorable lakes configuration indicated maximum baseflow reduction of approximately 0.02 cfs (8 gpm), about 16% of the maximum reduction in recharge, and maximum wetland stage reduction of approximately 0.3 feet. Moving the lakes farther from the stream decreased the baseflow reduction, because specific yield mitigated for a larger part of the recharge reduction as distance increased.

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Integration of a Detailed Groundwater Model into a Regional (HSPF) Model

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Expansion of Seattle-Tacoma International Airport (STIA) requires the importation of about 20 million cubic yards of fill. The fill would create an embankment up to 160 feet thick. Permitting requires the prediction of changes to flows in adjacent streams. The primary analysis tool was a basin-wide HSPF model supported by GIS. However, independent modeling of groundwater flows within the embankment predicted flow lags that could not be simulated by HSPF. Therefore, modeling of the embankment was conducted using a combination of numerical groundwater models. The groundwater analysis yielded daily lateral groundwater flows from soils at the base of the embankment, and downward leakage to a regional aquifer under the embankment. The lateral groundwater flows were imported back into HSPF as discharges directly to the stream, and the downward groundwater flows were imported back into the HSPF active groundwater reservoir. By this approach, water on and in the embankment was modeled independent of HSPF by methods that considered physical groundwater hydraulic variables, and reinserted back into HSPF at appropriate times and locations.

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Application of the Mike SHE model to Watershed Planning – Little and Middle Spokane Watersheds

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The planning unit representing Watershed Resource Inventory Areas (WRIAs) 55 and 57 chose to use Mike SHE modeling software from DHI Water and Environment as part of the technical assessment for the watershed planning process under RCW 90.82. The main goal of the modeling process is to support decision-making during development of the watershed plan. The model is intended to simulate the processes driving the hydrology of the watershed and provide a "what if" tool for stakeholders.

Mike SHE is a deterministic, distributed and physically based modeling system. The basic Mike SHE model includes six modular components; each describing a major flow process of the hydrologic cycle. These include interception/evapotranspiration, overland flow, channel flow, unsaturated zone flow, saturated zone flow, and snow melt. Additionally, in the Spokane Watersheds, simulation of lawn watering and agricultural irrigation was included. A primary benefit of the Mike SHE modeling environment is its ability to simulate groundwater and surface water interactions.

The modeled area encompasses two administrative watersheds: WRIA 55 and WRIA 57. These watersheds are located just west of the Washington-Idaho Stateline and encompass more than 700 square miles. The Spokane Valley includes one of the most productive aquifers in the United Sates: the Spokane Valley-Rathdrum Prairie Aquifer. This aquifer hydraulically links WRIA 55 and WRIA 57 influencing the decision to combine the planning process for the two watersheds. The Spokane Valley aquifer interacts with the Spokane River in WRIA 57 and discharges a significant amount of water into the lower Little Spokane River of WRIA 55.

This presentation will discuss the strengths and weaknesses of the Mike SHE model based on its application in the Little and Middle Spokane Watershed and application to watershed planning.

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Inverse Modeling of Alternative Conceptual Models of Groundwater Flow at the Hanford Site

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A regional-scale, three-dimensional groundwater flow and transport modeling effort is ongoing to quantify the environmental consequences of past waste disposal activities and support environmental management activities at the U.S. Department of Energy's Hanford Site in southeastern Washington. An important element of this effort is the identification and quantification of uncertainties associated with model predictions. It is recognized that such uncertainties arise not only from selection of inappropriate groundwater model parameters (parameter error), but also from the underlying conceptualization of the groundwater system (model error). Therefore, we have adopted an approach to uncertainty characterization that involves the evaluation of multiple alternative conceptual models (ACMs) within an inverse modeling framework.

Inverse modeling applied to a regional, three-dimensional aquifer is computationally demanding. Implementation was made feasible by development of a multi-processor implementation of the UCODE inverse modeling system. This system has been applied to evaluate the validity of several ACMs. An improved conceptual model of the 3D structure of the aquifer system, developed by Hanford Site geologists, was utilized as the basis for the ACMs. Initially, the pattern of transmissivities determined in a previous 2D inverse modeling exercise was mapped into hydraulic conductivities of the 3D model, and the inverse model was used to determine scaling factors for each layer. The inverse model led to estimates of some parameters (particularly specific yield) that were not plausible, suggesting conceptual model problems. Therefore, additional ACMs were developed and subjected to inverse analysis, including an alternative with modified boundary conditions (leaky underlying bedrock), an alternative incorporating surface recharge modifications based on surface run-on from an adjacent topographic feature, and an alternative incorporating an improved description of the timing and volume of waste discharges arriving at the water table (upper model boundary). Model predictions of transient hydraulic heads under each ACM were compared to 69,000 historical head observations, and estimated parameters were evaluated for plausibility. Finally, links to the former 2D model were abandoned in favor of a geologically-based aquifer zonation. The inverse framework is currently being used to modify the zonation pattern for hydraulic properties in the uppermost transmissive layer of the aquifer.

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Hydrofracturing a Shallow Aquitard to Enhance Solvent Recovery

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Weyerhaeuser Company operated the former Woods Line Railroad east of Klamath Falls, Oregon, that included a locomotive maintenance facility. Solvents used during engine maintenance impacted the unsaturated zone, an aquitard, and aquifer beneath the maintenance shop. Remediation of the unsaturated zone and aquifer are being performed using soil-vapor extraction (SVE) and a pump-and-treat system, respectively. The unsaturated zone is approximately 10-feet thick and consists of silt and fine sand. The aquifer extends from about 30 feet below grade and consists of sand.

Between the unsaturated zone and the aquifer is an aquitard composed of indurated diatomite. Soil borings and monitoring wells indicated that a high proportion of the mass of solvents released during locomotive maintenance were retained by the diatomite. To reduce the potential for migration of solvents from the aquitard to the aquifer, Weyerhaeuser decided to explore methods for removing the solvents from the aquitard.

Aquitard solvent removal options that were evaluated included excavation of the aquitard with above-grade air stripping, installation of horizontal wells combined with enhanced anaerobic bioremediation, 6-phase heating of the soil with SVE, and a dual-phase groundwater-SVE system. The latter option was chosen because of site constraints. Preliminary design of the dual-phase system indicated that 40 to 60 extraction wells would need to be installed to maximize capture of the solvents. To reduce the number of wells, Weyerhaeuser decided to hydrofracture the diatomite.

The hydrofracturing process required drilling to near the base of the diatomite and injecting water under pressure to enhance the naturally occurring vertical fractures in the diatomite. Two test boreholes were drilled and fractured using a dual-packer system. In the first borehole, hydrofracturing at the 20-foot depth was initiated after reaching an injection pressure of 325 psi. After fracturing began, the injection pressure was reduced to 100 psi, and the borehole intake rate was 44 gpm. The calculated permeability increased from <0.04 ft/day (pre-fracturing) to 3 ft/day after hydrofracturing. Similar results were observed in the second borehole. Based on these results, a full-scale hydrofracturing program was designed and implemented.

Subsequent hydrofracturing was performed using a guar gum and fine-sand slurry in place of water to maintain the fractures. Six extraction and 5 injection wells were installed in the fractured boreholes. Initial operation of the system in 2002 indicated the hydrofracturing enhanced solvent recovery in the aquitard.

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Field Application of In-Well Aeration System For Perchloroethene Remediation

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In-well aeration also called density driven convection (DDC) was tested for groundwater cleanup of perchloroethene (PCE) also called tetrachloroethylene and associated substances (trichloroethene, dichloroethenes, and vinyl chloride) at the Juanita Village site near the north shore of Lake Washington, Kirkland, Washington. Juanita Village LLC did not cause the contamination and have volunteered to cleanup the site under a Prospective Purchaser Consent Decree with Washington State Department of Ecology under the Model Toxics Control Act WAC 173-340-520. The technology involves injecting air below the water table in vertical wells that have been screened at two depths. The aerated water is forced up and out through the upper screens by inflow water through the bottom screens due to density differences. Volatile contaminants, such as PCE, are stripped from the water, as the air bubbles out of the water at the top of the water table. The contaminant-laden air is drawn off by a soil vapor extraction system and then passed through a series of carbon filters. The treated groundwater is never brought to the surface, but discharged through the upper screens into the unsaturated zone to percolate back down to the groundwater. This DDC treatment is designed using 13 treatment wells each with an estimated 100 ft radius of influence and 9 monitoring wells. Pilot testing and four quarters of full scale remediation show a significant decrease in PCE concentration. Results show PCE concentrations decreasing from a maximum 2600 to 63 ug/L (micrograms per liter or parts per billion) at the heart of the plume (MW-4). Currently, monthly air monitoring data show PCE mass removal rate of 1.25 pounds/month and a total estimated quantity of 217 pounds of PCE removed. Groundwater results show declining PCE concentrations in a majority of wells with several wells at or near the 5 ug/L cleanup level. PCE concentration has fluctuated in a few wells that may represent variations in substrate and localized concentration. Overall, DDC treatment shows an average site improvement at 68%. To date, none of the associated compounds, such as TCE, DCE, and VC has been detected in the groundwater. In summary, DDC has proved to be a reliable remediation treatment method. It is cost and time effective, and applicable to volatile and some semi-volatile organic compounds.

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Effectiveness of Open Bottomed Sheet Pile Containment Structures in Controlling Groundwater Contamination in a Tidally Fluctuating Aquifer

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Three open bottom (hanging) containment structures were installed in 1994 as an interim measure to control chlorinated solvent plumes at an aircraft parts and fabrication facility in King County, Washington. These containment structures, located within 350 feet of the tidally fluctuating Duwamish Waterway, were constructed by driving interlocking sealable (Waterloo Barrier™) sheet piles into the ground (to depths of 25 to 50 feet below the ground surface) using a vibratory hammer. A series of water quality and hydrologic studies were conducted to determine if the containment structures are effective in isolating the solvent plumes from the surrounding groundwater flow system and damping tidally induced water table fluctuations.

The water table aquifer is 80- to 90-feet thick and consists of sand and silty sand. Ground water in the aquifer discharges into the Duwamish Waterway, which can tidally fluctuate as much as 12 feet. Observed tidal efficiencies of wells in the vicinity of the containment structures ranged from 6 to 60 percent. Tidal efficiencies of closely located wells inside and outside of the containment structures are similar indicating that no significant attenuation of the tidal wave occurs due to the containment structures. Vertical gradients both inside and outside the containment structures are upward.

The maximum concentrations of trichloroethene (TCE) detected in groundwater within the contaminant structures range from 10,000 to 380,000 ug/L. The concentrations of TCE and associated degradation products have generally been declining. The spatial distribution of TCE has not changed demonstrating that little chemical migration is occurring inside the structures. In monitoring wells screened downgradient or below the containment structures, TCE and associated degradation products either have not been detected or if detected concentrations have been declining. The distribution of dissolved chlorinated solvents demonstrates that chemical migration from within the containment structures is prevented by the elimination of horizontal groundwater flow, absence of recharge and the presence of favorable vertical gradients.

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Remediation of Metals and Organics through the Use of ElectroChemical Remediation Technologies

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ElectroChemical Remediation Technologies (ECRTs) are a field, empirically-based suite and use electrochemical and/or electrokinetic processes to remediate organics and metals in soil, sediment, sludge, or ground water. ECRTs cause chemical reactions in the formation that (1) complex metals, transport these complexes and naturally-occurring ions down the electrokinetic gradient, and generally deposit them at the electrodes by the Induced Complexation process, and (2) mineralize organics by the ElectroChemicalGeoOxidation process. Reaction rates are inversely proportional to grain size. Over 50 sites totaling two million metric tons of soil, sediment sludge, and ground water with a wide range of organic and metal contaminants have been remediated in Europe using ECRTs. Presented will be results from demonstration and full-scale remediation projects in Europe and the U.S.

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Poster

Abstracts

Dissolved Pesticide Mass Discharge In A Semi Arid Dryland Agricultural Watershed At The Field And Basin Scale

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The goal of this research is to use environmental tracers to quantify the contributions of subsurface and surface runoff to predict the loading of non-point source pollutants to rivers at multiple scales of study (field to basin). Two environmental tracers, electrical conductivity (EC) and silica, are used to separate stream hydrographs into flow components and these are used to predict the mass discharge of two pesticides.

The study area is the Missouri Flat Creek watershed, a 7,000 ha semi-arid dryland agricultural setting located near Pullman, WA. Surface and ground water samples are collected at approximately two-week intervals from an ephemeral stream and a tile drain located in actively farmed and topographically constrained fields (~6 ha) and from four stream-gauging stations. Surface water discharge is monitored continuously. Samples are analyzed for two pesticides (the insecticide lindane or *gamma*-hexachlorocyclohexane (HCH) and the herbicide triallate, S-(2,3,3-trichloroallyl) diisopropylthiocarbamate), and the environmental tracers. Lindane is applied as a seed coating to winter and spring crops planted in the watershed. Triallate is applied to fields in a granular form to fall and spring cropped fields.

A three-component (overland flow, shallow soil water and ground water) chemical hydrograph separation is performed on stream flow by assigning EC and silica end-member concentrations to the components. Overland flow and shallow soil water end-member chemistry is represented by observed ephemeral stream and tile drain chemistry, respectively. The ground water end-member is qualitatively estimated from summer low flow (base flow) stream chemistry. The resulting flow components are used to estimate dissolved pesticide mass discharge contributed via each flow pathway and to predict stream pesticide mass discharge.

Ephemeral stream (edge of field) pesticide concentrations exhibit a first-order decline over two seasons following application. The prediction closely estimates seasonal trend, magnitude, and variability of observed dissolved triallate and lindane mass discharges. At two scales of stream observation (660 ha (field) and 4,700 ha (larger watershed)) for triallate and lindane the ratio of log predicted to log observed pesticide mass discharge is approximately 1. The agreement between predicted and observed pesticide mass discharge supports the hypothesis that in-stream dissolved pesticide is derived from annual surface runoff. The model allows estimation of temporal variation of discharge contributions.

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A Geologic Source of Arsenic in Washington State Ground Water: A Literature Review

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In 2001, the United States Environmental Protection Agency published a revised arsenic maximum contaminant level (MCL) for arsenic in drinking water of 10 μg/L. The regulatory MCL revision focused public attention on the occurrence and sources of arsenic in ground water. The goal of this project was to explore geologic source(s) to explain spatial ground water arsenic concentration patterns within Washington State at a regional scale. For this purpose, we overlay publicly available ground water arsenic concentration data, obtained from the United States Geological Survey and the Washington State Department of Health, with knowledge of potential geologic history and sources.

Five regions within Washington State containing significant numbers of ground water samples with arsenic concentrations ≥10μg/L were identified. (It is noted that regional coverage for many counties in Washington State was limited with western Washington having the most extensive data coverage.) The five regions identified were the Puget Sound area, the Bellingham and San Juan area, central Okanogan County, Yakima County especially along the Yakima River, and at the intersection of Benton, Franklin, and Walla Walla Counties. In all five areas, the elevated arsenic concentrations appear to occur within aquifers comprised of glacially derived sediments and weathered rock material from the Cascade Mountains or northern Idaho. Samples with arsenic concentrations ≥10μg/L were identified at all depths within these regions.

We hypothesize that the elevated (≥10μg/L) arsenic ground water concentrations occur in part because the aquifer materials incorporate glacially derived and transported sediments from arsenic-bearing parent rocks. The many historic mines in the Cascades that mark the locations of deposits where arsenic-bearing rocks were of primary or secondary economic value support this hypothesis. Subsequent to deposition, geochemical processes affect the release of arsenic from the sediments to groundwater. We recommend that further work to test this hypothesis coupled with an understanding of aquifer geochemical conditions associated with arsenic concentrations elevated above the MCL in these aquifers will provide benefit to water providers in the State of Washington.

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Rain-on-Snow and Nitrate Transport

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Rain-on-snow events are common during the late autumn and early spring in the western Cascade and Olympic Mountains of Washington, particularly at mid-elevation sites. These events can cause both moderate and extreme floods and can be important in shaping channel and floodplain morphology. In addition, these large pulses of water are highly effective in transporting solutes present in current precipitation or accumulated in the snowpack to surface water. As N deposition increases globally due to increases use of fossil fuels and fertilizers it is vital that we understand not only the effect of N on ecosystems, but how variation in the hydrologic cycle will affect the fate and effect of added N in both terrestrial and aquatic systems.

During the mid-1990s the Pacific Northwest coast experienced a period of elevated NO_3 deposition, primarily during the late winter and early spring that caused increases in the streamwater NO_3 concentration of West Twin Creek. West Twin is a first-order tributary of the Hoh River that has been the site of a watershed monitoring program since 1984. Previous work in the watershed had produced no evidence that it was approaching N saturation, and there was much evidence suggesting that the watershed would retain N. Subsequent research has strengthened this finding and shown that soils in the watershed can retain NO_3-N. Nonetheless, a pulse of NO_3 delivered between February 6 and March 6 1994 moved through the system without moderation. Meteorological and hydrologic data from this period suggest that the NO_3 was delivered during the rain portion of a rain-on-snow event, creating a large flux of both solutes and water which either overwhelmed or bypassed biological control mechanisms.

Nitrate Distributions in a Portion of the Abbotsford-Sumas Aquifer, Northwest Washington

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The Abbotsford-Sumas aquifer is a shallow, predominantly unconfined aquifer that spans regions in southwest British Columbia, Canada and northwest Washington, USA. The aquifer has a history of nitrate contamination because of the extensive agricultural practices that exist in the lowlands above the aquifer. Due to southerly groundwater-flow directions, land-use practices in British Columbia can contribute to elevated groundwater nitrate concentrations in Washington, making it difficult to manage nutrient loading in the region. Our study area (10 sq-km) is adjacent to the international boundary in northwest Washington. We are measuring groundwater nitrate from 25 domestic wells in the study area on a monthly basis to quantify nitrate distributions and to assess the impact of nutrient management plans. We are also attempting to estimate groundwater nitrate originating upgradient in British Columbia using well depth below the water table as a proxy for groundwater age.

Sampling started in July 2002. To date, most of the wells in the study area have yielded nitrate values above 3 mg nitrate as nitrogen per liter (mg-N L^{-1}), indicating anthropogenic sources. Nitrate concentrations in excess of 10 mg-N L^{-1} have been observed in over half of the domestic wells sampled. Nitrate concentrations in a few locations have exceeded 25 mg-N L^{-1}. The nitrate distribution is characteristic of non-point agricultural sources and consistent with historically observed nitrate contamination in many parts of the aquifer. The highest concentrations (>25 mg-N L^{-1}) are from shallow regions of the aquifer and are assumed related to agricultural practices in the study area. Nitrate concentrations (>10 mg-N L^{-1}) measured in deeper wells, and in wells near the international border, suggest agricultural sources in British Columbia. Nitrogen isotope data are also being used to assess source variations in the study area. Because of the identification of multiple sources in the study area, conservationists and farmers are faced with a difficult task in establishing effective management plans for protecting drinking water in the region.

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Predicting the Heterogeneous Distribution of Aquifer Permeability Through Lithofacies Mapping Method

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Prediction of permeability by way of lithofacies mapping techniques can be used to quantify subsurface heterogeneity. In this project, we test the hypothesis that hydrologic properties that control subsurface contaminant transport are correlated to lithofacies. The accuracy of using lithofacies to predict permeability was tested by comparing the statistical characterization of permeability (e.g. mean, variance, normality) by lithofacies determined for sediment samples for cores collected along two transects (parallel and transverse to groundwater flow) in the Borden aquifer (Ont., Canada). The original statistical characterization of permeability in ten lithofacies, (separated by second-order, typically weakly erosional bounding surfaces) was defined in cores oriented parallel to groundwater flow. Lithofacies mapping identified nine of these ten lithofacies in cores oriented transverse to the groundwater flow; the mean, variance, and shape of the permeability cumulative distribution function (cdf) were compared to those defined in the parallel orientation.

Samples from the cores along the section transverse to groundwater flow showed little variation in the permeability cdf from the parallel transect in six of the nine mapped lithofacies. Moderately- to well sorted, laminated and cross-stratified lithofacies returned predictable permeability measurements (e.g. similar mean, variance, cdf shape for samples from a particular lithofacies taken from each of the two core transects). The shapes of the cdfs are similar for most lithofacies, but three differ in their mean value and/or variance of k. The two lithofacies showing inconsistent mean k for two directions were massive coarse grained (MCG), and high-angle planar cross-stratified (HPXS) lithofacies. The massive fine-grained lithofacies (MFG) showed an inconsistent variance of k for samples from the two transects. These three lithofacies are generally more poorly sorted than the other six lithofacies. For these samples, it may be possible that relatively subtle differences in grain size and sorting cause these differences. Additionally, the lithofacies mapping methods appear to predict the occurrence and thickness of the units between the two transects, allowing for a three-dimensional characterization

This comparison study shows that lithofacies can provide a framework to estimate the three-dimensional permeability field spatial distribution for a sedimentary aquifer. Such a finding presents opportunities to improve contaminant transport prediction and remediation efficacy.

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Groundwater Modeling of the Tacoma Landfill

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Tacoma Landfill is part of the Commencement Bay/South Tacoma Channel Superfund Site. The City of Tacoma entered a Consent Decree with the Environmental Protection Agency and Department of Ecology in 1992 to remediate landfill groundwater contamination. Under the Consent Decree a groundwater extraction and treatment system was designed, installed, and put into operation to remediate groundwater contamination.

A three-dimensional numerical groundwater flow model was developed during 1991 to evaluate site conditions and select the extraction system at the point of compliance.

A numerical groundwater flow model is currently being developed using GMS 3.1 software. GMS 3.1 is a groundwater modeling package that provides support for MODFLOW, MODPATH, MT3D, and RT3-D. GMS 3.1 data entry is via a graphical interface. The computer based model provides 3-D representation of the groundwater flow system. The purpose of the model is to assess current site groundwater flow and capture zone conditions.

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Evaluation of the Interpretation of Groundwater Elevations and Landslide Slip Surfaces through the use of Ground Penetrating Radar

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Groundwater elevations and landslide slip surfaces are commonly delineated through the use of subsurface exploration such as borings, test pits, etc., together with instrumentation such as tiltmeters, inclinometers, extensometers and/or piezometers. These methods offer finite discrete data at specific locations. These locations are often sparse because of the high cost of borings and instrumentation. Landslide slip surfaces and groundwater elevations must then be determined by interpretation of the data and extrapolation between measured locations. There have been advances in technologies to assist in the interpretation of groundwater and landslide data, but there has been little development of new instrumentation technology in the field. Most methods used for groundwater and slip surface delineation incorporate invasive techniques such as borings and trenching and this is not always a feasible approach due to access and possible property damage associated with these methods. With little development of new technologies to delineate landslide slip surfaces and the associated risk commensurate with groundwater elevations, there is a clear need for new techniques to determine landslide slip surface location and associated groundwater elevation. This study will address one such technique: ground penetrating radar (GPR).

In this study, we present a preliminary assessment of ground penetrating radar data obtained from transects completed on a translational landslide located near Eldon, WA. Investigations conducted by the Washington State Department of Transportation delineated the translational landslide slip surface occurring at approximately 10-13 meters below ground surface with perched groundwater occurring above the slip surface at various elevations. Horizontal drains were installed in June of 2000 to lower the groundwater elevations above the landslide slip surface and decrease the level of risk groundwater will play on further landslide movement.

Preliminary GPR data obtained in September of 2002 displays radar anomalies where the landslide slip surface has been delineated through traditional exploration methods. The GPR data also displays high amplitude reflections, typical of groundwater, where groundwater is suspected to be located above the slip surface. This data indicates the possibility of using GPR to locate landslide slip surfaces and seasonal groundwater fluctuations that pose a risk to further landslide movement.

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Application of LIDAR Terrain Mapping to Flood-Hazard Mapping

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Hurricane Mitch, a category 5 hurricane, struck Honduras in late October 1998. Several days of intense rain from this hurricane caused devastating floods and landslides throughout the affected area, killing 7,000 people and destroying 33,000 homes and 95 bridges. The U.S. Agency for International Development requested that the U.S. Geological Survey develop flood-hazard maps for 15 municipalities in Honduras to help plan the rebuilding of housing and infrastructure. An airborne light-detection-and- ranging (LIDAR) survey was used to collect high-resolution topographic data that formed the basis for the flood-hazard maps.

The LIDAR terrain-mapping system and a vegetation-removal algorithm were used to obtain high-resolution, "bare-earth," digital-elevation models (DEMs) of the river floodplains and above-water portions of channels during low-flow conditions. Selected river cross sections were computed from the DEMs and used in a one-dimensional, steady-flow, step-backwater hydraulic model to estimate the water-surface profile of the 50-year flood discharge. The water-surface profiles and floodplain DEMs were used in a geographic information system to generate maps of the depth and extent of the 50-year flood inundation of each municipality.

The Bureau of Economic Geology, Coastal Studies, at the University of Texas oversaw the acquisition and post-processing of LIDAR data. Reported vertical accuracy was 0.15 meter at a 1,200-meter operating altitude. The accuracy of the LIDAR data was assessed by comparing results with independent Global Positioning System (GPS) field surveys. The comparisons showed vertical errors as much as 0.78 meter, but the standard deviations of errors were all within 0.11 meter for all sites. In all LIDAR surveys, horizontal agreement between the GPS-derived points and LIDAR data was within the 1-meter cell resolution of the DEM. Overall, the vegetation-removal algorithm worked well, although some crops, such as sugarcane and oranges, could not be removed or were only partially removed.

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Quantifying Thermal Variations in Lower Granite Reservoir using Satellites and 3-D CFD

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Validation against independent data is an essential element of any computational fluid dynamics (CFD) modeling activity. In the past, water temperature calibration datasets have generally originated from fixed temperature monitors. This project demonstrates that satellite images of corrected surface water temperatures can also be used as an additional dataset for synoptic calibration/validation of surface water temperatures calculated by CFD models.

As a case study, this ongoing project is focusing on water temperature conditions in Lower Granite Reservoir, a water body on the Lower Snake River of major importance for salmon migration. Project researchers are currently investigating the hydrodynamic impacts of cold-water releases from a tributary (Clearwater River) of the reservoir to facilitate salmon migration at thermally critical periods of the year. Preliminary field data indicate a complex, three-dimensional, thermally stratified water body downstream of the confluence, with water temperature differences in excess of 10°C during the summer months.

Imagery was obtained from the DOE Multispectral Thermal Imager (MTI) satellite. Satellite imagery was checked against in situ temperature loggers that were placed within the field of view. Water surface temperatures calculated from the satellite data are of suitable resolution (5 m visible, 20 m IR) and accuracy to synoptically validate a 3-D CFD model. Comparisons during April 2002 indicate differences between satellite-observed temperatures and field-measured temperatures of 1.0°C or less. CFD simulation results for the summer 2000 strong stratification period are similar to those observed by the DOE satellite during July 2002. These results indicate subduction of the cooler Clearwater River water under the warmer, less dense, Snake River water. These results are biologically significant to migrating anadromous salmon that must pass through this confluence area each year.

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Ground-Water Flooding Related To Local Washington Geology

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Ground-water flooding occurs almost exclusively in areas that have been covered by glaciers. The last extensive glacier in Washington advanced about 18,000 years ago. It left behind distinctive features such as ice contact depressions and outwash channels that are visible on the topographic and relief maps of the Southern Puget Sound area of Washington. In both cases, these are typically the lowest spot in the terrain. Large volumes of water flowing through the outwash channels eroded and modified the uplands but also deposited coarse sediments over the area.

Many of these outwash channels subsequently developed surface-water drainage systems. But in the abandoned outwash channels that have not developed drainage systems, a unique phenomenon may occur during flooding: The ground-water flow follows and moves progressively down the abandoned outwash channel. This is often called transient ground-water flooding. When the ground-water level rises in the low-lying areas, it is often called static ground-water flooding because it is not moving in any noticeable direction. In both cases, it can take several months for the ground water to recede from the area.

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The Hydrogeology of Northern Lummi Island, Washington

Bill Sullivan[1] and Robert Mitchell[2]

Lummi Island is a 28 sq-km island west of Bellingham in Whatcom County, northwestern Washington. The population of Lummi Island has grown steadily for decades to approximately 900 permanent and 2,500 seasonal residents. Our study focuses on the northern half of the island where most residents live and where groundwater is the sole source of potable water. The increasing demand for groundwater resources on the island has caused some wells to experience seasonal shortages and seawater intrusion, requiring an assessment of the hydrogeology for growth-management purposes. Prior to our study, the hydrogeology of the island was characterized only indirectly from maps and reports of bedrock and surficial geology, which describe two units: sandstone of the Tertiary Chuckanut Formation and a veneer of Pleistocene glacial drift, which includes glaciomarine drift at the surface and perhaps other non-marine deposits at depth. Little was known about the actual vertical or lateral extent of the units, or their hydrogeologic properties.

To characterize the hydrogeology of northern Lummi Island, we examined data collected from over 60 wells, including well logs, seasonal depth-to-water measurements, GPS locations, and water chemistry. These data were used to describe the hydrogeologic units and groundwater-flow patterns, and to delineate regions of the island affected by seawater intrusion. Preliminary assessment of the data confirms that northern Lummi Island has two major aquifers, with sandstone dominant in northern half of the study area and glacial drift dominant in the southern region. Holocene alluvial beach deposits comprise small, shallow unconfined aquifers in some coastal areas. Approximately 50% of wells in the study area draw from the sandstone aquifer and most of these are completed below sea level. The wells in the glacial-drift aquifer are completed in fine-sand lenses, which comprise both perched and confined aquifers. Artesian and flowing artesian wells indicate one or more confined aquifers near several coastal regions on the island. Seawater intrusion mainly affects coastal areas having relatively high densities of wells, and has affected every type of aquifer.

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Clover Creek Watershed: Using Indicators to Monitor the Environmental Health

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An ongoing assessment of the health of the Clover Creek watershed in Pierce County was conducted by students at Pacific Lutheran University in the class "Environmental Methods of Investigation." This study spans 10 years, during the summers of 1992-1996 and the springs of 2000-2002. The Clover Creek watershed has land use ranging from high density residential to small farms and large industries. It includes the city of Lakewood, unincorporated Pierce County, and McChord Air Force Base. Geological, chemical and biological field data from the stream were collected as well as assembling land use, economic, demographic, and political data from the entire watershed.

Using the goals of various stakeholders in the watershed (Pierce County, City of Lakewood, McChord Air Force Base, Chambers-Clover Watershed Management Committee and Clover Creek Council) and the data gathered, an indicator study of the environmental health of the watershed has been updated. These indicators include measures of the creek: turbidity, temperature, fecal coliform, pH, discharge, dissolved oxygen, nitrate, pollution tolerance index, and water quality index as well as characteristics of the watershed: average payroll, impervious surface, business sectors, sewered area, open space, population growth, and traffic counts.

These data reveal a creek system that meets most state standards for water quality of a Class A stream (temperature, pH, and dissolved oxygen) and that appears to be improving in health slightly over time. However, the impact of human activity is of concern for the health of the watershed as the population continues to grow and the pace of development remains high. For each indicator a goal or benchmark value was identified and specific recommendations were made to help the community improve the environmental health of the watershed. It is hoped that this study will be of use to various stakeholders as strategies for management of the Clover Creek watershed are developed in the future.

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Surface Water-Ground Water Interactions Along the Lower Dungeness River and Vertical Hydraulic Conductivity of Streambed Sediments, Clallam County, Washington, September 1999-July 2001

F. William Simonds[1] and Kirk A. Sinclair[2]

Three field methods were used to characterize the interchange between surface water and ground water along the lower 11.8 miles of the Dungeness River corridor in northeastern Clallam County. In-stream mini-piezometers were used to measure vertical hydraulic gradients between the Dungeness River and the water-table aquifer at 27 points along the river and helped to define the distribution of gaining and losing stream reaches. Seepage runs were used to quantify the net volume of water exchanged between the river and ground water within each of five river reaches, termed "seepage reaches." Continuous water-level and water-temperature monitoring at two off-stream well transects provided data on near-river horizontal hydraulic gradients and temporal patterns of water exchange for representative gaining and losing stream reaches.

Vertical hydraulic gradients in the mini-piezometers were generally negative between river miles 11.8 and 3.6, indicating loss of water from the river to ground water. Gradients decreased in the downstream direction from an average of -0.86 at river mile 10.3 to -0.23 at river mile 3.7. Small positive gradients (+0.01 to +0.02) indicating ground-water discharge occurred in three localized reaches below river mile 3.7. Data from the seepage runs and off-stream transect wells supported and were generally consistent with the mini-piezometer findings. An exception occurred between river miles 8.1 and 5.5 where seepage results showed a small gain and the mini-piezometers showed negative gradients.

Vertical hydraulic conductivity of the riverbed sediments was estimated using hydraulic gradient measurements from the mini-piezometers and estimated seepage fluxes. The resulting conductivity values ranged from an average of 1 to 29 feet per day and are comparable to values reported for similar river environments elsewhere.

The results of this study will be used to calibrate a transient, three-dimensional ground-water flow model of the Sequim-Dungeness peninsula. The model will be used to assess the potential effects on ground-water levels and river flows that result from future water use and land-use changes on the peninsula.

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Preliminary Numerical Modeling of Groundwater Flow on the Swinomish Indian Reservation

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The Swinomish Indian Reservation (Reservation) comprises an area of approximately ten square miles located west of the Swinomish Channel on the southeast portion of Fidalgo Island near LaConner, Washington. The Reservation is underlain by unconsolidated Quaternary glacial and non-glacial sediments above impermeable bedrock The groundwater system beneath the Reservation is an island aquifer system. Five hydrogeologic units have been identified within in the study area based on well logs and subsurface data. These units include two aquifers (the Vashon Advance (Va) and Sea-level (Sla) aquifers) sandwiched within three low-permeability units (an upper till unit (till), the Olympia Confining unit (Oc), and an undifferentiated unit (U)). A preliminary numerical model of the groundwater system was constructed using Visual Modflow (Waterloo Hydrogeologic Software, v. 2.8.1). Surface elevations, hydrogeologic unit contacts, boundary conditions, recharge rates, representative hydraulic properties for materials in each unit, and monitoring and domestic well locations and construction information were input based on information determined or collected in previous studies. Head observations for monitoring and domestic wells were also input for model calibration.

This groundwater flow model is used to assess potential impacts of specific permitted land uses to the availability and, to a limited qualitative extent, quality of groundwater on the Reservation. The model also provides insight into the relationships between groundwater and surficial waters (perennial and seasonal streams and wetlands) on the Reservation. Future iterations of the model will incorporate additional data as they become available to improve quantitative accuracy for these applications, as well as provide for new applications within land use planning and resource protection.

The preliminary numerical model of groundwater flow highlights data gaps limiting our understanding of the local groundwater system and the accuracy of the model. Many of the data input (or used to estimate values that were input) to the model were not collected specifically for Reservation-wide hydrogeologic analysis, but were scavenged from site-specific hydrogeologic or geotechnical studies and well logs. Estimates of hydraulic conductivity and storativity tend to be biased toward more productive horizons within hydrogeologic units. Some geographic areas of the Reservation are poorly represented in the data set, as are some stratigraphic units. The responses of the model to these data gaps allow us to target and prioritize future hydrogeologic studies and refine our groundwater monitoring program.

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Numerical Simulation of the Ground-Water Flow System of the Colville River Watershed, Stevens County, Washington

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Increased use of ground and surface water in watersheds of Washington State has created concern for sufficient in stream flow for fish passage and other uses. The U.S. Geological Survey, in cooperation with the Stevens County Conservation District and the Colville River Watershed Planning Unit, are working to develop a long-range sustainable watershed plan to meet the needs of current and future water demands within the watershed, while also working to protect and improve its natural resources. The ground-water flow system is not sufficiently understood at the watershed scale to effectively plan and manage the use of water resources. The broad objective of this study is to develop a better understanding of the ground-water flow system of the Colville River Basin for effective planning and management of the water resources. To achieve this objective, a regional ground-water flow model of the unconsolidated deposits was constructed to simulate different ground-water use scenarios.

Data from previous aquifer tests within the study area were used to help determine transmissivity values for the different aquifers. Specific-capacity data were used to estimate hydraulic conductivities where no aquifer tests are available. The hydrogeologic framework of unconsolidated deposits was delineated in an earlier study. The model synthesized these data to simulate the watershed ground-water flow system, including components of the ground-water budget, horizontal and vertical ground-water movement, and the relations between the water-budget components. The model was based on MODFLOW-2000, the latest version of a three-dimensional, finite-difference model written by the USGS. This model version includes the Observation, Sensitivity, and Parameter Estimation software package that uses nonlinear regression to refine the magnitude and distribution of key hydraulic parameters, as well as to identify sensitive parameters or subregions in the model domain where additional hydrogeologic information would improve the flow model.

The model was calibrated to data collected in Water Year 2002 using nonlinear regression, which also calculates statistics about many aspects of the system. Water resources planners will be able to use this time-averaged model to evaluate the impacts of different ground-water use scenarios on ground-water levels and surface-water discharge in the watershed.

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Characterization of geomorphology and hyporheic conditions of spring chinook salmon spawning habitat within the Yakima River Basin

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A better understanding of the critical features of salmon spawning habitat is needed in order to advance salmon restoration efforts in the Pacific Northwest. Certain characteristics of the hyporheic zone, including vertical head gradient, permeability, and nutrient flux, provide cues for salmon in the selection of spawning sites. Human activities such as irrigation practices, road construction, logging, and gravel mining can disrupt fluvial geomorphic processes and alter hydraulic properties of the hyporheic zone. Our objective is to characterize the fluvial geomorphology and hyporheic conditions of spring chinook salmon spawning habitat in the Yakima River Basin and to assess the effects of human activities on important habitat features.

To identify critical hyporheic features of spawning habitat, comparisons were made between spawning reaches and non-spawning reaches on two Yakima River tributaries: the American River and Little Naches River. Permeability, vertical head gradient, and water chemistry (dissolved oxygen, electrical conductivity, and temperature) were measured from 3 transects of piezometers installed along each reach. A solute transport experiment was conducted within each reach where potassium chloride was used as a conservative tracer. Solute pulse data were entered into a computer model of One-dimensional Transport with Inflow and Storage (the OTIS model) to determine the size of the transient storage zone (which includes the hyporheic zone) and the rate of solute exchange with the transient storage zone.

Preliminary analyses of data from piezometers indicate that substrate permeability is relatively higher in spawning reaches than non-spawning reaches, while vertical head gradients show no systematic trends between spawning and non-spawning reaches. In general, electrical conductivity and dissolved oxygen levels were also higher in the hyporheic water of spawning reaches than non-spawning reaches. Hyporheic temperature was lower in the spawning reaches, which may represent a higher amount of groundwater influx to the warm surface water conditions of late summer. Results from solute tracer experiments describing transient storage dynamics are forthcoming.

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An Overview of the System Assessment Capability; Inventory and Environmental Transport Simulation

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The U.S. Department of Energy (DOE) faces many decisions regarding future remedial actions and waste disposal at the Hanford Site in southeast Washington State. A new software framework, the System Assessment Capability, has been developed to provide the DOE with the means to predict cumulative impacts of waste disposal and remediation plans accounting for all of the hundreds of individual disposal locations on the 1517-square-kilometer Hanford Site. To support decision making in the face of uncertainty, the SAC was built as a stochastic framework so that uncertainty in predictions could be made based on uncertainty in input parameters and conceptual models.

To support impact estimates, detailed simulation of inventory and environmental transport are required. The SAC brings together in a unified framework several programs for this purpose. INVENTORY utilizes historical waste disposal data to estimate contaminant disposal quantities at hundreds of Hanford Site waste disposal locations. VADER predicts release to the vadose zone from the disposed inventory into the vadose zone using various models for different waste forms. STOMP simulates flow and contaminant transport in the vadose zone at individual disposal sites. The CFEST program is used in SAC to model the Hanford Site-Wide Groundwater Model driven by releases to the unconfined aquifer predicted by STOMP. MASS2 is used to simulate flow and contaminant transport in the Columbia River. The final product of the coordinated simulations of these inventory and environmental transport programs provides the basis for impacts estimation performed with other SAC modules.

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An Overview of the System Assessment Capability; Software Design and Implementation

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Waste management and disposal decisions at the Hanford Site, Washington, depend in part on an understanding of the risks and impacts associated with alternate disposal and remedial actions. A site-wide assessment of the risks and impacts associated with all wastes that will remain at the Hanford Site following cleanup and remedial action has been designed and the design implemented. The code is implemented in the Fortran95 language, and uses dynamic memory allocation. It is designed to run on a 128-CPU Linux® cluster.

The capability simulates contaminant release, migration, and fate from the initiation of Hanford Site operations in 1944 forward. It illustrates historical and near-term influences on long-term risk and impact, and therefore, provides an opportunity to history match to observed events. The design adopted separates the environmental and risk/impact simulations, and archives the environmental results so that the DOE, regulatory agencies, Tribal Nations, and stakeholders may explore multiple risk/impact scenarios. The capability is a stochastic simulation tool able to address 1000 waste discharge and disposal sites and 10 contaminants for a period of 1000 years. It has been designed to also simulate a deterministic case as a single stochastic realization. Human health and ecological risks as well as impacts to the regional economy and local cultures are quantified.

The capability is currently in a Revision 0 state corresponding to a proof-of-principle demonstration. A Revision 1 state is now under development to provide a tool suitable for regulatory applications requiring or benefiting from a site-wide assessment of risks and impacts associated with contaminants remaining at the Hanford Site after closure. Such assessments will be based on the planning baseline of the U.S. Department of Energy (Richland Operations Office and Office of River Protection) and will explore alternate cleanup and remedial actions.

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System Assessment Capability; Impacts and Uncertainty Analysis

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The U.S. Department of Energy (DOE) utilizes risk estimates in making decisions regarding future remedial actions and waste disposal at the Hanford Site in southeast Washington State. A new software framework, the System Assessment Capability, has been developed to provide DOE with the means to predict cumulative impacts of waste disposal and remediation activities at several hundred individual disposal locations on the 1517-square-kilometer Hanford Site. The SAC incorporates a stochastic framework to allow estimation of the uncertainty in impact predictions. Impacts are estimated for four components of the environment and society: ecological health, human health, economic conditions, and cultural resources.

This poster presents some impacts results for an initial run of the SAC using 10 contaminants. The ecological impacts estimation uses a food-web approach that analyses the effects on 57 representative species along the Columbia River from the Vernita Bridge to McNary Dam. The highest impacts are estimated to occur near the site of retired reactors. The human impacts analysis examines exposure scenarios ranging from the ingestion of contaminated water to farming or recreational activities on the Hanford site and in the Columbia River. The economics impacts model examines potential deviations from the current regional economy due to future migration of contaminants. Potential effects in the regional economy include job losses, agricultural production shifts, and loss of recreational activities if contaminant levels rise in the future. The cultural model examines the impacts of the contaminated groundwater on the newly created Hanford national monument. In general, the groundwater plumes developed in the model are similar to the historical record of groundwater contamination and contamination in the Columbia River. The uncertainty analysis shows about a 2 order of magnitude spread in most estimated impact metrics.

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A Systematic Approach for Developing Conceptual Models of Contaminant Transport at the Hanford Site

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The U.S. Department of Energy (DOE) faces many decisions regarding future remedial actions and waste disposal at the Hanford Site in southeast Washington State. To support these decisions, DOE recognized the need for a comprehensive and systematic approach to developing and documenting complete, consistent, and defensible conceptual models of contaminant release and migration. After reviewing existing conceptual model development methodologies that might be applicable to environmental assessments at the Hanford Site, DOE has initiated efforts to adapt and implement the Features, Events, and Processes (FEP) methodology used in performance assessments of nuclear waste disposal systems.

In adapting this methodology for use in the environmental assessments at Hanford, the international list of FEPs, compiled from nuclear waste disposal programs, was used to develop of a list of potentially relevant Hanford-specific FEPs. The international nuclear waste programs focus on deep geologic disposal while the Hanford Site represents disposals in shallow unconsolidated geologic deposits. Thus, graphical tool called the Process Relationship Diagram (PRD) was created to assist in identifying the international FEPs (and additional factors) that are specifically relevant to Hanford, and to illustrate the relationships among these factors. The PRD is similar in form and function to the Master Directed Diagram used by NIREX to provide a visual and systematic structure for the FEP methodology.

Adaptation of this approach is showing promise in facilitating the development of conceptual models and selection of potentially relevant factors to be incorporated into specific environmental assessments for the Hanford Site.

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Multi-Source Influence on Vertical Contaminant Distribution and Transport in a Thick Unconfined Aquifer Beneath the Hanford Site, Richland, Washington

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Since the 1950s large volumes of hazardous and dangerous liquids have been disposed to the uppermost unconfined aquifer at the US Department of Energy Hanford Site, Washington via cribs, ponds, and ditches. These effluent disposal episodes occurred at various locations, varied temporally, and in duration and volume. The volumes that reached the aquifer far exceeded any natural recharge and created localized groundwater mounding and contaminant plumes that have persisted for years.

Contaminated groundwater migrating beneath other disposal sites, located downgradient along the groundwater flow path, are subsequently impacted by more recent effluent sources. Groundwater monitoring results from shallow and deep aquifer wells suggest that the superimposed source volume and downgradient mounding may be driving the entrained groundwater contaminant plumes deeper into the aquifer, diluting portions of the existing plumes, and/or displacing the contaminants laterally.

Groundwater monitoring results from the State Approved Land Disposal Site (SALDS), an active state-permitted disposal pond, support this interpretation and provide the conceptual model for this multi-source contaminant distribution effect.

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Hanford Tank Farm Vadose Zone Characterization Process and Results

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In 1995, the DOE Grand Junction Office (DOE-GJO) was tasked to conduct baseline vadose zone characterization of gamma-emitting radionuclides in the vicinity of Hanford single shell tanks. This project utilized expertise and experience gained from the National Uranium Resource Evaluation (NURE) program. Spectral gamma logging systems with cryogenically cooled HPGe detectors were developed and deployed in existing cased boreholes. Over the next five years, 769 boreholes in twelve tank farms were logged. A high rate logging system was developed for zones of intense gamma flux. Man-made contaminants identified in the subsurface included ^{137}Cs, ^{60}Co, ^{152}Eu, ^{154}Eu, ^{125}Sb and ^{126}Sn. Concentration levels varied from 0.1 to more than 10^9 pCi/g. The high-resolution spectra allowed differentiation between natural and anthropogenic uranium. The technique of shape factor analysis was developed to assess the distribution of contamination with respect to the borehole.

Three-dimensional visualization methods were used to illustrate the nature and extent of subsurface contamination in each tank farm. Project results are documented in 133 Tank Summary Data Reports and 12 Tank Farm Reports. Addenda were also prepared for each tank form report to incorporate additional data and refinements in data analysis and interpretation. Since completion of the tank farms baseline in 2000, characterization logging is being extended into surrounding liquid waste disposal sites in the Hanford 200 Areas, and a monitoring program has been established in the tank farms. All data and reports are made available via the internet at:

http://www.gjo.doe.gov/programs/hanf/HTFVZ.html

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Evaluating Potential Sources for Tritium in Groundwater at the 100-K Area, Hanford Site, Washington

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Tritium concentrations in groundwater at a monitoring well near the 100-K solid waste burial ground began a rapid rise in fall 2000. The source for the tritium is uncertain; the well does not lie along a direct downgradient flow path from known waste site sources. However, the well may be within the area of influence of a treated-effluent injection well system, which has distorted the normal groundwater flow pattern. To help identify the source, several investigations were undertaken: Evaluate groundwater flow direction; simulate mound buildup caused by nearby injection wells; and determine the pattern of helium-3 enrichment in soil gas at locations near the monitoring well and burial ground.

Trend-surface analysis using water table elevation data collected since 1994 provided information on the orientation, magnitude, and seasonal variability of the hydraulic gradient in the vicinity of the well. Hourly data collected for ~2 weeks were also evaluated to determine higher frequency gradient variability. The results confirmed that the well does not lie in the direct downgradient flow path from known tritium sources.

A groundwater mound of uncertain size has been created beneath injection wells located ~700 meters to the east of the well, thus influencing the natural groundwater movement pattern in the general area. An analytical model was used to estimate mound characteristics at the injection wells, based on effluent injection rates and assumed hydraulic properties. The results suggest that a long-term hydraulic head increase of ~0.5 meters is possible at a distance of ~500 meters from the center of the injection network. The results support the possibility that mounding has displaced a potential groundwater plume located beneath the burial ground toward the west, i.e., toward the monitoring well, although the results are not conclusive.

Soil gas samples from locations near the burial ground were analyzed for helium isotopes. The helium-3/helium-4 ratio is higher in the presence of a nearby tritium source, which may be waste materials buried in the vadose zone and/or an underlying groundwater plume. The highest ratios were observed at locations closest to the burial ground. Recently measured ratios were consistently higher than those determined two years earlier at the same locations, and the distribution pattern was the same for both sampling events. The helium-3 enrichment is believed to be associated with a localized tritium plume in groundwater, which is consistent with a burial ground source.

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A Comparison of Actual Evapotranspiration Estimates to a Soil Moisture Budget and Plant Growth

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Evapotranspiration is an integral part of a hydrologic water balance. Actual evapotranspiration (AET) is the combined loss of water to the atmosphere through evaporation from the soil surface, evaporation of intercepted water, and plant transpiration. The standard approach to estimating AET is calculation of a reference-crop potential evapotranspiration (PET_0), assuming soil moisture is not limited. Grass is a widely adopted reference evaporating surface. Calculations of PET_0 are dependent only on climate parameters, without influence from soil parameters (ASCE Manual no. 70, FAO 56). The Penman-Monteith method was adopted as the standard for computing PET_0 in FAO 56. Input parameters include solar radiation, relative humidity, temperature and wind speed. Crop-specific potential evapotranspiration (PET_C) is related to PET_0 by multiplying by a seasonally-variable crop coefficient (K_C). Adjustments are made to PET_C to account for evaporation of water intercepted by the crop canopy.

AET equals PET when available soil moisture is not limiting, i.e. until the matric potential is greater than the roots' ability to extract soil moisture. This point typically occurs when soil moisture is near the midpoint between field capacity and the wilting point (FAO 56). For lower soil moisture values, AET declines linearly to zero at the wilting point.

An intensive study of a poplar tree cover planted on a landfill near Duvall, Washington yields data for comparing AET estimates from grass reference-crop PET and soil moisture with results from 1) soil moisture budgets at multiple locations and 2) water uptake estimates based on plant growth. The soil moisture budget assigns volumetric soil moisture measured by time domain transmissometry (TDT) or frequency domain reflectometry (FDR) probes at three depths to a representative length of the soil column. Losses in soil moisture during periods of no precipitation or runoff were compared to AET computed using the FAO 56 method. Plant growth was measured before and after a growing season, and estimates of total water uptake were estimated and compared to season total AET computed using the FAO 56 method. The comparisons provide empirical evidence to ground-truth evapotranspiration estimates based on climatological data.

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Hydrologically Separate Subbasins of the Palouse Aquifers

Dennis Owsley

Groundwater in the Palouse region supplies nearly 95% of the potable water in the area. Historically the groundwater levels for this region have been decreasing at a rate of one and a half feet per year. It is inevitable that at the current rates of water level declines, groundwater resources will eventually diminish.

In order to assess possible solutions to the water supply problem, the system that produces this water must be understood. The Palouse region is composed of loess sediments that blanket much of the area that are underline by thick basalt sequences. These basalt sequences contain the aquifers for the region and two main aquifers have been identified, an upper and a lower aquifer. The upper aquifer is known as the Wanapum and the lower is the Grande Ronde, with the emphasis of this research applied to declining Grande Ronde water levels.

Historically, domestic wells were drilled into the Wanapum formation and water levels soon began to decrease. As groundwater demands increased throughout the years, deeper wells have been drilled into the Grande Ronde with hopes of relieving the declining water levels of the Wanapum. Water levels stabilized in the upper aquifer and started declining in the deeper system as all municipal water sources for the region come from the deep Grande Ronde aquifer.

Due to a unique situation of water level declines of 1.5 feet per year throughout the region, it has been thought that all the groundwater in the region is hydraulically connected. Pumping test data, well logs, and geologic discrepancies have brought the notion that this is might not be the case. The idea of separate aquifers that lie within seperate sub basins of the larger Palouse basin is presented. Exact boundaries for each sub basin is still not clear, but with the aid of a proposed pumping test, sub basin boundaries should be definable.

Hydrologic Controls and Forest Land Management Implications of Deep-Seated Landslides:Examples from Southwest Washington

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Detailed air photo analysis and field mapping provide accurate identification of areas prone to or undergoing deep-seated landsliding, but offer little towards achieving an understanding of landslide mechanics and sensitivity to natural and human influences. Regional predictive slope stability models are ineffective in estimating movement frequency and rates of deep-seated landslides, making site-specific characterization of groundwater conditions and material strength properties necessary.

In southwest Washington the Lincoln Creek and Astoria Formations, Eocene to Oligocene marine sedimentary tuffaceous siltstones and sandstones, are notorious “bad actors” because of their rapid weathering characteristics, accelerated by regionally high annual precipitation and a lack of influence from Pleistocene glaciation. Landslide densities in areas underlain by these units commonly exceed 10/km^2, with large coalescing slides covering up to 0.3 km^2. Many of the landslides remain active for years at a time because residual soils are poorly drained, and high groundwater conditions persist throughout much of the year.

Landslides we’ve mapped, and for which we’ve assembled subsurface data, vary widely in size, slope gradient, soil and rock strength properties, and level of activity. Subsurface data also show great variability between landslides in the correlation of precipitation events to piezometric surface fluctuations and associated lag times.

Observed sensitivity of hill-slope stability to precipitation and groundwater changes suggests that much of the forested terrain in southwest Washington, and likely elsewhere, is sensitive to evapo-transpirative (E/T) changes resulting from timber removal. Where geologic information suggests a likelihood of deep-seated landslides, harvest plans should incorporate detailed, sub-basin scale landform mapping. Where deep-seated (and other) landslides are identified, cumulative hydrologic effects of timber removal should be evaluated. Mitigation alternatives should minimize the effects of E/T loss and the concentration/disruption of natural surface and groundwater flow patterns. Partial cuts and thinnings can provide alternatives to clear cutting. Helicopter and balloon harvesting techniques can provide alternatives to new road construction; and old roads should be obliterated wherever possible.

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