State of Washington Water Research Center Annual Technical Report FY 2004

Introduction

The mission of the State of Washington Water Research Center (SWWRC) is to: i) facilitate, coordinate, conduct, and administer water-related research important to the State of Washington and the region, ii) educate and train engineers, scientists, and other professionals through participation in research and outreach projects, and iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, conferences as well as other outreach and educational activities.

The SWWRC has developed a multi-pronged approach to accomplish these goals. To promote research and outreach, the SWWRC has been organized into six program areas: Watershed Management, Groundwater Systems, Ecohydraulic Restoration, Environmental Limnology, Vadose Zone Processes, and Outreach and Education. These programs have helped prepare several multidisciplinary research proposals and provide better links between faculty and the SWWRC. The Center is also involved in international research and education activities.

The SWWRC is continuing its intensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, participation in regional water quality meetings, and personal contacts. A new dynamic web page has been created to share information with stakeholders.

It is within this overall context that the USGS-funded project activities reported in this document must be inserted. These include the internally funded projects as well as the national proposals awarded to the Center. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as arsenic removal at small systems, emergency response and vulnerability, and storm water runoff regulations are also beginning to raise concerns. All of these issues will be important drivers of the activities of the SWWRC in the foreseeable future.

Research Program

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The Center supports competitively awarded internal grants involving water projects evaluated by the Joint Scientific Committee. The Center also actively seeks multidisciplinary research on the local and national levels. Meetings between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are apprized of any opportunities. The Center also submits proposals on its own behalf.

During FY 2004, three local research projects were selected for funding by the Center: (1) Phosphorus Contamination of Surface Waters, (2) Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality, and (3) Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions. As described below, these projects address state issues but are also relevant to national interests.

Two national projects are currently being run through the SWWRC: (1) Collaborative Research: Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams and (2) Using Environmental Tracers to Improve Prediction of Nonpoint Pollutant Loadings from Fields to Streams at Multiple Watershed Scales. Updates of these projects are also presented in this report.

Phosphorus Contamination of Surface Waters

Basic Information

Title:	Phosphorus Contamination of Surface Waters
Project Number:	2004WA75B
Start Date:	3/1/2004
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Washington Fifth
Research Category:	Ground-water Flow and Transport
Focus Category:	Surface Water, Groundwater, Water Quality
Descriptors:	Ground and Surface Water Quality, Phosphorus, Field Drainage, Solute Transport
Principal Investigators:	Markus Flury, Joseph Harrison, James Harsh, Claudio Stockle

Publication

1. Jerez Briones, Jorge, 2005. Aluminosilicate-Coated Silica Sand for Reactive Transport Experiments, PhD Dissertation, Washington State University, Pullman, WA, 135 p.
2. Mejias, Jaime H., 2005. Phosphorus Leaching from Manure-Impacted Soils Affected by Fluctuating Water Tables, PhD Dissertation, Washington State University, Pullman, WA, 155 p.
3. Flury, Markus, Claudio O. Stockle, Joseph Harriason, and James Harsh. 2005. Phosphorus Contamination of Surface Waters, State of Washington Water Research Center, Washington State University, Pullman, Washington, Water Research Center Report No. WRR-24, 30 pp.

PROBLEM AND RESEARCH OBJECTIVES

Long-term application of dairy manure to farmland has caused an accumulation of P in soils. There is a potential risk of P release to the soil solution and subsequent leaching of P out of the soil into surface waters, especially where seasonal flooding occurs. While many P sorption studies have been conducted, the influence of redox reactions on P chemistry and its potential impact on P movement into tile drains has not been investigated intensively. We hypothesized that soils containing high P levels release a considerable amount of P during flooding, thereby posing a latent risk for surface water eutrophication.

The goal of the proposed research was to study fate and transport of P in soils characterized by periodic anaerobic conditions. Specifically, we addressed the following objectives:

- Acquire relevant field data to understand the dynamics of dissolved P in tile effluents.
- Explore the effect of the soil redox potential on P release and transport in soils.
- Develop a tile-drain filter to reduce the concentration of dissolved P in tile effluents to comply with EPA water quality criteria.

METHODOLOGY

Field Study

Two dairy farms, typical for dairies in the Pacific Northwest, were selected as the experimental sites. We denote the field sites as Everson and Lynden. The soil series were identified as Pangborn muck and Briscot series, respectively. Dry soil bulk density was measured in the top soil (0-10 cm) using the intact core method, and soil texture was determined using a soil particle size analyzer. Soil samples for chemical analyses were taken at two depths (0-30 cm and 30-60 cm) with a manual auger. Soil pH was measured in a 1:2 (w/v) soil:water solution. Total organic carbon (TOC) and total organic nitrogen (TON) were determined in a Leco FP2000 Nitrogen and Carbon Analyser. Plant available P was measured with the Bray and Kurtz P-1 (Bray-P1) method according to standard procedures. Calcium-chloride-extractable P, oxalate extractable P, iron and aluminum were also obtained. Soil P sorption characteristics were assessed by performing P sorption isotherms and calculating the degree of saturation of the P sorption capacity of the soils. We installed nine tensiometers at soil depths of 25, 50, and 100 cm with three replicates each. The tensiometers were located five meters away from the ditch. The water tension inside the tensiometer was measured every 15 days with a pressure transducer and a digital display. At each location, two tile drains were selected and the outflow of the drains into the drainage ditch was monitored. At the Everson site the two drains were located in a pasture and a corn field each. The corn field was located right next to the pasture. Samples were collected from April 2004 through February 2005, with a sample frequency of 15 days. The flow rates were measured manually using a bucket and a stop watch with three replicates per tile drain. Weather data during sampling were collected in an automatic weather station.

Column Study

The effect of redox potential on P fate and transport was investigated using a laboratory column flow-through system. We used ferrihydrite-coated sand as porous medium and controlled redox potential using Fe-reducing bacteria. Phosphorus was sorbed onto the ferrihydrite with an initial breakthrough experiment, and the P release, caused by changes in redox potential and subsequent transport, was monitored in the column outflow. We determined P sorption isotherms on the ferrihydrite-coated sand in batch systems with 15 mM KCl background solution and two replicates at two different pH values: 4 and 7. Small columns of 1-cm i.d. and 10-cm length were packed with the ferrihydrite-coated sand. The column system was kept O_2-free by using air-tight N_2 boxes. We maintained a constant upward-flow by a peristaltic pump at a flow rate of 0.035 cm/min (=0.5 m/d). Redox potential and pH were monitored in five minute intervals with in-line electrodes connected to flow-through cells. The system was setup in a temperature-controlled growth chamber at 10^{o}C under dark conditions to mimic soil conditions.

Column outflow was analyzed for Fe^{2+}, P, and turbidity (bacteria concentration). We performed XRD analysis to determine secondary mineral formation. At the end of the experiments, the column was dissected in 4 increments and the 6 M HCl soluble Fe and P were measured colorimetrically. Phosphorus batch sorption isotherms were analyzed with the Langmuir isotherm.

The solubility equilibrium of the precipitates originated from the biogenic iron reduction and the stable solid mineral phases were predicted with the chemical speciation program Visual MINTEQ. Different cases were considered for modeling: (1) three combinations of low, medium and high concentrations of P, and (2) chemical speciation of solid phases in three different stages of the elution P curve.

Experimental breakthrough data of P transport were analyzed using the software package Hydrus-1d. Hydrus-1d numerically solves the Convection Dispersion Equation (CDE) for solute transport assuming linear and nonlinear non-equilibrium solute sorption. We selected the two-site sorption option. Hydrus 1-d was run both in direct and inverse mode using the sorption data obtained from batch experiments.

Filter design experiment

We tested a filter that can remove P efficiently from water flowing through a tile drain. Ferrihydrite has a large sorption capacity for P and is a useful filter material. The postulated filter uses ferrihydrite-coated sand. The ferrihydrite provides the sorption sites for P removal, while the sand matrix allows adequate water flow. We envisage that the filter consists of two PVC tubes that are installed at the tile-drain outlet. The first tube acts as a sediment trap (physical removal of sediments due to sedimentation). The second tube would contain ferrihydrite-coated silica sand.

We used the ferrihydrite-coated silica to test its P sorption capacity when used in a filter. In a column experiment the total capacity of the filter was obtained by integration of the elution P curve. Calculations were based on measured water flow rates in tile drains and measured saturated hydraulic conductivities of ferrihydrite-coated silica sand. The life-time of the filter medium was estimated using annual P (dissolved orthophosphate) loading data from the Lower Nooksack drainage area. We considered 5 tile lines per ha, and one filter per tile drain line. We also developed a methodology to coat hematite onto silica sand. Then we tested a hematite-coated sand filter media to increase the P sorption capacity.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The principal findings of this study are listed in itemized form below.

Field Study

- Mean P concentrations in drainage waters revealed that molybdate reactive P concentration in tile drain outflows was greater than eutrophication limits and likely associated with Fe^{2+} concentrations. P was released due to reductive dissolution of iron-P complexes, which was supported by the decrease in redox potential of the drainage water (Figure 1) and the periodic flooding detected by the soil water tension data (Figure 2).

- Monitoring data from the pasture system confirmed our hypothesis that in soils enriched with P and affected by fluctuating water tables, P is released as a result of iron reduction and transported off site via tile drains as indicated by the positive correlation between P and Fe^{2+} (Figure 3). In the corn field, Fe^{2+} was detected in the drain outflows but it was not related to P. Instead, a good correlation was found between P and Fe^{3+}, indicating that different processes affect the P release in cultivated soils.

- According to the light scattering analysis no colloids were detected in the water samples. It appears that P was transported in dissolved forms or in complexation with dissolved organic matter. We suspect that the release of P and Fe^{3+} to solution was a result of abiotic dissolution of iron phosphate minerals by dissolved organic matter rather than reductive dissolution. After dissolution P could have been transported in complexation with iron and dissolved organic matter.

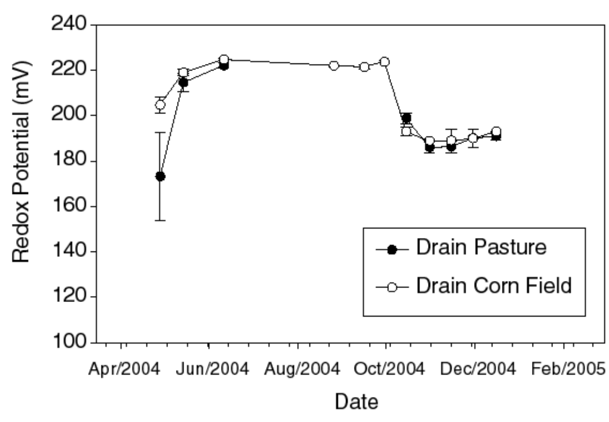

Figure 1: Redox potential in tile drain outflow.

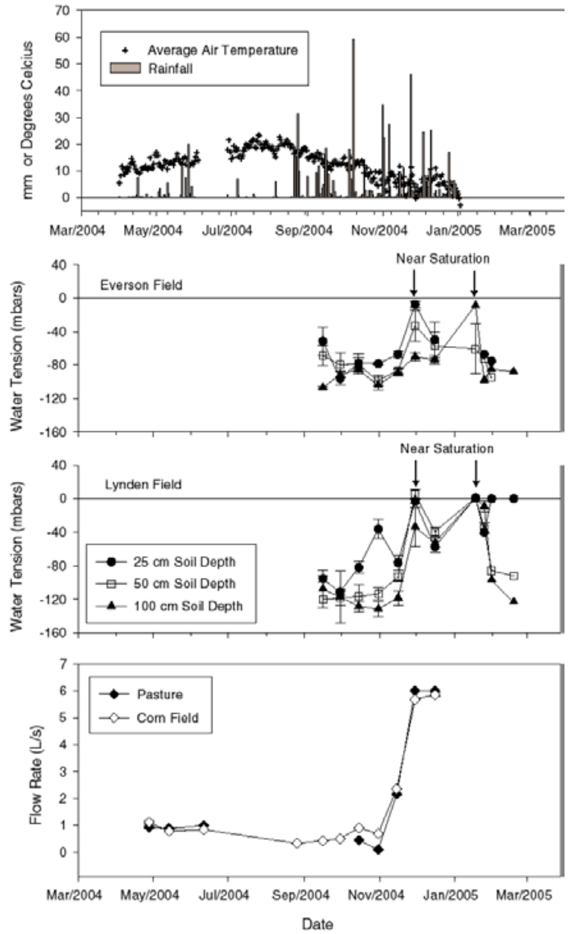

Figure 2: Temperature, rainfall (top), water tension (middle) in Everson and Lynden sites, and flow rate measured in the drain outlet in Everson site (bottom).

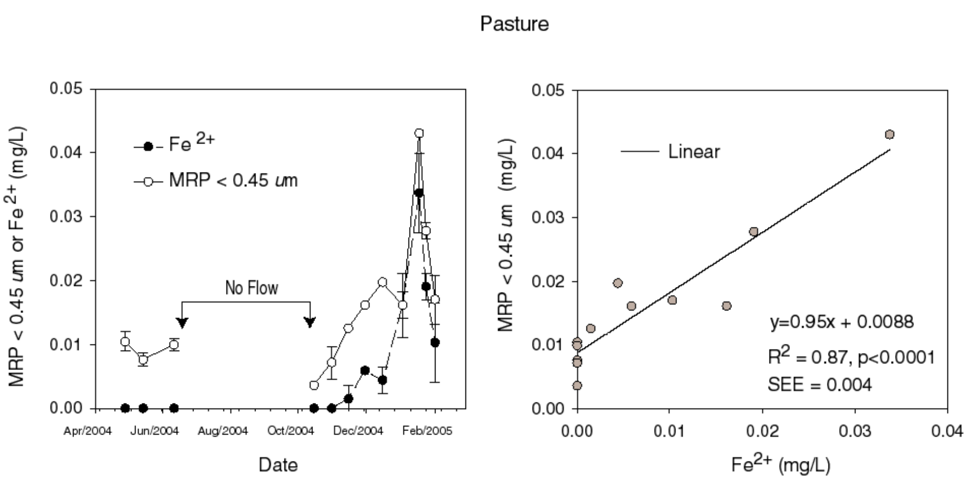

Figure 3: Molybdate-reactive P (MRP) and Fe^{2+} relationship in tile drain outflow from the pasture system in Everson.

Column Study

- We found that upon biotic reductive processes of P-bearing (hydr)oxides, P is released and mobilized during dynamic flow conditions. The redox potential of the P-saturated system was reduced by introducing Fe-reducing bacteria. The redox potential started to drop after 105 pore volumes, the net P leached out during the reductive part of the experiment was 0.19 μmoles (Figure 4). In relative terms, the amount of P lost during the reductive part of the experiment represents the 7 % of the total P in the column prior to the introduction of bacteria.

- An initially anaerobic system retained more P than the oxidized column due to precipitation reactions. However, the dissolution of the precipitated phases during the re-oxidation of the column caused release of most of the P fixed during the reductive period. Overall, a reduced environment fixed less P than an oxidized environment.

- Systems initially oxidized, under dynamic flow conditions and containing high amounts of chemisorbed P, represent an environmental risk when redox potentials are dropped below the point of Fe reduction (180 mV).

- Phosphorus initially fixed in a reductive environment is released more readily when oxic conditions are recovered, compared to P initially fixed in an oxidized environment.

Filter design experiment

- Preliminary experiments indicate that ferrihydrite-coated silica can remove 0.04 mg P/(g of sand) at 10^{o}C for sand particles of diameters between 0.25 and 0.5 mm. Calculations based on measured water flow rates in tile drains and measured saturated hydraulic conductivities of a ferrihydrite-coated silica sand (grain diameter between 0.25 and 0.5 mm, Ks = 40 cm/h), show that the filter can remove in total 4 g of P. A schematic of the proposed filter is shown in Figure 5.

- Considering an average of 5 tile lines per ha, and an annual P (dissolved orthophosphate) loading from the Lower Nooksack drainage area of 215 g/ha, we conclude that the sorption capacity of the filter is not enough to remove the bulk of the orthoposphate from the drain discharge.

- We therefore increased the sorption capacity of the filter by developing a methodology to coat silica sand with hematite instead of ferrihydrite. Hematite is smaller and has a greater surface area than ferrihydrite and can therefore remove more P. The P sorption capacity increased by a factor of 10, so that the filter can now remove 40 g of P, which allows us to remove the bulk of the orthoposphate from the drain discharge. The different filter capacity for P of hematite and ferrihydrite is illustrated in Figure 6.

- We estimate that the filter has to be replaced once year. Dissolving the iron by reductive processes may recycle the P retained in the filter.

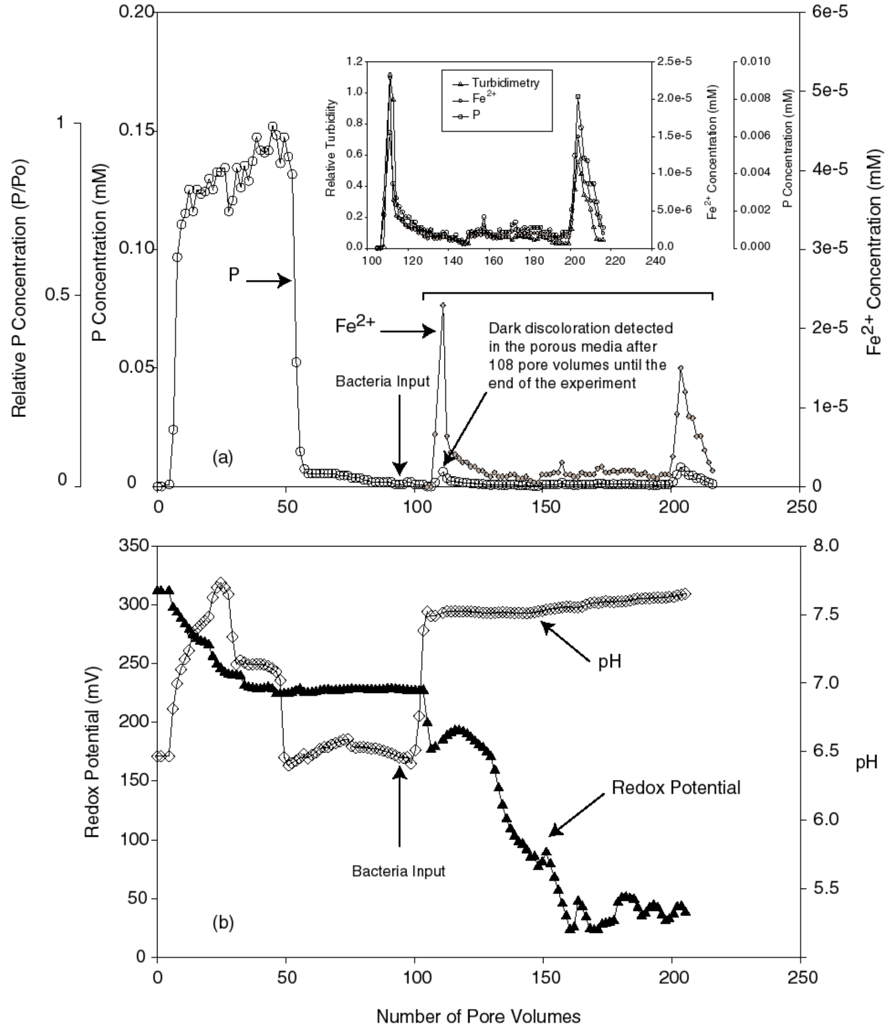

Figure 4: Phosphorus release from a P-saturated ferrihydrite coated sand column after biogenic iron reduction (top). Redox potential and pH variation during the experiment (bottom).

Significance of study

Release of P from agricultural lands to water ecosystems impairs surface water quality. The reductive dissolution of ferric iron associated with P is postulated as a mechanism controlling P transport and fate in manure-impacted soils affected by flooding. In this study we provide evidence that P was released upon ferric iron reduction in a pasture system as indicated by the significant relationship between P and ferrous iron. This evidence was corroborated in lab experiments where P was released upon iron reduction under dynamic flow conditions. These results confirm that redox processes are important mechanisms controlling the P transport and fate in agricultural soils. We found that the P levels in the drain outflow were higher than the 0.01 mg/L defined as a critical environmental limit. Therefore, this study suggests that soils with elevated P iron-bearing materials affected by anaerobic conditions should receive special management to avoid the redox potential decrease below critical limits. This study also proposes a remediation for controlling critical limits of P in the drainage water.

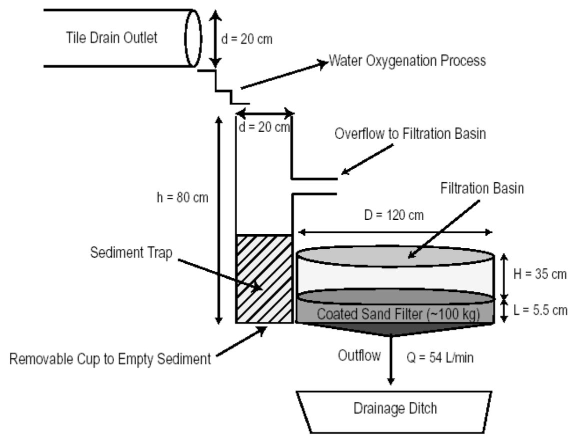

Figure 5: Schematic of the filter design to remove P from tile-drain outflow.

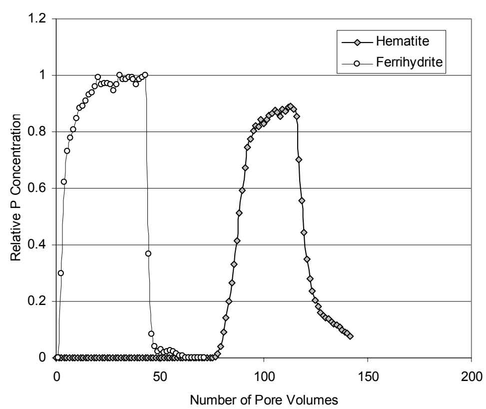

Figure 6: Phosphorus retention in porous filters made of hematite- and ferrihydrite-coated sands.

Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality

Basic Information

Title:	Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality
Project Number:	2004WA76B
Start Date:	3/1/2004
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Washington 5th
Research Category:	Engineering
Focus Category:	Ecology, Surface Water, Groundwater
Descriptors:	Salmonid, Habitat Quality, Touchet River, Hydraulic Conductivity, Slug Test, Geostatistical Analysis, MODFLOW
Principal Investigators:	Joan Q Wu, Timothy P Hanrahan

Publication

1. Leek, R., J.Q. Wu, L. Wang, T. Hanrahan, H. Qiu, and M.E. Barber, 2005. Three-dimensional characterization of riverbed hydraulic conductivity and its relation to salmonid habitat quality, Hydrological Processes (In preparation)

PROBLEM AND RESEARCH OBJECTIVES

The health and viability of fish stocks in the Pacific Northwest have long been a critical issue. The recent listing of salmon species as threatened or endangered by the National Marine Fisheries Service signifies the urgent need for fish habitat protection and restoration. Previous studies have overwhelmingly indicated the degradation of natural salmon habitat due to sedimentation from agricultural lands. As a result, many streams and rivers in the Pacific Northwest have been included on the 303(d) list for sedimentation. It is well established that excess sedimentation and its negative impact on the hydraulic properties of the riverbed can directly affect salmon habitat quality. The spatial variability of saturated hydraulic conductivity plays a major role in subsurface water flow and solute transport. The riverbed hydraulic conductivity also has an impact on fish egg survival rate. Yet in most hydrological studies the streambed is represented as a layer of uniform thickness and low permeability.

The main purpose of this study was to characterize the hydraulic properties of the riverbed and their relation to salmonid habitat quality by measuring the three-dimensional riverbed hydraulic conductivity. Field measurements were made within two representative reaches of the Touchet River in the dryland agricultural area of the Pacific Northwest. The specific objectives were: (1) to conduct a detailed field measurement of the three-dimensional distribution of hydraulic conductivity under the riverbed surface using slug tests; and (2) to perform statistical and spatial analyses of the field-measured hydraulic conductivity and the derived specific discharge data as well as their relationship to salmon habitat quality.

METHODOLOGY

Study Site and Sampling Scheme

The study site was located within two adjacent reaches of the Touchet River near Dayton, Washington. Sampling points were placed on a sampling grid with a spatial resolution of 5 m by 3 m by 0.3 m in the longitudinal, transverse, and vertical directions, respectively. The length of each sampled reach was 50 m while the depth reached 1.2 m below the riverbed surface wherever possible. For the chosen reaches, the width of the stream was rather uniform and therefore four measurements were taken across each lateral transect of 9 m. At each depth of a point on the sampling grid, estimates of hydraulic conductivity were made based on three replicates of slug tests as described below.

Measurement of Hydraulic Conductivity

Slug tests were performed by manually driving piezometers into the riverbed. The piezometers were constructed of 15-cm long commercial-grade well-screen connected at the lower end to a 12-cm drive point and welded at the upper end to a galvanized steel pipe (o.d. 4 cm). Individual piezometers were pounded into the riverbed to the desired depth using a solid steel drive rod. A control manifold was then threaded to the top of the piezometers (which remained above the water surface) allowing pressurization and rapid release of the pressure to facilitate the slug test. Once the piezometer was in place, the drive rod was removed, and the pressure transducer and temperature probe was lowered into the piezometer to the bottom plate of the screen section to measure hydraulic head and temperature.

To minimize the interference from any remaining fine sediment (<1 mm), and to establish hydraulic connectivity with the surrounding sediment at each test, the initial water in the piezometer after installation was removed using a hand pump. Additionally, the probe was lifted 8−10cm off the bottom of the piezometer to avoid interference from fine silt. The instrumentation in the probe was connected to the data logger located in a water-tight container on shore by a factory-sealed pressurized cable. The data logger was connected to and actively monitored by a laptop computer. The stream water temperature was also monitored with a thermocouple at the bed surface.

For a partially penetrating piezometer in the riverbed substrate under unconfined flow, the Bouwer and Rice method was adapted to estimate the saturated hydraulic conductivity K

$$K = \frac{r^2 \ln(R_e / R)}{2L_e} \frac{1}{t} \ln\left(\frac{\Delta h_o}{\Delta h_t}\right) \quad (1)$$

where r is the radius of the well casing, L_e is the length of the well screen, R_e/R is the ratio of the distance from the well, over which the average value of K is measured, to the radius of the gravel envelope, Δh_0 is the drawdown at time $t = 0$, Δh_t is the drawdown at time t.

Determination of Specific Discharge

The measured hydraulic head was then used to estimate vertical hydraulic gradient ($VHG = \Delta h/L$) where L is the depth from the riverbed surface to the measurement position. The vertical hydraulic gradient, in combination with K, determines the specific discharge (v) and therefore the losing or gaining condition at the measured position.

Statistical and Geostatistical Analyses

Descriptive statistics of both hydraulic conductivity K and specific discharge v, including their mean and standard deviation, were estimated. In addition, the normality of K and $\ln K$ were tested. Kriging was performed to obtain a three-dimensional geostatistical model of K and $\ln K$.

Estimation of Egg Survival Rate

The values of specific discharge v were used to estimate the expected egg survival at the study site. Survival estimates were based on a predictive model of percent survival as a function of specific discharge. The predictive model relating egg survival with the specific discharge through a riverbed derived from empirical data for sockeye salmon (Cooper, 1965) is given as:

$$S = 167.0 + 46.31 \log(v) \quad (2)$$

where S is percent survival.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The slug test data from this study yielded a three-dimensional characterization of the riverbed hydraulic conductivity as highly heterogeneous. Such a detailed characterization allows for improved conceptualization and quantification of the dynamic processes at the streambed interface that influence the health of the stream aquatic ecosystem, the hyporheic zone, and the exchange of surface and ground water through this interface.

An example of slug test results is shown in Fig. 1 below. Depth of recovery as a function of time was fitted to the Bouwer and Rice equation to obtain *K*. The rate of recovery is represented by the shape of the curve, and the faster the recovery, the greater the *K* value.

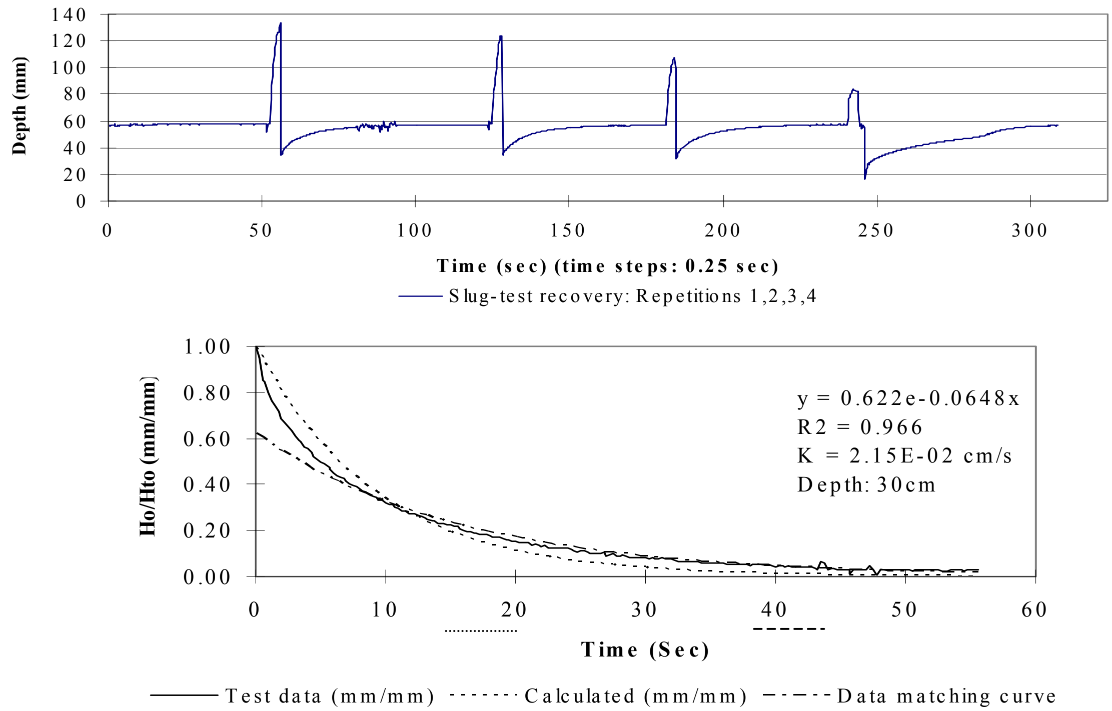

Fig 1**.** Typical slug test recovery curves for one location within the upper reach. In the lower panel, H_o/H_t is a dimensionless value representing head recovery. *K* is determined using the Bouwer-Rice equation through curve-matching.

Table 1 presents the summary statistics of the field-measured hydraulic properties at different depths for the upper reach. Within the riverbed of the upper reach, there exists significant spatial variability of the hydraulic conductivity spanning three orders of magnitude. The direction of flow varies from place to place with both down- and upwelling occurring in random form.

Fig 2 illustrates the spatially varying egg survival rate *S*, specific discharge *v*, vertical hydraulic gradient *VHG*, and hydraulic conductivity *K*, all calculated for the sediment depth of 30 cm in the upper reach. The egg survival statistics indicates that approximately 41% of the riverbed surface area in this upper reach will have habitat gravels, underlain by highly permeable material, which results in a survival rate greater than 55%. Further, 29% of this surface area provided an estimated survival rate greater than 75%. The location at about 35 m corresponds to a highly permeable (*K*) region (*K* = 0.467 cm/s), with negative *VHG* and positive *v*, and thus relatively high egg survival indexes (67 %, 54 % and 76 % across the transect).

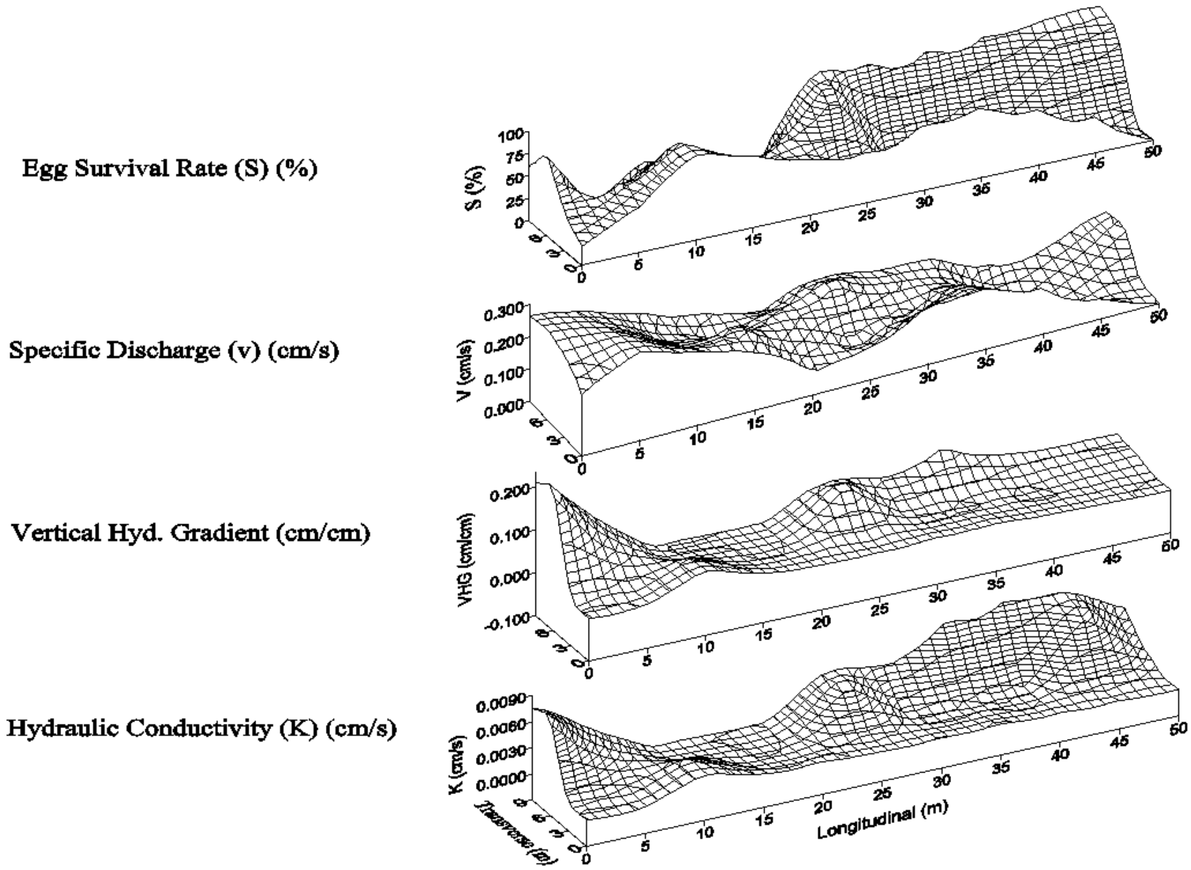

Fig. 2. Two-dimensional krigging of *S*, *v*, *VHG*, and *K* at the 30-cm depth of the upper reach.

In sum, a complete, three-dimensional characterization of riverbed hydraulic conductivity in the Touchet River, a Pacific Northwest stream on basaltic bedrock, was obtained in this project. Such characterization contributes to a better understanding of the natural heterogeneity of the riverbed and surface water and ground water interactions in this region. The study provides additional evidence that the streambed is a dynamic interface far more complex than previously generalized. The secondary product of the study is the preliminary assessment of salmon habitat quality based field measured riverbed hydraulic properties in a dryland reach typically found in the Touchet River watershed in the Lower Columbia River Basin. This study serves as a pilot study for characterizing riverbed heterogeneity using slug tests and relating riverbed hydraulic conductivity to salmon habitat quality. Additionally, it serves as a foundation for future efforts to assess the impact of agricultural management practices on stream water quantity and quality.

Table 1. Descriptive statistics of field-measured *K*, *VHG*, and *v* at different depths within the upper reach.

Descriptive Statistics	*VHG* (cm/cm)	*K* (cm/s)	*v* (cm/s)
30cm			
Minimum	-0.07	1.81E-03	-9.33E-04
Maximum	0.28	8.60E-01	2.43E-01
Mean	0.12	1.48E-01	2.03E-02
Standard Deviation	0.09	2.51E-01	4.44E-02
60cm			
Minimum	-0.03	1.12E-03	-1.52E-03
Maximum	0.25	7.46E-01	8.33E-02
Mean	0.10	7.79E-02	7.82E-03
Standard Deviation	0.07	1.52E-01	1.65E-02
90cm			
Minimum	0.03	1.05E-03	1.16E-04
Maximum	0.23	4.47E-01	4.52E-02
Mean	0.10	8.98E-02	7.90E-03
Standard Deviation	0.06	1.57E-01	1.54E-02
Bottom*			
Minimum	-0.16	1.68E-03	-2.34E-01
Maximum	0.35	1.45E+00	5.17E-02
Mean	0.08	2.28E-01	1.37E-03
Standard Deviation	0.10	3.61E-01	4.68E-02

* None of the piezometers in the upper reach were driven to the full 120-cm depth as in the lower reach. Sediments ranged in depth from less than 30 cm to approximately 110 cm.

Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions

Basic Information

Title:	Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions
Project Number:	2004WA91B
Start Date:	3/1/2004
End Date:	5/31/2005
Funding Source:	104B
Congressional District:	Washington 5th
Research Category:	Biological Sciences
Focus Category:	Surface Water, Ecology, Water Use
Descriptors:	Aquatic Habitat, Periphyton, Habitat Modeling, Instream Flow Methodology, Flow Measurement
Principal Investigators:	Rollin Hotchkiss, Mark Charles Stone, Richard Zack

Publication

1. Stone, Mark C., 2005, Natural stream flow fields: observations and implications for benthic organisms, Department of Civil and Environmental Engineering, College of Engineering and Architecture, Washington State University, Pullman, Washington, 200pp.
2. Stone, Mark C., Rollin Hotchkiss, and Richard Zack, Natural Stream Flow Fields: Measurements and Implications for Benthic Organisms, State of Washington Water Research Center, Washington State University, Pullman, Washington, Water Research Center Report No. WRR-22, 133 pp.
3. Stone, Mark C., Rollin H. Hotchkiss, and R.R. Morrison, 2005, The influence of successional development on periphyton scour resistance, in proceedings of the World Water and Environmental Resources Congress, Anchorage, Alaska, 10pp.

PROBLEM AND RESEARCH OBJECTIVES

Hydropower development, channelization of streams, water withdrawals, land use changes, and other anthropogenic activities have caused severe damage to aquatic ecosystems. To restore ecosystem processes and functions, we must advance our knowledge of these systems. This requires a better understanding of physical flow features and the influence of these features on aquatic organisms. Improved flow field descriptions will advance stream restoration efforts by allowing reproduction of important flow features. Advanced measurement techniques will allow for easier analysis of aquatic ecosystems. Increased knowledge of the influence of flow on aquatic organisms will improve our ability to manage and restore streams and rivers.

This research addressed this need by meeting the following objectives:

Objective 1: a) Evaluate the adequacy of existing empirical relationships for describing natural stream flow fields and b) investigate spatial distributions of flow variables

Objective 2: Test the adequacy of acoustic Doppler current profiler (ADCP) instruments for measuring velocity, shear stress, and turbulence distributions in cobble bed streams

Objective 3: Investigate temporal variations in periphyton resistance to shear stress

Objective 4: Investigate the influence of flow on benthic organisms by developing habitat suitability criteria (HSC) for periphyton assemblages and macroinvertebrates

METHODOLOGY

Objective 1 was met by characterizing mean and turbulent flow field distributions in two cobble bed river stream reaches. An acoustic Doppler velocimeter (ADV) was used to collected high frequency velocity data in three to four cross sections in each river. Observations were made at seven points per vertical profile at three to five stations in each cross section, for a total of approximately 100 samples per stream reach. Each reach was approximately 50 meters long and 15 meters wide and included riffle, run, and pool stream units. Data were analyzed to calculate mean and turbulence variables including turbulence intensity (TI), turbulent kinetic energy (TKE), correlations, and integral scales. The data were compared to laboratory derived empirical equations and the spatial heterogeneity was investigated in the horizontal and vertical planes.

Objective 2 was accomplished by conducting ADCP and ADV measurements at nine coincident stations in two cobble bed rivers. The ADCP was mounted in a Riverboat and anchored with taglines to the river banks. Data was collected for 20 minutes and the instrument position was marked and surveyed. The ADV was then placed in the same position and data were collected in a vertical profile. Velocity and shear stress measurements were statistically compared between instruments. A physical evaluation of ADCP turbulence measurements was also completed.

Objective 3 was completed by colonizing ceramic tiles in a stream for various time periods and then exposing the slides to increasing shear stress in the laboratory. The tiles were colonized for periods from 2 weeks to 12 weeks. Additionally, new tiles were colonized every two weeks to evaluate the effects of successional development. Following the shear stress exercise, the remaining periphyton was removed from the slides and the ash free dry mass (AFDM) was determined in order to calculate mass scour and percent scour. An ANOVA was completed to test a series of hypotheses.

Objective 4 was met by collecting periphyton AFDM and macroinvertebrate frequency samples in two stream reaches. The biological observations were combined with physical measurements of flow velocity, substrate size, and water depth. The data were then combined to investigate relationships between biological and physical stream variables. The relationships were normalized to produce HSC.

PRINCIPAL FINDINGS AND SIGNIFICANCE

It was found that the log-law adequately predicted velocity distributions for all stream units and transverse locations. Shear stress observations were not significantly different than predicted values, but results were marginal with a high level of variance. All turbulence observations were significantly different than empirical predictions. Sample variance was too high for TI and TKE observations to produce regression equations. Regression equations were proposed for integral time and length scales. ANOVA results showed significant differences in velocity and turbulence measurements between stream units for nearly all variables. However, significant differences by vertical locations were only observed for streamwise velocity distributions. These results contradict existing concepts of open channel turbulence, which have been developed through laboratory experiments. A TKE budget approach was suggested to improve turbulence predictions.

ADCP measurements for velocity magnitude and shear stress (when determined from velocity magnitude using the log law) were adequate. However, three dimensional velocity components and turbulence measurements were inadequate. Sample error was high because high velocities required the instrument to be operated in a “noisy” mode. The instrument sampling volume was too large and sampling frequency too slow to conduct turbulence measurements. These results have broad implications, considering the large numbers of ADCP instruments in use by the USGS and other agencies.

Periphyton shear stress resistance increased with successional development. However, resistance was not a function of time of the year. AFDM scour was a linear function of shear stress. AFDM increased significantly with both successional development and time of the growth season. These results can be used to improve reservoir release management and stream restoration efforts.

HSC curves were produced for both periphyton and macroinvertebrates. This included HSC functions for substrate size and water depth and velocity. Velocity HSC functions reveled an increase in periphyton AFDM and a decrease in macroinvertebrate frequencies with an increase in water velocity. Depth HSC functions revealed a similar but less distinct trend. Particle size HSC functions were less apparent and were found to be dependent on discretization interval. The HSC curves can be combined with a habitat simulation to determine the impacts of a changed flow regime. This will allow for a more thorough investigation of the value of instream flows.

Collaborative Research:Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams

Basic Information

Title:	Collaborative Research:Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams
Project Number:	2002WA12G
Start Date:	8/1/2002
End Date:	7/31/2005
Funding Source:	104G
Congressional District:	Washington FIfth
Research Category:	Engineering
Focus Category:	Sediments, Hydrology, Geomorphological Processes
Descriptors:	Restoration, Bedforms Migration, Stage-Discharge Relations
Principal Investigators:	Thanos N Papanicolaou, Lisa Louise Ely

Publication

1. Hendrick, Ross R., Lisa L. Ely, A. N. Papanicolaou, and Kyle B. Strom, 2004, The role of geomorphic and hydrologic feature on sediment clusters in gravel-bed streams, Washington: A field-based approach, "in" Abstracts with Programs, Geological Society of America Rocky Mountain/Cordilleran Section Meeting, Boise, Idaho, May 3-5, 2005, 36(4):31.
2. Hendrick, Ross R., Ely, Lisa L., Marcell, Janielle L., Papanicolaou, Athanasios N., and Strom, Kyle B., 2005, Tracking the Evolution of Sediment Clusters after High Flow Events, and their Effects on Sediment Transport: Entiat River, Washington: A Field-Based Approach, "in" Abstracts with Programs, Geological Society of America, 37(4):103.
3. Marcell, Janielle L., Ely, Lisa L. and Hendrick, Ross R., 2005, Evolution of Sediment Cluster Morphologies on the American River, Cascade Mountains, Washington, "in" Abstracts with Programs, Geological Society of America, 37(4):45.
4. Strom, Kyle, Athanasios N. Papanicolaou,B. Billing, Lisa L. Ely, and Ross R. Hendricks, 2005 Characterization of Particle Cluster Bedforms in Mountain Streams. Presentation at the World Water and Environmental Resources Congress, EWRI, ASCE, May 15-19, 2005.
5. Marcell, Janielle, 2004, Patterns of Sediment transport in the American River, Cascade Mountains, Washington (poster presentation) "in" Thirteenth Regional Conference on Undergraduate Research, Murdock College Science Research Program, Lewis and Clark College, November 19-20, 2004.

PROBLEM AND RESEARCH OBJECTIVES

1. Develop a stage-discharge relation to determine the required flow conditions for cluster development and disintegration in the field at the American and Entiat River sites.
2. Analyze the flux of individual sediment particles through cluster bedforms.
3. Characterization of Particle Cluster Bedforms at the American River site.

METHODOLOGY

Stage data for the American River site was collected and logged for high flows in 2003 and 2004 with the Global Water Instruments water-level recorder, which was installed at the site in Spring, 2003. The discharge at the Entiat River was determined directly from the USGS gage. Channel cross sections were surveyed on both rivers, and velocities at the American and Entiat River sites were calculated using the HEC-RAS water-surface profile model.

Clusters were marked, photographed and surveyed before and after each major high-flow event. Sediment movement within individual clusters was analyzed from photographs.

To achieve objective 3 data were recorded at the site, for the reach-scale stream morphology, stream slope, grain size distribution, cluster type, and geometric properties. Five main types of clusters where identified. Namely the comet, heap, line, pebble, and ring shaped clusters. These cluster types can be roughly correlated to other cluster types noted in the literature from field and laboratory studies. Descriptive cluster geometry ratios are presented to aid in defining artificial cluster creation in numerical and analytical modeling of flow over a clustered bed.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Entiat River Study Site. On the Entiat River, the evolution of cluster beforms and movement of individual sediment particles within clusters were monitored for 4 peak flows that inundated the study site. The peak flows were Oct., 2003, 57 m^3s^{-1}; Nov. 2003, 13 m^3s^{-1}; May 2004, 39 m^3s^{-1}, and Jan. 2005, 22 m^3s^{-1}. Sediment cluster bedforms had a measurable impact on sediment entrainment during the two intermediate flow events of 22 and 39 m^3s^{-1} that inundated the gravel bar at the study site. Under these flows, the critical shear stress required to entrain sediment particles was 38-51% greater for sediment within clusters than for isolated sediment particles on the gravel bar. All clusters were mobilized during the highest peak in the 2-year record, 57 m^3s^{-1}, which occurred in October, 2003. Therefore the clusters did not significantly impact the overall sediment transport during this event, as the entire bed was mobilized at the study site. No measurable sediment movement occurred within the clusters during the lowest inundation event of 13 m^3s^{-1}. The mean annual peak flow on the Entiat River is ~80 m^3s^{-1}, which means that on average, sediment clusters on this river are are likely at least partially mobilized and reformed on a semi-annual basis. At site 1 on the Entiat River, which had a fairly well-sorted sediment size distribution, the diamond cluster form was the most stable over the 2-year period. At site 2, with a greater range of sediment sizes and larger anchor clasts, all cluster forms were equally stable.

American River Study Site.

The current study has examined the shape and geometric properties of naturally occurring cluster microforms on a mountainous gravel bed river. Our focus was the evolution of the cluster morphologies during periods of moderate peak flows. It was our hypothesis that this evolution would only occur during moderate flow conditions because during high flow periods the clusters would be completely reorganized.

Five main types of discrete cluster microforms were observed, those being the pebble, line, comet, heap, and ring type clusters. Although deciphering cluster shape is subjective, examining cluster geometric properties reveals that there are physical differences among cluster types. These physical differences might be related to a point at which a cluster is in it's evolutionary cycle. In addition, individual cluster types and their associated shapes are also likely to effect the way in which a particular cluster type will effect sediment transport and the near bed flow field. If we wish to understand the accumulative effect of a clustered bed on river hydraulics and sediment transport, we must identify individual cluster types and account for the effects these have on the turbulent structure of the the flow. The geometric ratios presented here in could be used as a first approximation to defining cluster topography in modeling efforts.

On the American River the 2003 peak flow was 31.5 m3/sec and the 2004 peak flow was 24 m3/sec, which are moderate-sized annual peaks compared to the historic record. Our hypotheses were that 1) transverse line clusters are incipient forms that would ultimately transform into upstream or downstream triangles; 2) upstream and downstream triangle clusters are intermediate cluster forms which ultimately form diamond clusters; and 3) diamond clusters are the final cluster form and are therefore the most stable. The results were that no flows during the 2-year period were sufficient to mobilize the sediment clusters, and all cluster forms were therefore stable throughout the study period. In contrast, individual sediment particles were added, moved and removed from the clusters. The diamond clusters experienced the greatest amount of individual sediment movement through the stable cluster bedforms and the transverse lines the least.

The field study areas on both rivers have experienced below-average peak flows during the 2-year study period. This period of low to moderate flows was advantageous because we were able to investigate the flux of sediment through the stable cluster forms without the complete destruction and reorganization of the clusters. Understanding the sediment movement through the clusters helps determine the sediment flux and transport patterns throughout the stream. The response of the channel bed morphology to flows in unregulated rivers such as the Entiat and American Rivers, has practical implications for river management, channel restoration and maintenance of aquatic habitat in regulated streams by guiding the determination of peak discharges necessary to maintain or mobilize cluster bedforms.

Additional analyses underway include: 1) continued examination of critical shear stresses involved in sediment entrainment, 2) determination of cluster density at different sites, 3) incorporation of sediment and flow data into the 3STID flow model at the University of Iowa to refine the bed-velocity calculations at the cluster sites and 4) analysis of the geomorphic settings of gravel clusters.

Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales

Basic Information

Title:	Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales
Project Number:	2002WA19G
Start Date:	8/1/2002
End Date:	5/31/2006
Funding Source:	104G
Congressional District:	Washington FIfth
Research Category:	Ground-water Flow and Transport
Focus Category:	Non Point Pollution, Nitrate Contamination, Hydrology
Descriptors:	Catchment Hydrology, Environmental Tracers
Principal Investigators:	C Kent Keller, Richelle Allen-King, Shulin Chen

Publication

1. Allen-King, R., 2003, Ground and Surface Water Contributions to Chemical Mass Discharge: Field to Basin Scales, Keynote Address, "in" Abstracts, 4th Symposium on the Hydrogeology of Washington State, April 8-10 2003, Tacoma, WA. (http://www.ecy.wa.gov/events/hg/index.htm)
2. Keller, C.Kent, 2003, Using environmental tracers to understand agrichemical transport pathways to Palouse surface water, Invited Presentation to WSU Water Quality Research and Extension Colloquium, April 24, 2003, Washington State University, Pullman, WA.
3. Simmons, Amy N., 2003, Dissolved Pesticide Mass Discharge in a Semi-arid Dryland Agricultural Watershed at the Field and Basin Scale, M.S. Dissertation, Department of Geology, Washington State University, Pullman, Washington, 165 pp.
4. Simmons, A.N., L.L. Bissey, R.M. Allen-King, C.K. Keller, and J.L. Smith, 2003, Estimated dissolved agricultural mass discharges using environmental tracers in a semi-arid dryland agricultural watershed (Abstract), "in" Abstracts with Programs, Geological Society of America Annual Meeting, November 2-5, 2003, Seattle, Washington, Abstracts with Programs 34(7), Paper No. 130-12, p. 316.
5. Simmons, Amy N., Richelle M. Allen-King, C. Kent Keller, and Jeffrey L. Smith, 2003, Dissolved pesticide mass discharge in a semi-arid dryland agricultural watershed at the field and basin scale.

Proceedings of the Fourth Symposium on the Hydrogeology of Washington State, April 8-10, 2003, Tacoma, Washington, p. 78. http://www.ecy.wa.gov/events/hg/abstracts_talks.htm

6. Suzuki, K., C. K. Keller, and J. Vervoort, 2004. Weathering in and calcium losses from semi-arid agricultural landscapes: Insight from strontium isotope ratios, in EOS Transactions, American Geophysical Union 85(47), F873.
7. Wannamaker, C. N., A. Goodwin, C. K. Keller, R. Allen-King, and J. L Smith, 2004. Edge of field nitrate loss and oxygen-18 dynamics in a dryland agriculture setting, in EOS Transactions, American Geophysical Union 85(47), F912.

PROBLEM AND RESEARCH OBJECTIVES

Among the most serious consequences of agricultural-N application perturbations is N loading of terrestrial and coastal ocean waters with associated effects on water quality, aquatic and marine habitat and productivity, and other environmentally critical variables and processes. In the US, tens of thousands of river and shore reaches are considered impaired by the EPA, and many of these impairments are believed to be attributable to agricultural non-point sources. This means that it is important to understand how agricultural practices are related to streamwater N loading, in various climate/cropping associations.

In this work we are studying how field-scale processes influence delivery of nitrogen (primarily as dissolved nitrate, NO_3) to streams. We have hypothesized that in our semiarid dryland farming region, stream NO_3 discharge, from field and small catchment to basin scales, is principally controlled by the response of field-scale flow and transport processes to drainage regime and strongly seasonal hydrology. We are testing this hypothesis by expanding our ongoing study of field-scale processes to include undrained settings, and developing a spatially- and temporally-detailed ^{18}O data set which can be used, in parallel with geochemical data sets, for simultaneous isotope and geochemical hydrograph separations at multiple watershed scales. The isotope data are needed to identify water sources ("new" vs "old"). Used in combination with pathway information from the geochemical tracers, they will help us understand how temporal evolution of soil NO_3 distributions is related to transport times to streams.

The concentration and mass discharge of an environmental tracer at a watershed gauging station are the averaged consequences of hydrologic processes across the entire watershed. The watershed-scale averaging property of stream discharge and streamwater isotope geochemistry has been used for decades to interpret variation of sources of streamflow over the course of hydrologic events. These signals, when combined with measurements internal to the watershed (such as monitoring at smaller catchment scales and inside catchments), can reveal the underlying processes and their spatial variation. Stream-gauge monitoring of nested watersheds thus generates measurements that appropriately and consistently (and naturally) provide information about spatial variability at each scale.

METHODOLOGY

Our two field locations are near Pullman, WA, within the Missouri Flat Creek watershed of the South Fork of the Palouse River. The Missouri Flat Creek drainage has a long record of study by USGS and WSU scientists. The fields are subject to typical farming practices and crop rotation, receiving N fertilizer during fall and spring planting, and they represent typical bottom-slope, streamflow-generating locations. The undrained field exhibits intermittent winter-spring surface runoff while the tile-drained field does not. These fields represent the principal settings we assume to control streamflow generation and NO_3 discharges.

The tile-drained location was instrumented in 2001 with suction lysimeters (operated at 0.5 bar) and zero-tension pan lysimeters. These samplers were installed horiontally in triplicate at 0.2, 0.5, and 1.0 m depths from a trench (to permit location of sampler intakes beneath undisturbed field soil). They allow us to sample subsurface-pathway events (pans) as well as resident porewater over a range of saturation conditions (suction). In addition, depth profiles of 5 thermistors and 5 TDR moisture probes were installed via the trench wall. Data from these instruments are logged continuously by the weather station (with precip gauge/sampler) located nearby. With this array, we monitor subsurface conditions above a tile drain which drains approximately 10 ha and outlets

10 m distant. The undrained location has soil-water samplers in parallel with the tile-drained location.

Pressure transducers and dataloggers have been deployed and rating curves developed that measure water discharge from nested 660–7000 ha watersheds.

PRINCIPAL FINDINGS AND SIGNIFICANCE

During the reporting period we have extended all of our existing datasets, refined our discharge-estimation procedures such that preliminary N stream fluxes may be estimated, and performed nearly 1500 ^{18}O analyses. Annual nitrate fluxes exiting the watersheds range from 5 to >20 kg (N)/ha, corresponding to approximately 5-20% of typical annualized mean application rates. The ratio of annual nitrate flux to annual runoff *increases* with annual runoff, i.e. larger flows are generally associated with larger N concentrations which typically reach 15-40 mg (N) /L in late February/March. This pattern is different from those observed in humid regions where most such studies have been conducted.

Monitoring of soil water, tile drainage, and ephemeral surface runoff, suggest strong nitrate concentration response to fertilizer application timing in shallow soil and in-field runoff, but not at larger scales. Soil-profile water content dynamics and tile-drain flow rates suggest that high-nitrate soil water is mobilized throughout the profile when water contents near saturation are attained (Figure 1).

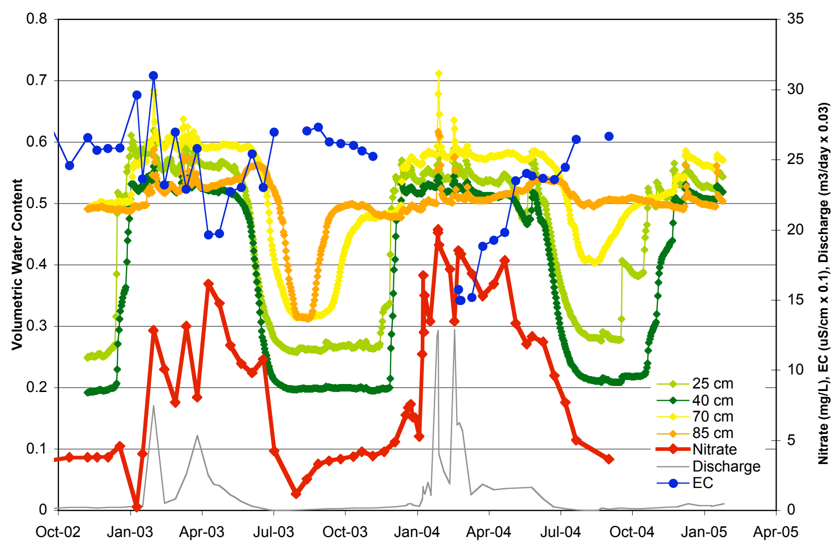

Figure 1. Nitrate and EC concentrations (red and blue respectively) in discharge (gray) from the tile drain. Note relationships of nitrate changes to changes in discharge and shallow soil moisture content (green and yellow). EC is tracer of water-mineral reaction progress and indicates relative subsurface residence time. Low EC values may indicate increased contributions of water from the shallow part of the profile.

This process can explain the generation of high-nitrate seepage and drainage to ditches almost immediately at the onset of high flow, once the antecedent profile is sufficiently wet. High flows also appear to increase contributions of shallow-profile water to runoff by raising water tables, as suggested by temporal behavior of electrical-conductivity values (Figure 1).

The foregoing interpretations do not implicate any sort of subsurface bypass- or preferential-flow processes in the transport of nitrate from point of ground-surface application to discharge in surface water or tile drainage. They are also apparently consistent with vertical soilwater velocities of months to a few years per meter. We are presently studying oxygen-18 temporal dynamics to test these ideas (Figure 2). Tile drainage is apparently "anchored" at a fairly constant ^{18}O value of –15 per mil, indicating substantial filtering and damping of fluctuations evident in the soil profile above the tile drain. However, relatively subtle seasonal fluctuations are also evident in the tile-drain signal. We are presently attempting to apply simple analytical convolution-integral models to these data to attempt to estimate means and ranges (dispersion) of surface-to-drain travel times. We will attempt similar modeling at larger scales.

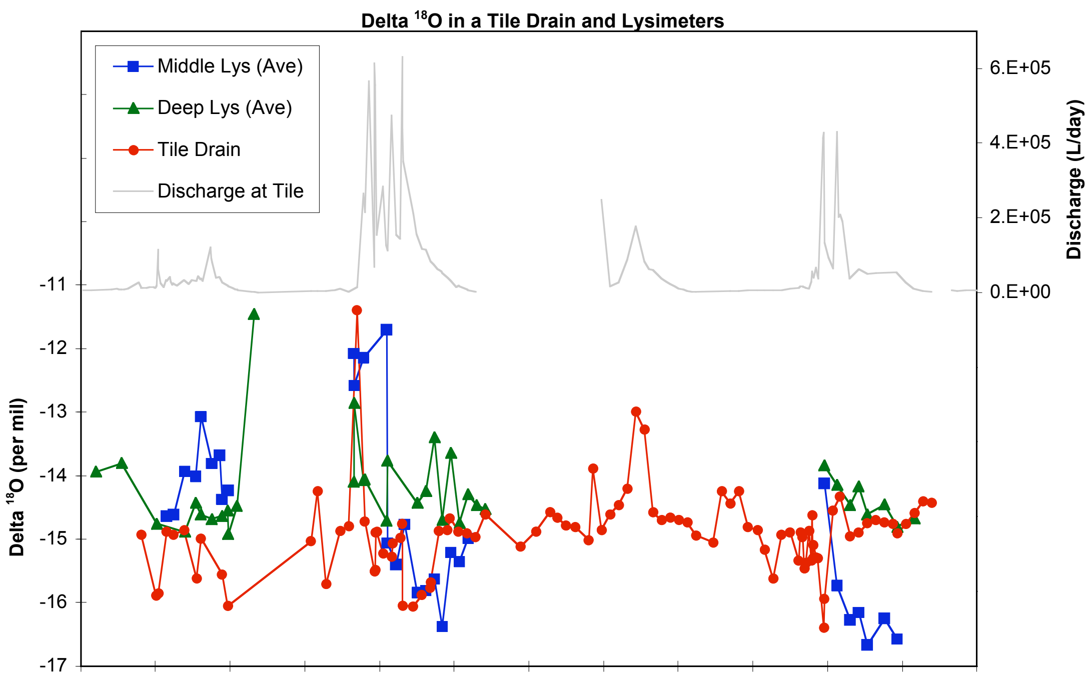

Figure 2. Blue and green symbols represent soil water at 40 and 85 cm depth, respectively. Shallow fluctuations are damped in deeper soil water and tile drainage.

Information Transfer Program

The Water Research Center believes that Outreach and Education are important components to its mission. The primary goal is to facilitate information exchange by providing opportunities for combining the academic work of research universities in the state with potential users and water stakeholders. This process occurs through a variety of activities, formal and informal, that raise the visibility of university research results throughout the Pacific Northwest. Federal, state and local agencies, non-governmental organizations, watershed groups, and concerned citizens are in need of interpreted science that can be applied to solving the regions water problems. The Center makes substantial efforts to facilitate this process.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2002WA4B
Start Date:	3/1/2004
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Washington Fifth
Research Category:	Not Applicable
Focus Category:	Management and Planning, Education, None
Descriptors:	
Principal Investigators:	Michael Ernest Barber

Publication

The following items constitute the core of the technology transfer activities of the SWWRC.

Meetings with the Spokane/Rathdrum Prairie Aquifer Committee continued into 2004 which culminated in a joint project with the USGS and the Water Institutes in Idaho and Washington aimed at determining water availability across state boundaries. A public forum was held to discuss issues with the general public.

Attended AGU conference to present poster session on possible hydrologic observatory for the Spokane River basin. Discussed possibility with several agencies and institutions in the region to solicit support and ideas.

Attended UCOWR meeting in Portland, Oregon to network with regional water professionals, attend NIWR Board meeting, and participate in conference. The Center was a co-sponsor of the Allocating Water: Economics and the Environment conference held in the summer of 2004.

Coordinated Water Summit across campus bringing together Deans and Department Chairs in order to increase awareness and communication of water research being done on campus.

SWWRC organized a Research/Extension faculty colloquium to increase technology transfer between water research and users of information.

We began the planning phase of a regional groundwater conference by selecting a steering committee and hold discussion on conference themes.

Participated as a panel member in a regional workshop held in Spokane, Washington to discuss water reuse issues.

Continued funding for a USDA-CSREES grant was received. The projects helps to coordinate research and extension activities of the Water Research Institutes and Extension Services in Alaska, Idaho, Oregon, and Washington with EPA Region 10. Six meetings are held each year and communication between researchers, extension faculty, and government agencies is expanding rapidly.

Updating our Web site is a continuous process. This is an important avenue for us to present information about the activities of the Center and the research faculty in the state as well as news and events, research reports, and opportunities for research funding. This media requires nearly continuous work to ensure that the material is current ant the look of the page is up to date. We also continued the process of having research reports available for download via PDF format rather than mailing of paper copies.

Our database of interested stakeholders is also constantly being updated. Currently over 2,500 names are included. A second database of water resources expertise at Land Grant Universities in the Pacific Northwest was also initiated.

The Center assisted in summer train-the-trainer for individuals involved in volunteer monitoring activities. Various aspects of water quality monitoring were presented by a team of experts from Oregon State University, Washington State University, and the University of Idaho.

The Water Center Director traveled to Jordan on three separate occasions to coordinate and participate in research project aimed at educating and training professional staff at the Jordan Ministry of Water and Irrigation. The Center is working with Department Chairs at WSU to create interdisciplinary programs in Water Science and Engineering that involve research and education efforts at three Jordanian Universities. This led to a project to assist the USGS with a project to train three junior level hydrogeologists in Jordan.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	4	0	0	7
Masters	1	5	0	0	6
Ph.D.	4	1	0	0	5
Post-Doc.	0	0	0	0	0
Total	8	10	0	0	18

Notable Awards and Achievements

This past year the State of Washington Water Research Center went through a formal 5-year review by a panel of external reviewers compiled by the USGS. Of the 54 water resources research institutes nationwide, the SWWRC was recognized as one of the six Exemplary Programs.

During 2004, the State of Washington Water Research Center converted to pdf format all past project completion reports resulting from research funded through the State Water Resources Research Institute program. Almost 300 of these reports, along with other project reports and special reports published by the Center, are available for downloading from the Center's website. Reports can be searched by categories, keywords, authors, or report numbers. The reports are located at http://www.swwrc.wsu.edu/asp/publications.asp

Publications from Prior Projects

1. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Dissertations - Abdou, Hesham M., 2003, Modeling Pesticide Leaching at Field-to-Regional Scale Using an Integrated GIS/Solute Transport Approach, Ph.D. Dissertation, Department of Crop and Soil Science, Washington State University, Pullman, Washington, 131 pp.
2. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Articles in Refereed Scientific Journals - Abdou, Hesham M. and Markus Flury, 2004, Simulation of water flow and solute transport in free-drainage lysimeters and field soils with heterogeneous structures, European Journal of Soil Science, 55(2) 229-241.
3. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Articles in Refereed Scientific Journals - Flury, Markus, James B. Harsh, and Jon B. Mathison, 2003, Miscible displacement of salinity fronts: Implications for colloid mobilization, Water Resources Research, 39(12) 1373, doi:10.1029/2003WR002491.
4. 2001WA1041B ("Dye Tracers for Vadose Zone Hydrology") - Dissertations - Mon, Jarai (formerly Nu Nu Wai), 2004, Sorption and its Effects on Transport of Organic Dyes and Cesium in Soils, PhD. Dissertation, Department of Crop and Soil Sciences, Washington State University, Pullman,

Washington, 159 pages.

5. 2000WA4G ("Integration of Surface Irrigation Techniques to Reduce Sediment Loading in the Yakima River Basin of Washington") - Other Publications - South Yakima Conservation District, National Resources Conservation Service, and Washington State University, 2004, Controlling surface erosion from rill irrigated fields, brochure published by NRCS, Yakima, Washington
6. 2002WA15B ("Development of a Comprehensive Monitoring Protocol to Characterize the Concentration and Associated Health Risks of Salmonid Pathogens Suspended in Water") - Articles in Refereed Scientific Journals - Warsen, A., M. J. Krug, S. LaFrentz, D. R. Stanek, F. J. Loge, and D. R. Call. 2004. Simultaneous discrimination between 15 fish pathogens using 16S rDNA PCR and DNA microarrays. Applied and Environmental Microbiology 70:4216-4221.