overall increase in the evapotranspiration for all scenarios. Faced with these conditions, water companies are planning for less reliable groundwater resources within an overall risk-based approach to managing future water supply and demand.

H23F CC: 520 A Tuesday 1330h

Advanced Methods for Probabilistic Hydrometeorologic Forecasting III

Presiding: **J Demargne,** NOAA Hydrology Laboratory**; A Pietroniro,** National Hydrology Research Center

H23F-01 1330h

Ensemble streamflow forecasting in snowmelt-dominated river basins

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We are undertaking a detailed study to improve both the accuracy and probabilistic information content of streamflow forecasts in the Colorado River basin. Our two main research objectives are: (1) Development and evaluation of methods to assimilate station-based measurements of snow water equivalent into the NWS River Forecast System; and (2) Development and evaluation of methods to produce forecast inputs on time scales of days through to seasons. For forecast lead times up to two weeks, our experimental forecasting methods have significantly higher skill than the operational methods used by the NWS. On seasonal time scales, our experimental forecasting methods add skill over the operational methods, especially in the lower Colorado River basin where ENSO signals are strong. Further, in specific cases, assimilation of SNOTEL measurements of snow water equivalent are found to improve streamflow forecasts.

H23F-02 1345h

Probabilistic Hydroclimatic Forecasts based on MultiModel Ensembling

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Seasonal forecasts of precipitation/streamflow are essential for the management of water supply systems as well as for developing various strategies of crop management in rain fed agriculture. However, climatic forecasts from different General Circulation Models (GCMs) and statistical models can differ significantly across these models, thereby necessitating the development of methodologies that focus on optimal combination of model ensembles. IRI dynamical climate forecast system pursues such an approach to develop IRI Net Assessment Forecast. In this study, we develop a similar approach to develop multimodel ensembles of streamflow forecasts conditioned on climatic indices. The methodology obtains multimodel streamflow ensembles through an iterative weighting scheme. The performance of the multimodel ensemble is compared with the skill of individual model based approach.

H23F-03 1400h

Towards Operational Probabilistic Quantitative Precipitation Estimation Using NEXRAD

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Large uncertainties associated with the operational quantitative precipitation estimates produced by the U.S. national network of WSR-88D radars known as NEXRAD are well-acknowledged. These uncertainties include both systematic and random effects of numerous sources. Quantitative description of the precipitation estimation errors would help the U.S. National Weather Service (NWS) forecasters in making operational decisions on issuing forecasts and warnings on flooding potential. It would also help the commercial sector and other agencies that use the rainfall products in making risk-based decisions. Currently such information is not available. The authors describe a comprehensive plan of introducing probabilistic quantitative precipitation estimation into the operational NWS environment. The plan focuses on radar-based estimates and includes research and development, experimental, and implementation components. The authors discuss three different possible approaches with their merits and problems. They recommend one of the approaches based on a parameterization of radar-rainfall errors taking into account space and time scale, range, seasonal, synoptic and climatic dependencies. They discuss details of the resources required and the implementation feasibility.

H23F-04 1415h

Wavelet-Based Evaluation of Rainfall-Runoff Models

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Objective functions (e.g. the Nash-Sutcliffe efficiency index) are crucial to the inter-comparison of rainfall-runoff models with different process representations and parameterisations. They are also routinely used as the target of model optimisation and as the parameters used to describe model uncertainty under different parameter sets. The problems of objective functions are well-established, as individual functions may require one or more of: (a) a mean error of zero; (b) a distribution of error that is Gaussian (either before or after some form of transformation); (c) an error series that is not autocorrelated; and (d) an error series that is homoscedastic (i.e. the variance of the error does not change as a function of time). Unfortunately, there are good reasons why these four requirements do not hold. This largely relates to the fact that hydrological processes are influenced by a number of scales of variation (from the storm event through to seasonal variation in soil moisture conditions). The associated error series therefore integrates errors due to a range of time scales and magnitudes of variability (e.g. high magnitude, short duration error in the prediction of a flood peak will be superimposed upon low magnitude, long duration error due to inadequate evapotranspiration treatment). These errors will also be inter-correlated (i.e. the magnitude of flood peak error will depend upon the magnitude of evapotranspiration error). In this paper, a method for addressing this problem is developed and evaluated. This is based upon disaggregation of the error series using a time-frequency localisation based upon wavelet analysis. Wavelet analysis measures the fit of a data series to a wavelet basis function with a range of scales and at all time periods. Thus, it yields the characteristic time scale of a phenomenon present in a data series at all time periods. This paper develops and evaluates a continuous wavelet transform for disaggregating observed runoff data and predictions from a modified form of the classical TOPMODEL. Use of the cross-wavelet spectrum and phase coherence allows explicit identification of when model predictions diverge from observations and the associated time scale over which this occurs. The paper shows that such divergence can be hidden by more conventional objective functions and so provides an additional explanation of possible causes of model equifinality.

H23F-05 1430h

Appraisal of Forecast Value for Groundwater Resources Management

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Seasonal climate forecasts present an opportunity to increase the efficiency with which water resources are managed. However, the probabilistic nature of forecasts poses challenges to potential users and complicates evaluation of the forecasts' quality and value. In this study we use Bayesian decision modeling to evaluate the performance of a seasonal precipitation forecast. We generate an optimal decision map by which probabilistic categorical forecasts are re-categorized and evaluated. In this way, forecast performance is assessed not in terms of the observed climate state but rather in terms of the decision indicated by the forecast. Preposterior analysis via stochastic dynamic programming is used to determine the expected value of the forecast. The application setting is the Palar River basin in Tamil Nadu, India, where demand for water exceeds economically available resources leading to income loss, economic displacement and environmental degradation. Instead of targeting forecasts for use by farmers, we propose that water managers use forecasts to set economic parameters to signal the expected availability of water in the coming season. The economic signal promotes efficient use of water while mitigating the farmers' personal risk of forecast-based decisions.

H23F-06 1445h INVITED

Seasonal to Interannual Hydroclimatic Prediction: From Identification of Dynamics to Multi-Attribute Forecasts

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Dynamical and Statistical Models for seasonal to interannual forecasts of key hydroclimatic state variables have been explored in recent years. Many authors report success based on typical performance metrics. Thus, a casual external observer may feel that we are at the verge of a breakthrough in hydrologic prediction, and hence in water resource management. This talk explores this notion, with particular regard to the multi-scale (time and space) nature of hydrologic fluxes, and of the management variables and styles that the water resources community has become accustomed to. A conceptual framework for the nascent predictive science of hydroclimatology is developed and exemplified. Aspects of the dynamics that need to be understood, and a unifying estimation/inference framework are proposed.

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H24A CC: 520 C Tuesday 1530h

Coupling Microbial Activity, Water Flow, and Solute Transport in the Subsurface I *(joint with B)*

Presiding: **J E Smith,** McMaster University**; M Rockhold,** Pacific Northwest National Laboratory

H24A-01 1530h

Effects of Diffusion Fragmentation and Spatial Constraints on Soil Microbial Diversity

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Evidences show unparalleled microbial diversity at very small scale in soils as compared with aquatic habitats (oceans) - soils contain numerous genotypes per unit volume. Yet the causes of such abundance remain largely unknown due to our limited understanding of relationship between soil microbes and their environment and interaction among microbial populations. We developed a conceptual model for the role of habitat heterogeneity, induced by physical constraints and fragmentation of diffusion pathways on abundance and coexistence among microbial genotypes. The model simulates competition between two microbial cultures with different key growth and diffusion (motility) properties within a soil domain. Diffusion-reaction equation is used to simulate nutrient capture, growth and spreading of the microbial population. Spatial constraints according to soil pore sizes are introduced to limit maximum microbial volume within a specific soil volume. In the absence of spatial constraints, only one of the

two species prevails following initial coexistence period. Simulation results in homogeneous domain show that with under low diffusion coefficients simulating "drier" soil conditions, coexistence of both cultures is maintained indefinitely. In contrast, under high diffusion rates one species prevails and the other is extinct throughout the domain. Uneven initial inoculation, domain heterogeneity, extent of unsaturated conditions induce higher coexistence potential within a given soil domain.

H24A-02 1545h INVITED

Microbial Growth, Water Flow, and Solute Transport in Unsaturated Porous Media

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We present an investigation that studied interactions between microbial growth, water flow, and solute transport in variably saturated porous media. The experimental system provided for continuous, noninvasive observation of microbial activity, while simultaneously monitoring water content and solute flow paths in a two-dimensional porous matrix. The spatial and temporal development of microbial colonization by a *Pseudomonas fluorescens* bacterium was monitored by induction of a bioluminescent phenotype. A model was developed that allowed quantification of population density from bioluminescence measurements. Liquid saturation was quantified from the transmission of light through the system, and solute flow paths were determined with a dye tracer. Dramatic changes in microbial colonization were observed, including upward migration against flow. This migration was particularly interesting because it cannot be explained by passive transport. Bacterial growth and accumulation significantly impacted the hydrologic properties of the media, including apparent desaturation within the colonized region, diversion of flow around the colonized region, and lowering of the capillary fringe height.

H24A-03 1600h

Microbially Induced Changes in Unsaturated Zone Hydraulic Properties During Soil Flushing Remediation Trails

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Field trials were conducted to assess a cyclodextrin as a soil flushing remediation agent. During those trials, data collected with Time Domain Reflectometry (TDR), the Guelph Permeameter, and timed-application without-ponding showed significant and substantial changes in water holding capacity, field-saturated hydraulic conductivity, and infiltration rates respectively. The changes were large enough to limit the treatment period for the highest application rate plots. The changes were assumed to be due to bioclogging. Subsequent experiments in one meter tall laboratory columns instrumented with TDR directly assessed the proportion of the observed hydraulic changes that could be attributed to microbial-induced changes versus abiotic effects. While small abiotic effects were observed in columns receiving treatments containing a biocide, large changes in hydraulic properties consistent with those observed in the field were attributable to enhanced microbial activity.

H24A-04 1615h INVITED

Analytical and Numerical Modeling Study of Bioprotection From Zinc Toxicity in Sulfidic Systems

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In the context of increasing metal pollution, it is important to understand the role microbes play at metals-contaminated sites, particularly, in metal detoxification and immobilization. Bioprotection is a community relationship in which one microbial type protects a community by reducing the bioavailability of a toxic metal and, in return, receives a key community service (e.g., substrate) from other members. Bioprotection should be key in shaping community structure and function at metals-contaminated sites; moreover, induction of pore-water metal gradients should be a key microbial metal-resistance and bioprotection mechanism. Within a complex microbial community, sulfate-reducing bacteria (SRB) are outstanding candidates for providing bioprotection to the entire community, because they provide passive metal protection by producing sulfide, which forms sparingly soluble complexes with many toxic metals (e.g., Ni, Zn, Cd, Pb, Cu, and Hg). Additionally, SRB can also effect the direct and indirect reductive precipitation of metals (e.g., Cr and U). In order to understand how bioprotection from Zn toxicity ought to work in sulfidic systems, we describe the biogeochemistry of sulfidic systems, including stoichiometry and kinetics of reactive ligand (e.g., sulfide and functional groups of extracellular polymeric substances (EPS)) generation, Zn speciation, and Zn bioavailability and toxic response. Importantly, we use the biogeochemical portrayal possible with an expanded version of the numerical model CCBATCH to examine the effect of coupling one-dimensional steady-state groundwater flow with equilibrium- and kinetic-based reactions relevant when a microbial community and metals are present together. Analytical and numerical solutions to differential mass balances are the two key tools we exploit to test the bioprotection concepts. In this presentation, we describe how we use analytical solutions to derive metal-resistance criteria for two sulfidic systems: permeable reactive barriers and sediments. The first step in the derivation of an analytical solution is defining the domain, along with its boundary conditions, in a way that captures the crucial microbiological, geochemical, and transport phenomena, but is simple enough so that complex numerical solution can be avoided. Then, the next steps are writing the differential mass balance equation for the relevant variables, rewriting the mass balance equations in the dimensionless domain by using dimensionless parameters, and finally solving the system of equations. Solution in the dimensionless domain naturally leads to relationships among dimensionless parameters that are metal-resistance criteria. Our results show that precipitation and sorption can contribute to retarding a metal plume, and we compute an overall retardation factor that is consistent with the gradient-resistance mechanism. The retardation factor captures the combined effects of sorption and precipitation. Diffusion-dominated systems (i.e., sediments) have greater potential to withstand metal contamination than advection-dominated systems (i.e., aquifers). When diffusion controls transport, the metal flux affecting a bioactive zone is typically orders of magnitude smaller, and, additionally, a greater fraction of soluble detoxifying ligand is available for reaction with the metal, since it is not swept out by advection. In summary, the retardation factor quantifies when bioprotection can be effective in diffusion- and advection-dominated systems, helping us decide on the feasibility of bioremediation in metals-contaminated sites.

H24A-05 1630h

Microbial Reduction of Fe(III) and U(VI) in Aquifers: Simulations Exploring Coupled Effects of Heterogeneity and Fe(II) Sorption

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Uranium is a significant groundwater contaminant at many former mining and processing sites. In its oxidized state, U(VI) is soluble and mobile, although strongly retarded by sorption to natural iron oxide surfaces. It has been demonstrated that commonly occurring subsurface microorganisms can reduce uranium and other metals when provided sufficient carbon as an electron donor. Reduced U(IV) precipitates as a solid phase; therefore biostimulation provides a potential strategy for in situ removal from contaminated groundwater. However, these biogeochemical reactions occur in the context of a complex heterogeneous environment in which flow and transport dynamics and abiotic reactions can have significant impacts. We have constructed a high-resolution numerical model of groundwater flow and multicomponent reactive transport that incorporates heterogeneity in hydraulic conductivity and initial Fe(III) distribution, microbial growth and transport dynamics, and effects of sorption or precipitation of biogenic Fe(II) on availability of Fe(III) as an electron acceptor. The biogeochemical reaction models and their parameters are based on laboratory experiments; the heterogeneous field-scale property distributions are based on interpretations of geophysical and other observations at a highly characterized field site. The model is being run in Monte Carlo mode to examine the controls that these factors exert on 1) the initial distribution of sorbed uranium in an oxic environment and 2) the reduction and immobilization of uranium upon introduction of a soluble electron donor.

H24A-06 1645h

The Relationship Between Partial Contaminant Source Zone Remediation and Groundwater Plume Attenuation

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Analytical solutions are developed that relate changes in the contaminant mass in a source area to the behavior of biologically reactive dissolved contaminant groundwater plumes. Based on data from field experiments, laboratory experiments, numerical streamtube models, and numerical multiphase flow models, the chemical discharge from a source region is assumed to be a nonlinear power function of the fraction of contaminant mass removed from the source zone. This function can approximately represent source zone mass discharge behavior over a wide range of site conditions ranging from simple homogeneous systems, to complex heterogeneous systems. A mass balance on the source zone with advective transport and first order decay leads to a nonlinear differential equation that is solved analytically to provide a prediction of the time-dependent contaminant mass discharge leaving the source zone. The solution for source zone mass discharge is coupled semi-analytically with a modified version of the Domenico (1987) analytical solution for three-dimensional reactive advective and dispersive transport in groundwater. The semi-analytical model then employs the BIOCHLOR (Aziz et al., 2000; Sun et al., 1999) transformations to model sequential first order parent-daughter biological decay reactions of chlorinated ethenes and ethanes in the groundwater plume. The resulting semi-analytic model thus allows for transient simulation of complex source zone behavior that is fully coupled to a dissolved contaminant plume undergoing sequential biological reactions. Analyses of several realistic scenarios show that substantial changes in the ground water plume can result from the partial removal of contaminant mass from the source zone. These results, however, are sensitive to the nature of the source mass reduction-source discharge reduction curve, and to the rates of degradation of the primary contaminant and its daughter products in the ground water plume. Aziz, C.E., C.J. Newell, J.R. Gonzales, P. Haas, T.P. Clement, and Y. Sun, 2000, BIOCHLOR Natural Attenuation Decision Support System User's Manual Version 1.0, US EPA Report EPA/600/R-00/008 Domenico, P.A., 1987, An analytical model for multidimensional transport of a decaying contaminant species, J. Hydrol., 91: 49-58. Sun, Y., J.N. Petersen, T.P. Clement, and R.S. Skeen, 1999, A new analytical solution for multi-species transport equations with serial and parallel reactions, Water Resour. Res., 35(1): 185-190.