State of Washington Water Research Center Annual Technical Report FY 2003

Introduction

The mission of the State of Washington Water Research Center (SWWRC) is to:

i) facilitate, coordinate, 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; iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, and 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 five program areas: Watershed Management, Water Resources and Biotic Systems, Groundwater Systems, Irrigated Systems, 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, water reuse, 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. 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.

Non-point Pesticide Transport from Fields to Streams: Testing the Predictive Capability of a Geochemical Tracer Approach

Basic Information

Title:	Non-point Pesticide Transport from Fields to Streams: Testing the Predictive Capability of a Geochemical Tracer Approach
Project Number:	2003WA40B
Start Date:	3/1/2003
End Date:	2/29/2004
Funding Source:	104B
Congressional District:	Fifth
Research Category:	Ground-water Flow and Transport
Focus Category:	Non Point Pollution, Water Quality, Hydrogeochemistry
Descriptors:	Non-point pollutants, lindane, triallate, pesticides, water quality, tracers
Principal Investigators:	Richelle Allen-King, C Kent Keller

Publication

1. Allen-King, Richelle and C. Kent Keller, 2004, Non-point Pesticide Transport from Fields to Streams: Testing the Predictive Capability of a Geochemical Tracer Approach. State of Washington Water Research Center, Washington State University, Pullman, Washington, State of Washington Water Research Center Report WRR-19, 39pp.
2. Simmons, A. N., L. L. Bissey, R. M. Allen-King, C.K. Keller, J. L. Smith, 2003, Estimated dissolved agricultural mass discharges using environmental tracers in a semi-arid dryland agricultural watershed (Abstract), "in" Geological Society of America Abstracts with Programs, 35(6): page 316, Abstract No. 130-12.

Problem and Research Objectives

Forecasting from previous research in the Palouse basin indicates that lindane concentrations in surface runoff should decrease significantly following the relatively step-wise decrease in use of this chemical in the 2002 water year. A log-linear decline in surface runoff lindane concentrations characterized by an approximately 129 day half-life in an individual field over two years of study followed a single fall application[*1*]. The overall goal of this project was to measure the response of the stream system to the relatively step-wise change in application practice on total pesticide stream discharge over multiple catchment scales.

Methodology

Field Area Description

The research was conducted in the Missouri Flat Creek Watershed (MFC), a semi-arid agricultural watershed, near Pullman, Washington at N 46 43'40" latitude and W 117 11'30" longitude. Annual precipitation for the region is 31-58 cm/yr [*2*] with the average near the Cunningham Agronomy Farm (CAF) of 56 cm [*3*]. Undulating hills and basins of wind-blown loess deposited over basalt dominate the topography. The annual mean summer and winter temperatures are 27^{o}C and -7^{o}C, respectively [*3*]. The soils of the Palouse area, MFC, and CAF are comprised of mostly silt loam type soils [*4*].

Because lindane is applied as a seed treatment, local seed company trends give a good indication of lindane use in the area. Whitman County seed distributors and chemical sales representatives were contacted to obtain information about lindane applied to seeds to be used in the 2002 water year (WY, Fall 2002 and Spring 2003 crops). Whitman County Growers, Inc., indicated that 60-70% of winter wheat sold during fall 2002 was treated with "Cruiser" instead of lindane (G. Hatley, Pers. Comm., Oct. 11, 2002). Columbia Grain International used "Cruiser" on all seeds instead of lindane unless the farmers specifically requested lindane (K. Moser, Pers. Comm., Oct. 11, 2002). However, representatives from the Gustafson, the producer and distributer of lindane and 'Gaucho' (one of the replacement chemicals), stated that they had not observed a decline in lindane sales in the Palouse region during fall 2002 (S. Mansker, Oct 28, 2002, pers. comm.; N. Anderson, Nov. 4, 2002, pers. comm.). During the two years prior to fall 2002, most crops planted in the region were treated with lindane prior to planting (Simmons, 2003). While the lindane application information is not completely consistent between the seed distributors versus lindane distributors, the information presented is consistent among the seed distributors suggesting that lindane use likely declined significantly between the 2001 and 2002 WYs.

Traditionally, triallate is applied to 7% of wheat, barley, and pea crops planted annually in Whitman County [*1*]. In Whitman County, triallate was applied to 10% of winter wheat, 85% of spring barley, peas, lentils, and garbanzos for the 2002 WY.

Triallate was applied to almost the entire CAF in October 2000 using an application rate of 1.5lbs/acre[*1*]. Lindane was applied as a seed treatment to all crops (with the exception of winter and spring canola) planted on CAF during the 2000-2001 water years [*1*]. The WSU seed house (which provided some of the wheat seeds at CAF) bought no seeds that were treated with lindane for the 2002 WY (Pers. Comm., Nov. 5, 2002). Pesticide application data confirms that no lindane was used on seeds planted at CAF for the 2002 WY. Pesticide application data also shows that triallate has not been applied to CAF fields since the 2000 WY ([*1*])

Sampling Locations

Stream samples were collected at four locations within the MFC drainage and a tile drain. Samples were collected from a tile drained field (location TD-12) and an ephemeral stream at a non-tile drained field (ES-6) within the CAF. The ephemeral stream draining a single field discharges into an ephemeral stream that drains several fields (ES-106). The smallest watershed scale sampling location is called ES-6, and is a naturally occurring ephemeral stream that flows on 6 hectares of CAF that is not tile drained. The tile drain (TD-12) is installed at a depth of approximately one meter on another CAF cropped field. The 660 ha sampling location (MFC-660) gains water from both the instrumented tile-drained and non-tile drained fields, and is located at a culvert that feeds into MFC. The area of the largest watershed scale sampling location (MFC-4700) is 4700 ha and is located on MFC.

Sample Collection and Analysis

Tile drain and surface water samples were collected fortnightly during the 2002 WY. Surface water sample collection/filtration methods are consistent with recommended United States Geological Survey (USGS) methods [*5*]. During field collection, pesticide samples are filtered in the field (weather permitting). Samples for triallate and lindane analysis were passed through a through a pre-baked, in-line, glass fiber membrane (0.7 µm pore size) in a stainless steel holder, directly into a 30 ml borosilicate glass vial, and sealed with a PTFE lined silicone septa. Pesticide samples were refrigerated until analysis.

All samples were analyzed for the pesticides triallate and lindane, electrical conductivity (EC), and turbidity. Electrical conductivity and turbidity were measured in the laboratory immediately after sampling using an Orion® temperature compensated probe and a Hach® 2100P portable turbidimeter, respectively. Silica concentrations are going to be determined in the near future. Silica concentrations will be determined by spectrophotometric methods [*6*]. Pesticides were analyzed using solid-phase microextraction (SPME) and gas chromatography with electron capture detection according to previously established methods [*1,7*]. The ascribed non-detectable value of the pesticides of interest is 0.005µg/L. All of our field blanks, with the exception of a triallate value of 0.007µg/L on February 28, 2003 contained no detectable lindane or triallate. All triallate concentrations in all field samples collected on February 28, 2003 were greater than the limit of detection.

We performed six and nine field sample duplicate pesticide analyses for lindane and triallate, respectively. The average percent differences between the pairs were 13.6% and 18.9% for lindane and triallate, respectively. The initial analysis of one sample collected on July 4, 2003 contained no detectable lindane or triallate and 0.007 µg/L and 0.014 µg/L for lindane and triallate, respectively, in the duplicate analysis. The initial reports less than detectable concentrations are ascribed to sample processing error. The detected concentrations are assumed correct because these pesticides were detected in all other surface samples collected on the same date.

Principal Findings and Significance

Strong seasonal trends were observed for both triallate and lindane at all drainage scales with greater concentrations observed during the winter and spring, wet seasons, compared to the summer dry period.

At MFC-660 and MFC-4700, the data indicate that the lindane concentration has declined compared to the triallate concentration during the most recent WY compared to prior years. At both of these locations, which integrate over many fields and much of Whitman county, respectively, the mean, median, minimum, maximum and geometric mean of the lindane concentration:triallate concentration ratio for all samples was lower in the 2002 compared to the 2001 WY (Tables 1 and 2). The geometric mean lindane concentration (Table 1) and frequency of lindane detection declined at MFC-660 (60% during the 2002 WR compared to 79% in the 2001 WR) while the mean detected triallate concentration (Table 1) and frequency of triallate detection remained essentially constant over the three water years (detection in 73-75% of samples). The mean lindane concentration and frequency of lindane detection also declined at MFC-4700 (42% during the 2003 WR compared to

84% in the 2002 WR) while the mean detected triallate concentration and frequency of triallate detection remained essentially constant over these same two water years (Table 2).

Contrary to the data at the larger scales of MFC-4700 and MFC-660, the data at ES-106 suggests an increase in lindane concentrations with respect to triallate concentrations. At the ES-106 location, the mean, median, and geometric mean of the lindane concentration:triallate concentration ratio increased from the 2000-2002 WYs (Table 3). The geometric mean lindane and triallate concentrations at ES-106 decreased over the three years but the detection frequency remained relatively constant with both chemicals detected in nearly all of the samples collected. It appears that the difference in the concentration ratio trend in the smaller drainage compared to the larger drainages is associated with a more rapid decline in the triallate concentration compared to the lindane concentration at the ES-106 location. Behavior within the smaller drainages more closely reflects application patterns specific to the fields whereas the larger drainages integrate over many fields.

(1) Simmons, A. N., *Dissolved pesticide mass discharge in a semi-arid dryland agricultural watershed at the field and basin scale,* M.S., 2003, Washington State University, Pullman, WA, pp.

(2) Donaldson, N. C. *Soil survey of Whitman County, Washington*; U.S. Department of Agriculture, 1980.

(3) Geyer, D. J.; Keller, C. K.; Smith, J. L.; Johnstone, D. L. *Journal of Contaminant Hydrology* **1992**, *11*, 127-147.

(4) Allen-King, R. M.; Keller, C. K.; Barber, M. E.; Flury, M.; Smith, J. L. "Surface and Subsurface Transport Pathways of Non-Point Agricultural Pollutants: Analysis of the Problem over Four Decades of Basin Scale," Washington, State of Washington Water Research Center Report No. WRR-12, State of Washington Water Research Center, Washington State University, Pullman, WA, 2002, 84 pp.

(5) Shelton, L. R. *Field guide for collection and processing stream-water samples for the National Water-Quality Assessment Program*; Sacramento, CA U.S. Geological Survey: Denver, CO, 1994.

(6) APHA; (American Public Health Association); AWWA (American Water Works Association); WPCA (Water Pollution Control Federation) *Standard Methods for the Examination of Water and Wastewater*; 15th ed., 1981.

(7) Schaumloffel, J. C.; Allen-King, R. M.; Talmage, D. In *Abstracts Of Papers Of The American Chemical Society*, 2000; Vol. 220, p U83.

Table 1 -Lindane concentration: triallate concentration ratios for 2000-2002 water years at MFC-660. Only samples with detectable lindane or triallate were included in the statistics describing the concentration ratios.

	2000	2001	2002
m	15	28	15
mean (lindane):(triallate)	0.83	1.51	0.62
median (lindane):(triallate)	0.73	0.90	0.58
minimum (lindane):(triallate)	0.19	0.36	0.07
maximum (lindane):(triallate)	1.74	8.80	2.15
geometric mean (lindane):(triallate)	0.73	0.99	0.44
n	12	23	11
geomean detectable (lindane)*	0.019	0.019	0.011
m"	10	22	9
geomean detectable (triallate)*	0.024	0.020	0.021
m"	11	21	11

m=total number of samples
n=samples with detectable concentrations of lindane or triallate
*Only m' or m" samples with detectable lindane and triallate, respectively, included.

Table 2 -Lindane concentration : triallate concentration ratios for 2000-2002 water years at MFC-4700. Only samples with detectable lindane or triallate were included in the statistics describing the concentration ratios.

	2000	2001	2002
m	14	25	19
mean (lindane):(triallate)	1.06	1.23	0.47
median (lindane):(triallate)	0.87	0.96	0.41
minimum (lindane):(triallate)	0.55	0.13	0.01
maximum (lindane):(triallate)	2.04	5.09	1.42
geometric mean (lindane):(triallate)	0.95	0.94	0.26
n	8	22	12
geomean detectable (lindane)*	0.017	0.021	0.012
m"	7	21	8
geomean detectable (triallate)*	0.018	0.032	0.036
m"	7	17	12

m=total number of samples
n=samples with detectable concentrations of lindane or triallate.
*Only m' or m" samples with detectable lindane and triallate, respectively, included.

Table 3 -Lindane concentration: triallate concentration ratios for 2000-2002 water years at ES-106. Only samples with detectable lindane or triallate were included in the statistics describing the concentration ratios.

	2000	**2001**	**2002**
m	7	19	9
mean (lindane):(triallate)	0.58	0.97	1.41
median (lindane):(triallate)	0.41	0.54	1.21
minimum (lindane):(triallate)	0.24	0.21	0.15
maximum (lindane):(triallate)	1.28	4.75	3.56
geometric mean (lindane):(triallate)	0.48	0.69	0.97
n	7	19	9
geomean detectable (lindane)*	0.109	0.032	0.016
m'	7	19	9
geomean detectable (triallate)*	0.228	0.047	0.019
m''	7	19	8

m=total number of samples
n=samples with detectable concentrations of lindane or triallate
*Only m' or m'' samples with detectable lindane and triallate, respectively, included

Water Use of Potato under Sprinkler and Subsurface Drip Irrigation

Basic Information

Title:	Water Use of Potato under Sprinkler and Subsurface Drip Irrigation
Project Number:	2003WA41B
Start Date:	1/1/1997
End Date:	1/1/1997
Funding Source:	104B
Congressional District:	Fourth
Research Category:	Water Quality
Focus Category:	Irrigation, Water Use, Nitrate Contamination
Descriptors:	Drip, Irrigation, Water use, Nitrate, Potatoes
Principal Investigators:	Clyde William Fraisse, Eileen Perry, Francis Pierce, Claudio Osvaldo Stockle

Publication

Problem and Research Objectives

Irrigation is essential for high yields and net returns for a myriad of crops in the PNW, particularly for potato. But overhead (sprinkler) irrigation applied intensively on the coarse soils of the Columbia Basin may have negative impacts on both water quality and water availability. Potato rotational crops are typically grown on soils low in organic matter content that are highly susceptible to agri-chemical leaching under poor irrigation scheduling. Groundwater protection from nitrate (NO_3-N) contamination is an important public concern and a major environmental issue in this region and other parts of the nation. Overall, in Washington, 23% of the 574 wells sampled contained NO_3-N concentrations in excess of the EPA's maximum contaminant level (Ryker and Fran, 1999). Water availability is also a concern in the PNW. According to the Washington State Department of Ecology, 2001 was the second driest year on record leading to the declaration of a statewide drought emergency on March 14th, 2001. Although the situation improved during the last couple of years, water availability for irrigation continues to be a major concern in the State of Washington.

Drip irrigation offers the potential for significant water savings and reduced impact on surface and groundwater quality through more efficient delivery of water and chemicals. A better understanding and quantification of these potential benefits are an important step towards the adoption of drip irrigation by the potato industry.

The main objective of this research project was to compare potato irrigation under sprinkler and subsurface drip irrigation. We believe that a better understanding of potato water use under drip will help establish drip irrigation as a viable commercial option for potato production in the PNW. Drip irrigation and associated management strategies will promote protection of surface water and groundwater quantity and quality in the Pacific Northwest

Methodology

Field studies were located at the USDA-ARS Paterson, WA research site on a Quincy loamy sand (mixed mesic Xeric Torripsamments) soil. Sprinkler and drip irrigation plots were established in an area of approximately 2 acres. Each sprinkler plot consisted 6 80 feet long rows 34" apart. Each drip plot consisted of 3 double beds according to the design shown in Figures 1 and 2.

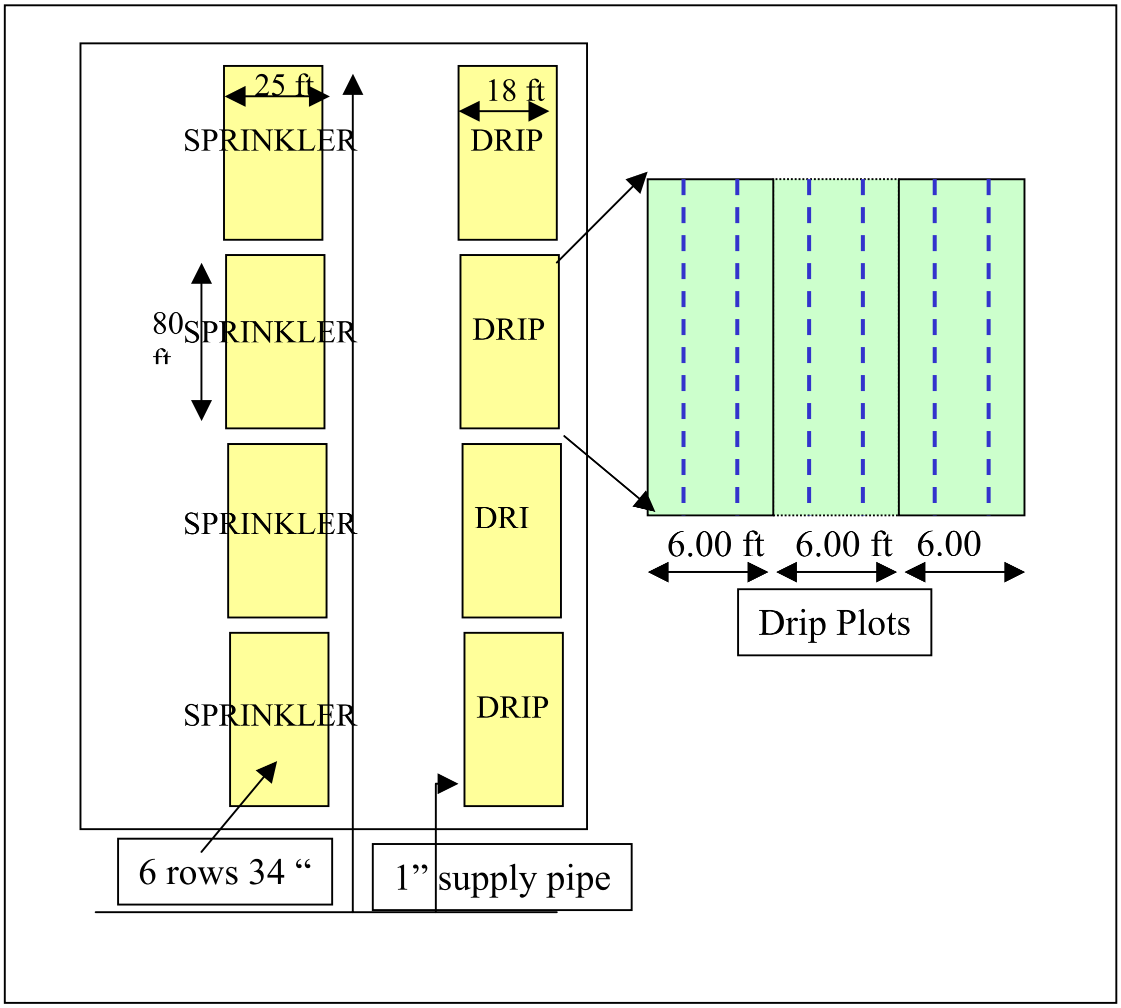

Figure 1. Drip and sprinkler plots layout.

Sprinkler plots were irrigated by a solid set system consisting of 55 Nelson R10 Turbo 9° (blue plate) white nozzle size (#70) with pressure regulators. Drip lines were TSX 500 6 mil, 12 in spacing and flow rate of 0.22gpm / 100ft. One potato variety, Ranger Russet was planted in all plots. Soil water content was monitored in all plots using Campbell Scientific CS616 TDR sensors and irrigation was automated to start and stop according to preset thresholds established by the investigators.

Figure 2. Planting of drip irrigation potato plots, May 1st, 2003.

Figure 3. Installation of subsurface drip lines.

Figure 4. Drip (top) and sprinkler (bottom) plots.

Principal Findings and Significance

Initial results obtained during the 2003 cropping season indicated a number of important conclusions. First and foremost, drip irrigation in a very sandy soil such as the one found in the area where the research was conducted requires special attention. The fact that no pre-planting irrigation was applied to the research plots due to the fact that drip tapes can only be installed after planting, combined with the fact that drip lines were installed between rows resulted in initial water stress to the crop. The narrow wet bulb created around drip outlets resulted in under irrigation of young potato plants. Figure 5 demonstrates the fact that irrigation wasn't fully effective since only the inner part of the rows were reaching the wet bulb created around the drip tape.

Figure 5. Drip irrigated plots showing wet zone created by subsurface drip lines.

Sprinkler irrigation plots had excellent development throughout the season resulting in above average yields. It should be noticed that solid set systems are not typical in the region, most sprinkler irrigation systems are center pivots. Initial plans requested the use of a linear system for the sprinkler irrigation component of this research. However, operational constraints where the linear system is currently installed caused the experiment to be conducted in the USDA-ARS research site.

A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery

Basic Information

Title:	A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery
Project Number:	1999WA0014G
Start Date:	9/1/1999
End Date:	8/31/2003
Funding Source:	104G
Congressional District:	Washington FIfth
Research Category:	Water Quality
Focus Category:	Sediments, Agriculture, Models
Descriptors:	Sediment Delivery, Best Management Practice, Watershed, Soil Erosion, Water Quality, Watershed Management, Runoff, Conservation Farming
Principal Investigators:	Shulin Chen, Rollin H Hotchkiss, Donald Klepper McCool

Publication

1. Wang, G., S. Chen, J. Boll, C. Stockle, and D. McCool, 2002, Modeling Overland Flow Based on Saint-Venant Equations for a Discretized Hillslope System, Hydrological Processes, 16(12):2409-2421.
2. Mancilla, Gabriel, 2001, Prediction of Rill Density, Transport Capacity and Associated Soil Loss of Different Tillage Systems Under Winter Conditions, "MS Dissertation," Department of Biological Systems Engineering, College of Engineering and Architecture, Washington State University, Pullman, Washington, 80 pp.
3. Mancilla, Gabriel, Shulin Chen, and Don McCool, 2001, Flow Velocity and Rill Density Distributions from Runoff on Agricultural Land, "in" Proceedings, ASAE Annual International Meeting, July 30-August 1, 2001, Sacramento, California, ASAE Paper 01-012078.
4. Mancilla, Gabriel, Shulin Chen, and Don McCool, 2002, Soil Loss Prediction Under Different Tillage Systems, Based on the Estimation of Rill Density, Flow Velocity Distributions and Transport Capacity, "in" Proceedings, Research and Extension Regional Water Quality Conference, February 20-21, 2002, Vancouver, Washington, State of Washington Water Research Center, Washington State University, Pullman, Washington, 3 pp.

5. Shulin Chen and M. Khalid Alvi, 2003. The effect of frozen soil depth on winter infiltration hydrology of Pataha Creek Watershed (Poster), presented at the ASAE Annual International Meeting, July 27-30, 2003, Las Vegas, Nevada, Poster No 139, Paper No. 032160.
6. Fu, G., Shulin Chen, and Donald K. McCool. 2003. Soil Erosion and Its Response to No-till Practice Estimated with ArcView GIS. Presentation at the 2003 Annual International Meeting of the American Association of Agricultural Engineers, Las Vegas, Nevada.
7. Wang, Guangde, Shulin Chen, and Jan Boll, 2003, A Semi-analytical Solution of the Saint-Venant Equations for Channel Flood Routing, Water Resources Research, 39(4):1076- 1085.
8. Wang, Guangde, Shulin Chen, Jan Boll, and V.P. Singh. 2003. Non-linear Convective-diffusion Equation with Mixing Cell Method for Channel Flood Routing. Journal of Hydrological Engineering, 8(5):259-265.
9. Mancilla, Gabriel, Shulin Chen, and Guangde Wang, 2004, A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery, State of Washington Water Research Center, Washington State University, Pullman, Washington, Water Research Center Report No. WRR-16, 39 pp.

PROBLEM AND RESEARCH OBJECTIVES

This project addressed a priority area of water research in the Pacific Northwest. The increased listing of salmon species as threatened or endangered by the National Marine Fisheries Service, under provisions of the Endangered Species Act, has profound impacts to agricultural practices and agriculture sustainability. The Northwest Wheat and Range Region (NWRR) that encompasses northern Idaho, northeastern Oregon, and eastern Washington has one of the highest soil erosion levels of the United States. Ground freezing and thawing cycles reduce the soil strength so particles can be easily removed and transported by runoff. In addition, currently practiced farming systems tend to leave the soil unprotected to the rain energy, which results in a high rate of erosion. Protecting fish habitat by controlling soil loss and associated sediment and chemical loading to the streams is a major challenge to the farmers in this region. Direct seed (no-till) farming has been recommended to farmers as a conservation land management practice to reduce soil erosion. Even though the use of direct seeding at Pataha watershed has increased, the effectiveness of this practice needed to be evaluated at a watershed scale. This project pursued the finding of supportive data to document the benefits of direct seeding as a Best Management Practice for the reduction of erosion and sediment delivery.

The objectives of this research were to:

1. compare soil loss from no-till and traditional farming fields;
2. evaluate models for sediment delivery process under no-till and traditional farming conditions; and
3. develop a model for predicting sediment delivery within the entire watershed.

METHODOLOGY

The Study Watershed

This project was conducted in the Pataha Creek Watershed in southeastern Washington which covers an area of about 479 square kilometers. Winter wheat, spring wheat, barley, peas, and bluegrass are the major crops grown. The Pataha Creek meanders through the watershed from its beginning in the Umatilla National Forest to its end where it flows into the Tucannon River in northeast Columbia County, a stream which is of critical important for improving salmon habitat and restoring salmon runs in the IPNW. Pataha Creek is the principal tributary to the Tucannon River and is often considered as a separate water body. High levels of sediment have been identified as the main problem associated with fish habitat and water quality deterioration in the lower Tucannon River. The Northwest Power Planning Council and the Bonneville Power Administration designated Pataha Creek Watershed as a “model watershed” to reduce soil erosion on cropland through conservation practices. Promotion of no-tillage farming has been carried out in the watershed and more and more farms have started to use no-till management for managing their lands.

Average annual precipitation with the Pataha Creek Watershed is approximately 16 inches per year although the amount is not evenly distributed. The majority of the precipitation occurs between September and May, or during the winter, with approximately 30 percent of it falling as snow. Precipitation amounts range from more than 1,000 mm a year in the higher elevations of the forested area to about 250 to 400 mm a year in lower elevations. The watershed can be classified into three different zones, i.e., high-precipitation zone, intermediate-precipitation zone (this zone can be further divided into intermediate wet precipitation zone and intermediate dry precipitation zone), and low-precipitation zone. The elevation in the Pataha Creek Watershed also changes greatly from the upper to lower portion. The elevation is about 470 m at Marengo in the lowlands and about 1,700 m at the upper boundary of the forested region.

Approximately 31% of the land in the watershed is used for dryland farming of small grains, while irrigated cropland comprises only about 3%. Most of the crops are grown in the lower and middle reaches on bluffs above the creek valleys. An estimated 42% of the land is used for grazing. These lands are located on the steep valley hillsides and forested lands along the streams and in the upper reaches, respectively. Forested land comprises about 9% of the watershed and supports grazing and some logging (Pomeroy Conservation District 1988). The majority (90%) of land in the watershed is privately owned. Federally owned land in the upper portions of the watershed accounts for roughly 7% of the area, while state land comprises the remaining 2.6%.

Runoff and Infiltration Study

The purpose of the runoff study was to investigate the difference between no-till and conventional tillage systems in terms of amount of runoff produced for a comparable rainfall event assuming the more runoff that is produced, the higher the probability of erosion. One-square meter runoff plots with borders and runoff collectors were installed in the fields of different precipitation areas for the study, which was conducted in the 1999-2000, 2000-2001, 2001-2002, and 2002-2003 winter seasons.

In the first 3 years of this project, runoff plots were installed separately in three different zones according to the precipitation level: high, intermediate and lower precipitation rate, respectively, with 12 plots in each. However, both the intermediate and lower precipitation zones had scarcely any activity in terms of runoff. Therefore, in the 2002-2003 season the runoff plots were only established in the high precipitation zone. This zone was divided in four sections according to tillage system and geographic orientation: no-till with north-facing orientation; no-till with south-facing orientation; conventional tillage with north-facing orientation; and conventional tillage with south-facing orientation. Four runoff plots were installed in each of the areas, totaling 12 runoff plots in the watershed, located in the Columbia Center/Mountain Road area of Garfield County. In addition to the runoff plots, a frost tube was placed in each of the four areas of the high precipitation zone. Also, soil moisture and soil temperature of each area were recorded every 15 minutes by using soil moisture probes and thermocouples, established at 0, 10, 20 and 30 cm of the soil profile. An automatic weather station was also installed in the high precipitation zone, and additional manually read precipitation gauges were available across the watershed, operated by the conservation district. Additionally, a hydraulic conductivity determination study was performed for each season by using a Guelph permeameter on direct seeding fields and conventional tillage areas.

Runoff plot service consisted of monitoring the volume of water in the catchments attached to the plots, as well as checking and correcting the plot borders for frost heaving, overflow or underflow conditions. Ancillary service of instrumentation was also performed. In addition, data was downloaded from the soil moisture and thermocouples readings, and frost tubes were checked every time the weather conditions predicted a possible freezing of the soil. Trips from Pullman to Garfield County were scheduled on a precipitation event bases through web-based weather information sources. A local worker was assigned to this project and consultations were made with conservation district personnel.

Rill Formation Study

Because 90% of soil erosion in the NWRR occurs as rill erosion, experiments were conducted to determine the number of rill formed under different land management conditions at a specified runoff level. To manage different amount of runoff, this part of the study was conducted under a more controlled condition at the Palouse Conservation Field Station (USDA-ARS) near Washington State University's Pullman campus. The test site had an area of approximate 0.4 ha, with an average longitudinal slope of 23 %, and it was divided into 4 different tillage treatments: no-till; conventional seedbed tillage (chisel plow, disk, and harrow); moldboard plow primary tillage only; and chisel plow primary tillage only. Flow applied, antecedent soil moisture content, slope, random roughness, percentage of residue cover, and bulk density were variables investigated as they affect formation and distribution of rills. The number of rill produced per unit width of the slope and water flow velocity distribution were recorded.

Model Simulation for Sediment Delivery Prediction

ArcView GIS and the Revised Universal Soil Loss Equation (RUSLE) were integrated to estimate soil erosion and its response to no-till practice in Pataha Creek Watershed. With the aid of GIS, the L and S factors of the RUSLE were calculated from DEM, the R_{eq} factor calculated from precipitation maps, the K factor directly from the national SSURGO database, and the C calculated from RUSLE using crop rotation and land use maps. Soil erosion from each cell was then obtained with these factors applied in a GIS environment. The Sediment Delivery Distributed (SEDD) Model integrated with GIS was employed to determine the transport of eroded soil to river channel at the watershed scale.

Sediment Delivery Study

Monitoring systems were implemented in Pataha Watershed to measure the sediment delivery from sub-watersheds. Two sub-watersheds were selected, one with primarily no-till practice and the other with mostly conventional tillage system. Installed instrumentation consisted of water level recorders and automated sampler systems, a recording precipitation gauge, frost tubes, and manually read precipitation gauges. Similar settings were established in another watershed located close to the Pullman-Moscow Regional Airport since in this watershed, rill formation was more feasible to be generated than in the Pataha Watershed. Periodic observation was used to record any rill development process.

Hydrological and Sediment Delivery Modeling

An integrated watershed hydrological model framework was developed for application in the NWRR region. The framework built upon recent theoretical advancements and involves integration of seven major components: (1) a newly developed procedure for surface runoff routing, (2) a subsurface flow routing model with an analytical solution, (3) an infiltration modeling strategy, (4) a modification in rill dominated erosion and sediment delivery modeling, (5) a procedure for overland transport modeling, (6) a new scheme for channel flow routing, and (7) sediment and pollutant transport models based on the channel flow routing scheme and simplified solutions. As part of the framework, a sediment transport model was developed for predicting sediment delivery to the main channel. Transport of sediments in the channel was also modeled.

RESULTS AND DISCUSSION

Soil Loss Comparison Between Direct Seed Cropping and Traditional Farming Systems

Observation indicates that the direct seeding system dramatically reduced the chance of soil erosion. It can be presumed that this no-till beneficial effect was achieved by 1) increasing infiltration rates due to the presence of macropores and cavities generated by the standing stubble, 2) the reduction of the flow velocity and concentration due to the residue on the ground, 3) higher organic matter, and both microbial and worm activity, which increases soil porosity, soil aggregation, stability and structure, and 4) insulating soil from the deep freezing process through a residue cover effect. Results of this project verified all of the assumptions.

Runoff Plot Study

Conditions of mild winters did not produce significant erosion events. Only a few small rills were observed in the conventional farming field where apparently a strong influence from sub-surface flow generated an ex-filtration process and subsequent rill development.

Soil loss was determined from the installed runoff plots during the first season of the study (1999-2000). After that season, erosion was estimated by observation. Unforeseen circumstances in some of the conventional tillage plots made the runoff estimations in the high precipitation zone for season 2000-2001 and the intermediate precipitation zone for season 2001-2002 unreliable. Therefore, the respective data was neither included in this report nor used for any analysis.

Table 1 summarizes the runoff and soil erosion amounts collected in the runoff plots for the season of 1999-2000. The plots were located in three zones classified by precipitation: Zone 1 (high precipitation area); Zone 2 (intermediate precipitation area); and Zone 3 (low precipitation area). A forest site was added for comparison purposes. The values are limited to one square meter and represent respective averages of 9 plots in conventional tillage fields, 9 plots in direct seed or no-till fields, and 3 plots in the forest site. It can be clearly noticed that the protective effect of direct seeding (no-till) on the soil reduced the amount of soil loss. In fact, the recorded soil loss for the conventional tillage in that season was almost twice that in the direct seeding system plots. However, the collected runoff was not so different. This means, at similar runoff, direct seeding reduced soil erosion in almost 50%. This clearly demonstrates the effect of residue and stubble in dissipating the flow shear stress responsible for soil detachment, by maintaining laminar flow and reducing the slope effect.

Table 1. Runoff Plot Summary for 1999-2000 Season

Season	Zone	Precipitation (mm)	Conventional Till Plots		Direct Seeding Plots	
			Runoff (mm)	TSS (mg)	Runoff (mm)	TSS (mg)
1999-2000 Nov. 23 – Mar. 28	1	244.3	42.6	38792.5	45.8	27377.7
	2	208.5	0.2	117.4	2.6	1252.6
	3	196.1	13.7	12586.3	0.5	133.3
	Forest	283.5	12.8	940.5		

No evidence of soil loss was reported in the subsequent seasons of this project at Pataha Creek Watershed. The conditions in the study areas were not favorable for gathering data in terms of runoff and soil loss. In addition to the mild winter seasons, analysis of soil temperature sensors in the ground indicated a general situation towards a diurnal variation of freezing and thawing cycles; showing then a shallow and short-lasting frozen depth. Precipitation events were of low intensities and occurred when the soil was not thawing. In consequence, both the snowmelt and rainfall events were not capable of producing considerable runoff in any of the plots established in the area for the following seasons of this project (Table 2). Even more, during season 2002-2003 no runoff was detected. Of course, soil erosion data collection was also not effective. A notable fact from Table 2 can be however highlighted; specifically that higher runoff amounts were observed in the conventionally farmed area. In season 2000-2001, this was verified for both the intermediate and low precipitation zones, with runoff amounts that were more than 50% and 4% of the recorded precipitation, respectively. In the direct seeding plots, the runoff for the respective zones was only 1% and 0.03% of the correspondent precipitation amount. In season 2001-2002, at the high precipitation zone plots, runoff in the conventionally tilled plots was almost 6% of the precipitation, while in the direct seeding plots it was only 0.09% which was even less than the forested area. This data confirm the importance of direct seeding as a conservative tool for cropping systems. The data clearly indicates that direct seeding reduced runoff amounts by allowing more water to infiltrate, and thus diminished the potential for soil erosion.

The capability of direct seeding for increasing infiltration was also tested against the infiltration rates for conventional tillage by using a Guelph permeameter. The study was conducted during the spring of 2000. The results, represented in Figure 1, for the first 15 minutes of the experiment, clearly indicate the better characteristics of direct seeding to infiltrate, store, and redistribute water. Some farmers at Pataha watershed have mentioned that channels usually dry in summer are now continuously flowing. They attribute this condition to the direct seeding storage capability.

Saturated hydraulic conductivity studies for conventional tillage and direct seeding (short and long term) were also conducted for this project. The results showed that the saturated hydraulic conductivity in the conventional system was approximately 5.5 times less than the long-time direct seeding and only half of the short-term direct seeding hydraulic conductivity.

Table 2. Runoff Plots Summary for Seasons 2000-2001 and 2001-2002

Season	Zone	Precipitation (mm)	Runoff, Conventional Tillage Plots (mm)	Runoff, Direct Seeding Plots (mm)	Runoff, Forest (mm)
2000-2001 Dec. 18 – Mar. 27	1	109.2	--	26.3	
	2	95.5	54.9	1.0	
	3	111.5	4.9	0.04	
	Forest	109.2			78.1
2001-2002 Nov. 15 – Mar. 12	1	128.8	7.3	0.12	
	2	93.2	--	0	
	3	134.4	0	0.07	
	Forest	128.8			0.49

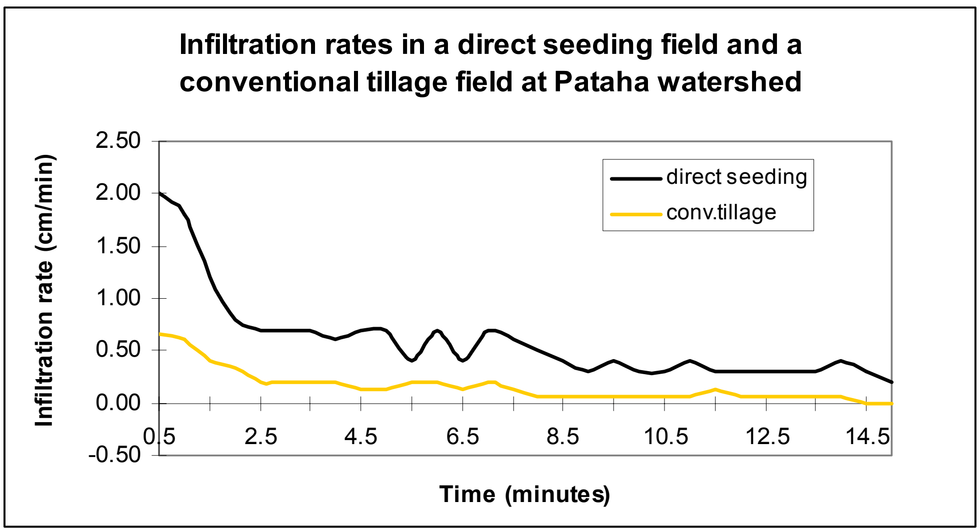

Figure 1. Infiltration Rates from Guelph Permeameter Study

Soil Freeze-Thaw and Water Content as Affecting Runoff and Ex-filtration Processes

In certain locations of the Pacific Northwest, processes of freeze and thaw affect the soil/water interactions and thus the hydrological process. These phenomena are directly related to the probability of large amounts of soil loss being linked even to moderate precipitation events. When the soil is frozen, the ensuing rainfall or snowmelt cannot infiltrate and flow as runoff, but even so the soil loss will remain reduced due to the compacted frozen ground and its reduced ability for detachment. However, when the top profile of the soil is thawed some water can infiltrate until the point where it hits the subjacent frozen layer. In this case, the infiltration capacity is promptly overcome and water can start flowing over the soil as well, but this time the thawed soil top profile is loose and oversaturated and can be easily detached. In addition, as the underground becomes saturated with water, ex-filtration can begin to occur and then increase the potential runoff. These processes are commonly found at the Pacific Northwest, usually generating rill erosion.

At Pataha watershed, there was not an observed match between a rainfall or snowmelt event and a highly susceptible soil condition to erosion. Whenever rainfall or snowmelt occurred, the soil was either not in a thawing process or water-saturated or the event was of really small intensity. Certainly, for the objectives of this research, this could represent an issue, especially for modeling purposes. However, it emphasized the importance that the critical processes of soil freezing and thawing have on the phenomena of soil erosion.

The contrast between conventional tillage fields and direct seeding fields indicates that direct seeding soils had less freezing events and more shallow freezing depths which is unquestionably due to the protective effect of residue on soil. This is important because it would imply less thawing processes, so less potential for soil erosion.

For comparison purposes, soil temperature and moisture sensors were also installed at a small watershed next to the Pullman-Moscow Regional Airport in Whitman County. Even though similar unfavorable erosion situations were observed at the Pullman-Moscow small watershed some trends could be seen regarding the ex-filtration process. In the conventionally tilled field, the soil profile had average volumetric soil moistures of about 0.35 m^3/m^3 and more than 0.4 m^3/m^3 at the surface when the ex-filtration process occurred and a rill was formed. This apparent threshold value of soil moisture may vary regarding the soil characteristics but in this case the soil characteristics between the two sites were nearly identical. The measured soil moisture content in the testing field at Pataha Watershed did not reach the value of 0.4 m^3/m^3, consequently, no ex-filtration process was observed at the site. High observed evaporation rates at Pataha watershed could be the reason for this result.

<u>Rill Formation Susceptibility under Direct Seeding and Tilled Cropping Systems</u>

Through this part of the study, the identification of the major variables involved in the formation of rills at different tillage systems, as well as the potential for each tillage system to form rills were addressed. This research was conducted at the USDA-ARS Palouse Conservation Farm, located in the proximity of Pullman (WA). In this farm four different tillage systems were studied: direct seeding (previous peas); conventional tillage (chisel plow, disk and harrow sequence); moldboard plow only; and chisel plow only, by establishing plots of 7.316 square meters. Water was applied over the plots as laminar flow at three different rates and three replications. Results revealed the high susceptibility of the conventional tillage system for rill formation and the excellent control against the formation of rills of direct seeding. Formation of rills in direct seeding only occurred at a small scale when huge amounts of flow (very unlikely in nature) were applied.

In the study; flow applied, antecedent soil moisture content, and slope generally induced rill generation. The effect of random roughness on rill formation varied among the different tillage treatments. Residue cover was inversely related to rill generation, and so was bulk density. The residue effect was very important when the coverage on the ground was more than 35%, such as can be found in direct seeding systems. Flow velocity was fairly reduced on these conditions, so the hydraulic shear stress was reduced. Therefore, the chance for soil erosion and formation of rills was strongly reduced. In general, higher flow velocities implied the generation of more and larger rills, resulting in an increased capacity for transporting sediment.

Transport of Sediments in Channel

In general, Pataha Creek sediment concentration was low, normally varying between less than 10 mg/L and 100 mg/L especially between May and November. In winter months, at the lower parts of the Creek (Marengo site) sediment concentration was less than 200 mg/L most of the time, but rose as high as 1,800 mg/L after a period of days of heavy rain. On the other hand, Upper Pataha (Columbia Center site) exhibited concentration values as high as 2,000 mg/Lto 10,000 mg/L in year 2002. During the period of January-April 2003, sediment concentration was low the majority of the time at the site with occasional higher concentrations. Some evidence of logging activities in the forests was found close to the Upper Pataha site in year 2002, which might have contributed to the high values of sediment in the channel flow for that season. The high concentration of sediment in Upper Pataha decreased with the Creek route, probably due to deposition due to the reduction in velocity of the flow. The increase in direct seeding acreage might have also affected the recharge of the Creek, making it more uniform by reducing surface runoff associated with precipitation events, and increasing subsurface flow related creek base flow, thus decreasing peak discharge rate and reducing the movement of sediments.

An event of rill sediment input to channel was observed only at the Pullman-Moscow Regional Airport Watershed during the winter of 2003. The sediment concentration in the channel followed the precipitation trend perfectly. This indicated that flow increased with precipitation and transported sediments previously deposited in the channel bed. At a certain stage, the ex-filtration process occurred and a rill formed. The rill sediment concentration was observed higher than that in the channel indicating that rill erosion could have great erosion potential. However, in this case, precipitation did not last and the ex-filtration process decreased, so the sediment in the channel was not noticeably affected.

Sediment Delivery Model Evaluation under No-till and Conventional Tillage Farming Conditions

RUSLE-SEDD Evaluation

The special characteristics of the winter season in the Inland Pacific Northwest and the implications it has on the soil condition makes current soil erosion and sediment delivery models unsuitable. For this reason, this project focused its efforts on developing new knowledge and relations that could allow for an improvement in the current models or to develop new process based on inputs adapted to the conditions of the study area. Certainly, this is an ambitious goal and its scope goes beyond the end of the current project, but it is fairly justified regarding the need for a confident physically based modeling tool for the IPNW.

Therefore, RUSLE was employed to estimate soil loss and SEDD was used to evaluate and compare sediment delivery in direct seeding and conventional tillage conditions. These models were integrated to ArcView GIS to estimate soil loss and associated sediment delivery on Pataha

Creek watershed. The results showed that the average cell soil loss was about 11.09 t/ha·yr in Pataha Creek Watershed at current land use pattern. The transport of eroded soil to river channel at the watershed scale was estimated as 4.71 t/ha·yr or about 42.4% of the total soil loss. Channel erosion was not included in this study.

The impacts of direct seeding practices on soil loss and sediment yield to river channel were studied by running RUSLE under a scenario of all of the agricultural land direct seeding practices. The average cell soil loss decreased from 11.09 t/ha·yr to 3.10 t/ha·yr for the whole watershed and from 17.67 t/ha·yr to 3.89 t/ha·yr for croplands under the no-till scenario. The average cell sediment yield to river channel decreased from 4.71 t/ha·yr to 1.49 t/ha·yr for the entire watershed and from 7.11 t/ha·yr to 1.55 t/ha·yr for cropland under the direct seeding scenario. The contribution of cropland decreased from 92.4% to 72.8% for soil loss and from 87.4% to 60.1% for sediment yield to the river channel if all of the cropland in the Pataha Creek were in no-till. Clearly, it can be concluded that direct seeding is important in reducing the production and delivery of sediments, particularly within watersheds like Pataha Creek Watershed that are comprised of about 58% agricultural land. Thus, the adoption of direct seeding as an observed cropping practice would benefit most of the watershed.

The integration of RUSLE and SEDD with GIS systems provides an interesting and useful tool for predicting soil loss and delivery of sediments under different scenarios. Therefore, this tool can be beneficial towards improving land management and planning.

<u>SHAW Model Evaluation</u>

Up to date, there is no available process-based soil erosion and delivery model totally adapted to the soil characteristics and processes found at the IPNW. Certainly, a winter routine is highly required. The SHAW (Simultaneous Heat and Water) model developed at the end of the 1980's, includes many relations already developed and tested that might be used to develop a new winter routine for process-based soil erosion models. In the scope of this project, SHAW model was tested for the conditions found at the Pataha Creek Watershed.

The first drawback in running SHAW was the point-nature of the model; that is, SHAW was not developed for a watershed level and are only suitable at a point level. Therefore, for soil erosion implications the model might not be appropriate, especially if rill formation is considered, which can start at point level, but then is projected to a continuous area. Soil temperature and moisture sensors employed in this research were point level values, so SHAW could be fully compared to the real values. SHAW runs were conducted for conventional tillage areas at four depths of the soil profile for temperature and moisture content, as well as for direct seeding areas at the same depths. The soil surface and 10 cm depth results are presented in this report.

SHAW performs well for soil temperature in conventional tillage, but in general tends to over predict the moisture content. On the other hand, the model performs well for both soil temperature and moisture content in the direct seeding case. Certainly, SHAW is mainly a heat model and is better built to predict temperature movement in the soil which is reflected in our results. The soil moisture routine SHAW uses, especially the infiltration module based on the Green-Ampt model did not reflect the lower infiltration capacity that occurred in conventional tillage and most of the time over predicted the soil moisture values. This did not happen in the direct seeding prediction, where infiltration was higher because of the better conditions of soil structure inherent to direct seeding, and also the reduced amount of days with frozen layers. Under these conditions SHAW performed better.

Developing a Model for Predicting Sediment Delivery of the Entire Watershed

A new sediment transport model was developed. The model is applicable for determining the sediment delivery from a channel and suitable for use in the laboratory. It is assumed that actual erosion from the land is also being delivered to the channel. This methodology includes two basic features: 1) estimating flow discharge, flow velocity, and flow depth by using a new Muskingum method coming from the complete Saint-Venant equations (Wang and Chen, 2003); and 2) estimating sediment discharge and elevation of a deformable bed using the Karim methodology.

The method is based on three basic equations for unsteady flow in a wide rectangular channel with a deformable bed:

- Flow continuity: $\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=0$ (1)
- Flow momentum: $\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}(\frac{q^2}{h}+\frac{1}{2}gh^2)+gh\frac{\partial z}{\partial x}+ghS_f=0$ (2)
- Sediment continuity: $\frac{\partial}{\partial t}[(1-p)z+\frac{q_s h}{q}]+\frac{\partial q_s}{\partial x}=0$ (3)

where h is the flow depth; t is time; q is the flow discharge per unit width; x is the distance step; g is the acceleration of gravity; z is the channel bed elevation; S_f is friction slope; p is the porosity of the bed; and q_s is the sediment discharge. The complete St. Venant equations and sediment continuity equation are worked uncoupled when being solved. By using the Froude number, the complete St. Venant equations are converted into a nonlinear convective diffusion equation, which was discretized in space using a mixing cell method. The nonlinear convective diffusion equation reduces to a nonlinear ordinary differential equation where the optimal space interval will be the same as the characteristic reach length. A four-point finite difference method was used to solve the ordinary differential equation with Δx being equal to characteristic reach length to obtain flow discharge, flow velocity, and flow depth. The term, q_s, total sediment discharge, is estimated from the model Karim proposed in 1998:

$$\frac{q_s}{\sqrt{(SG-1)gd_{50}^3}}=0.00139[\frac{V}{\sqrt{(SG-1)gd_{50}}}]^{2.97}(\frac{u_*}{w_f})^{1.47} \qquad (4)$$

where

$$u_*=\sqrt{gh_0S} \qquad (5)$$

$$w_f=\frac{8\nu}{d_{50}}[(1+0.0139d_*^3)^{0.5}-1] \qquad (6)$$

$$d_* = d_{50}[(SG-1)g/\nu^2]^{1/3} \qquad (7)$$

where SG is the specific gravity of sediment; d_{50} is the mean diameter of the particles; u_* is the dimensionless shear velocity; w_f is the sediment settling velocity; S is the slope; and ν is the kinematic viscosity of the water.

A four-point finite difference method was also used to discretize the sediment continuity equation with the same space interval Δx and time step Δt. The channel bottom elevation z was calculated and channel bottom slope was estimated. If the difference between estimated slope and original slope is larger than the specified tolerance, the estimated slope will be used to calculate flow discharge, flow velocity, flow depth, total sediment discharge, channel bottom elevation, and channel bottom slope until the difference is less than the specified tolerance.

Introducing the Froude number in the flow momentum equation, re-writing the flow continuity equation, and combining them obtains a parabolic type nonlinear diffusion equation in the form:

$$\frac{\partial Q}{\partial t} = \frac{(1-\frac{F_r^2}{4})C^2Bh^3}{2Q}\frac{\partial^2 Q}{\partial x^2} - \frac{3Q}{2Bh}\frac{\partial Q}{\partial x} - \frac{1}{(1-\frac{F_r^2}{4})}\frac{\partial}{\partial t}(\frac{\partial z}{\partial x}) \qquad (8)$$

with Q as the flow discharge; Fr the Froude number; B the channel width; and C is a coefficient. The use of mixing cell to solve the last equation and a backward application of the Taylor series expansion, plus the simplification of some terms leads to:

$$\Delta x = \frac{(1-\frac{F_r^2}{4})C^2B^2h^4}{3Q^2} \qquad (9)$$

$$\frac{\partial Q}{\partial t} = -\frac{3Q}{2Bh}\frac{Q_i - Q_{i-1}}{\Delta x} - \frac{1}{(1-\frac{F_r^2}{4})}\frac{\partial}{\partial t}(\frac{\partial z}{\partial x}) \qquad (10)$$

For uncoupled models, the last term of equation (10) is assumed to be zero. Introducing the relation between h and Q:

$$h = (\frac{Q}{C\sqrt{s}B})^{\frac{2}{3}} \qquad (11)$$

and using it with equation (10) yields:

$$\frac{\partial Q}{\partial t} - \frac{3Q_i^{1/3}C^{2/3}s^{1/3}}{2B^{1/3}}\frac{Q_i - Q_{i-1}}{\Delta x} \qquad (12),$$

Remembering that the distance step Δx is calculated through:

$$\Delta x = \frac{2(1 - F_r^2 / 4)h}{3S} \qquad (13)$$

A four-point finite difference method can be used to solve Equation (12) in the plane x/t. The method used iterative values for Qi, h and Δx.

Numerical simulation indicated that the new approach for estimating sediment transport in a deformable bed is reasonable and acceptable for practical use. The new approach procedure is very easy and convenient for practical use. However, more data is required to continue testing the model for different conditions.

CONCLUSIONS

Despite the fact that the mild winters did not generate appreciable erosive processes in the Pataha Creek Watershed, the different experiments and measurements developed in the scope of this project gave enough support for the following conclusions.

1. No-till is a farming practice that protects soil from being eroded and as such diminishes the suspended sediments in the main channels. Therefore, no-till brings great environmental benefits and thus is a suitable tool for improving fish habitat.

2. No-till decreased erosion susceptibility by:

    - Having higher soil infiltration capacity and hydraulic conductivity, resulting in less runoff.
    - Maintaining higher soil temperatures in winter so that the frost depth is shallower.
    - Avoiding rill formation as water concentration is reduced because the residue helps to slow down and spread the water flow.

3. The ex-filtration process seemed to be significant in terms of runoff generation and soil erosion. Modeling tools with respect to this phenomenon is required.

4. Integration of GIS to RUSLE and SEDD can be a useful tool for watershed planning. The modeling results clearly demonstrated the importance of no-till for reducing erosion and delivery of sediments to the creek channels.

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Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the Yakima River Basin

Basic Information

Title:	Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the Yakima River Basin
Project Number:	2000WA4G
Start Date:	9/1/2000
End Date:	8/31/2003
Funding Source:	104G
Congressional District:	Washington Fourth
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Sediments, Irrigation
Descriptors:	Grass lining, check dams, surface drains, tailwater, surge irrigation, PAM, polyacrylamide, Yakima River, salmon recovery, surface irrigation, nutrient loading, sediment loading, erosion, non-point pollution
Principal Investigators:	Brian G. Leib, Robert Stevens, Ariel Szogi

Publication

1. Leib, Brian G., Robert G. Stevens, and Cristoti A. Redulla, 2002, Integration of surface irrigation techniques to reduce sediment loading in the Yakima River Basin of Washington, USA, "in" Proceedings of the International Workshop on Conservation Agriculture for Wheat and Cotton Production in Limited Water Resource Areas, Tashkent, Uzbekistan, October 13 18, 2002. Paper available at http://siip.prosser.wsu.edu/uzbek_2002.pdf
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Problem and Research Objectives

Surface (rill) irrigation has been identified as one of the main sources of excess sediment in the Yakima River Basin. In turn, it is this source of water quality degradation that is thought to be one of the causes for declining salmon runs in the Yakima River. The Washington Department of Ecology has set a sediment limit for irrigation return flows of 25 NTUs (56 mg/l). Some irrigators are converting their rill irrigation systems to either sprinklers or drip irrigation at a cost of $300 to $1000 per acre. In some cases, this large capital investment in improved irrigation systems is being offset by cost share and low interest loan programs. However, there is not enough cost share money to match the rill acreage and many irrigators cannot afford to convert their irrigation systems even if cost share were available to everyone. Therefore, many rill irrigators are attempting to improve their existing systems in order to keep their operations as profitable as possible. Many rill irrigators are applying Polyacrylamide (PAM) and successfully decreasing sediment loads from furrows by 80 to 90 percent. Unfortunately, this cleaner water often erodes sediment from the tailwater ditch causing elevated NTU levels still too high to be returned to irrigation district canals and drainage ditches. The focus of this research is on inexpensive methods to further reduce sediment and nutrient loads from rill irrigation. Sediment loads are being evaluated for PAM ($20/ac per year) used with Surge irrigation ($125/ac), tailwater drains ($75/ac), tailwater checks ($25/ac), and grass-lined tail ditches ($25/ac).

Methodology

The five treatments are: Treatment 1) PAM alone as the control, Treatment 2) PAM and Surge irrigation, Treatment 3) PAM and closely spaced surface drains in the tailwater ditch, Treatment 4) PAM with a grass-lined tailwater ditch, and Treatment 5) PAM and tailwater checks. The treatments were installed at two locations during the 2001 and 2002 growing season. Data was collected during 5 irrigation events in 2001 and 11 irrigation events in 2002. The treatments were randomized at each site and the treatments were large enough to allow 24 to16 furrows to flow into the tailwater ditch depending upon the site.

Each treatment was monitored for inflow, outflow, soil moisture, sediment load, nutrient concentration. Inflows were estimated by measuring the time needed to full a bucket of a known volume. Outflow from each treatment was measured by a flow meter that received water from a collection sump and sump pump. Soil moisture was monitored with the neutron probe and access tubes. Average advance time was also recorded. Sediment samples were collected at periodic intervals during irrigation runoff events. These samples were analyzed with an NTU meter and gravimetrically with filter paper.

Composite samples were also collected from irrigation runoff events for nutrient analysis. Samples were taken as water fell into the tailwater sumps. Samples were kept at 4 ^{o}C until chemical analyses. All water quality analyses were performed using EPA methods (U.S. EPA, 1983). Soluble compounds were determined in samples filtered with a 0.45µm pore-size membrane and analyzed for ammonium-nitrogen, nitrate-nitrogen, and soluble reactive phosphorus. Unfiltered samples were analyzed for total Kjeldahl nitrogen, and total phosphorus.

After outflow was measured, the tailwater effluent was delivered to a sediment trapping boxes consisting of slotted apple crates lined with filter fabric to retain sediment. The number of boxes was dependant on the expected tailwater flow. The depth of sediment added to the boxes was measured at the end of the irrigation season.

PAM was applied to all the furrows just below the point of water delivery and at the time when the furrow soil had been disturbed by field operations. Similarly, all other cultural practices such as weed control and fertilization was held constant between treatments according to standard production practices.

Principal Findings and Significance

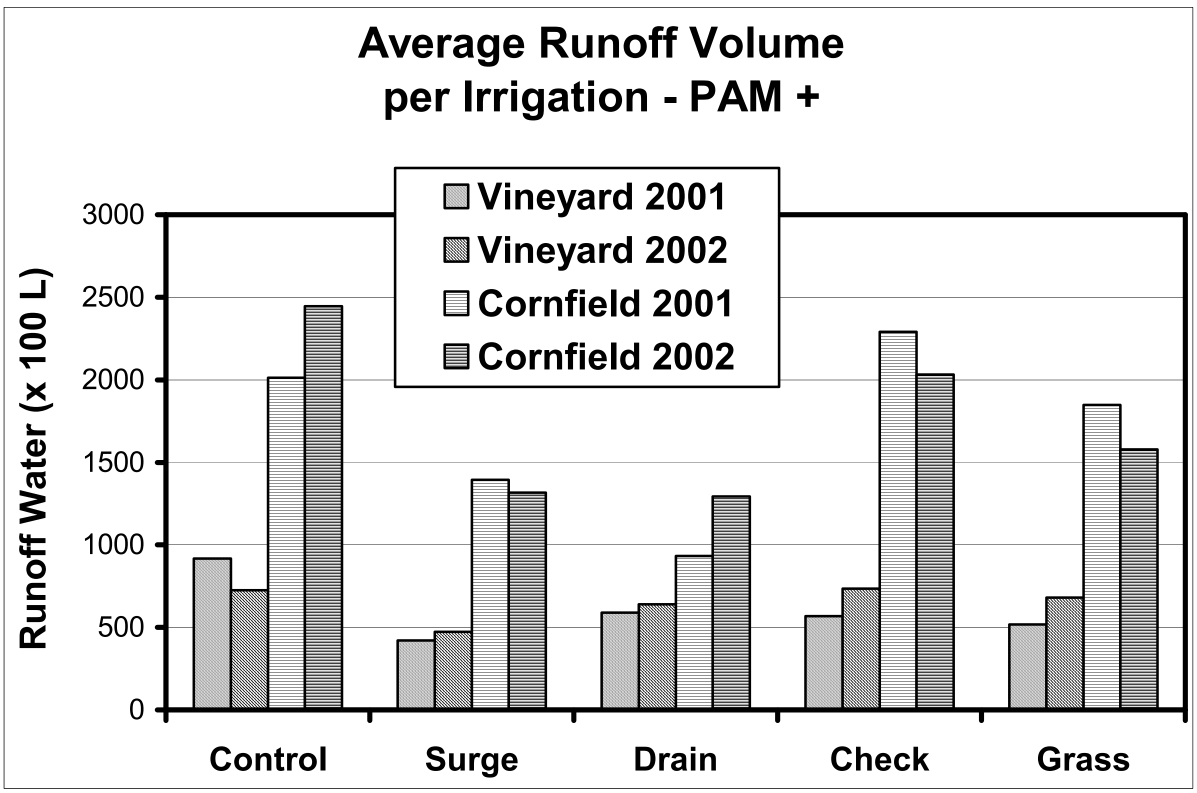
Polyacrylamide was applied by patch method at two vineyards with slope of 1.3% and a cornfield with slope of 0.2%. The soil at the vineyards was a Shano silt loam while that at the cornfield was prevalently an Esquatzel fine sandy loam. Results (see Figures below) from the control plots revealed that the patch method of PAM application alone was not sufficient to reduce the sediment load in the runoff to meet the proposed standard (< 56 $mg \cdot L^{-1}$).

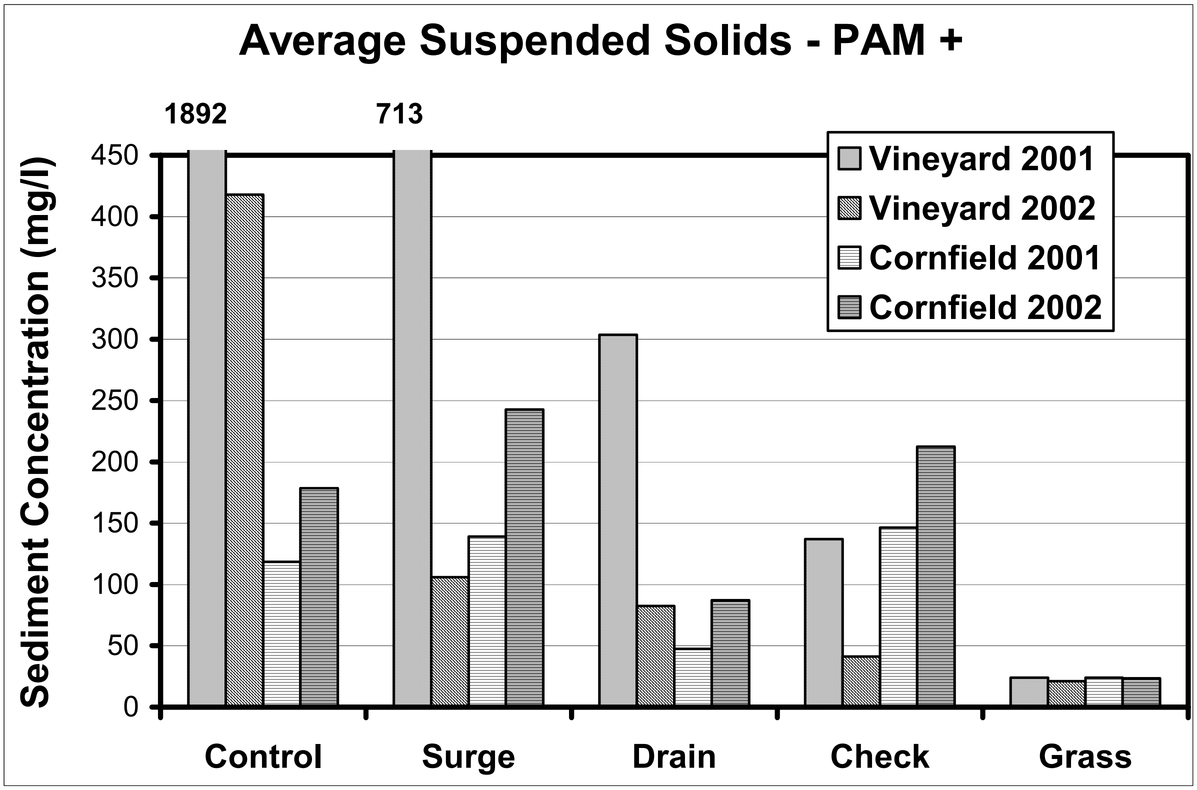
Combining PAM with other erosion control practices was more effective in further reducing sediment transport at the vineyards than at the cornfield. There were many possible reasons for this result, but field slope appeared to be an important factor that caused different responses between the vineyard and the cornfield. The 1.3% slope in the vineyard created sub critical flow conditions (shallow and rippled, more total energy in the water velocity) that produced furrow erosion at the lower end of the field, clear runoff water (due to PAM), and bed load movement of sediment down the tailwater ditch when no additional erosion control practices were applied. In contrast, the 0.2% slope in the cornfield created supercritical flow conditions (deep and smooth, more of the total energy in the depth of water) that resulted in little furrow erosion at the lower end of the field, murky runoff water and transport of fine suspended particles. Of course the difference in soil, crop, and cultural practices are also factors.

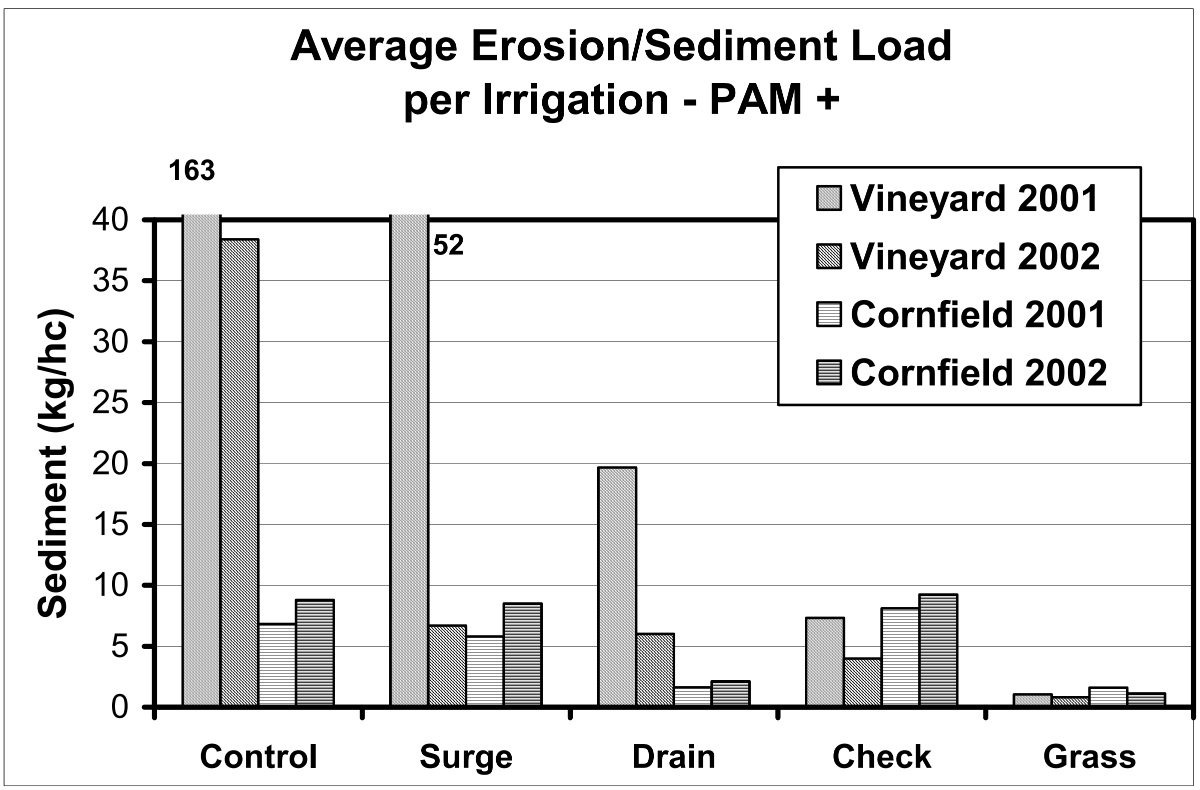
The grass-lined tailwater ditch in combination with PAM provided the greatest reduction in sediment load for all sites tested and the sediment concentration was consistently below 56 mg L^{-1}. At the vineyards, sediment loads from the check, surge, and drain treatments were similar (not statistically different) but they produced higher sediment loads than the grass treatment and lower sediment loads than the control treatment. In the cornfield, sediment concentration from the control, check, surge, and drain treatments were similar to each other (not statistically different).

The grass treatment reduced end of furrow erosion, impeded bed load transport of sediment, and limited soil/water contact making it effective in both the vineyards and the cornfield. The check dams reduced end of furrow erosion and impeded bed load transport of sediment making it effective in the vineyards but the increase in soil/water contact may have reduced the effectiveness in the cornfield. Surge and Drains treatments did not reduce end of furrow erosion in the vineyard but did decrease bedload transport of sediment due to reduced flow in the tailwater ditch. The reduce flow of these treatment did create slightly lower water levels in the tailwater ditch of the cornfield but the reduced soil/water contact did not reduce concentration of sediment suspended in the runoff water. In fact, the pulsing of water with surge seemed to stir up more sediment than the continuous furrow flow in the other treatments.

The best recommendation at this time is to use PAM in conjunction with grass lined tailwater ditches because it was the only treatment to maintain the water quality standards being implemented in the Yakima River basin of Washington, USA under the varied conditions of the vineyards and the cornfield. Of course the possible combinations of soils, slopes, weather, crops, and cultural practices would require many similar experiments in other locations to make this recommendation more universal. Perhaps modeling these erosion and sediment transport processes would be a means of extrapolating the result to more areas with less direct experimentation. It should also be noted that there are more possible combinations of best management practices than have been tested in this research. For example surge irrigation, PAM application, and a grass lined tailwater ditch was not tested. There are also other potential best management that could be combined with the practices tested by this research such as, straw mulched furrows and no-till/reduced tillage cultural practices in furrow irrigation.




Average Suspended Solids - PAM +
1892
713
Sediment Concentration (mg/l)
450
400
350
300
250
200
150
100
50
0
Vineyard 2001
Vineyard 2002
Cornfield 2001
Cornfield 2002
Control
Surge
Drain
Check
Grass


Average Erosion/Sediment Load
per Irrigation - PAM +
163
52
Sediment (kg/hc)
40
35
30
25
20
15
10
5
0
Vineyard 2001
Vineyard 2002
Cornfield 2001
Cornfield 2002
Control
Surge
Drain
Check
Grass

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:	7/31/2004
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 (Abstract), "in" Abstracts with Programs, Geological Society of America Rocky Mountain/Cordilleran Section Meeting, Boise, Idaho, May 3-5, 2004, 36(4):31.

Problem and Research Objectives

The overall objectives of this collaborative study are to investigate the specific hydraulic conditions that control the evolution of cluster bedforms in both laboratory and field settings and to investigate the corresponding effects of the clusters on near-bed turbulence and channel stability. A cluster microform is a grouping of sediment particles, usually around a larger anchor sediment particle, against which a stoss of imbricate clasts develops and behind which a wake tail grows. Cluster bedforms may play a signficant role in delaying gravel transport through a stream and have been shown to provide important habitat for fish and stream invertebrates. Understanding the hydraulic conditions under which these bedforms develop and disintegrate is critical for managing, restoring and maintaining aquatic stream habitats in disturbed, natural and flow-regulated streams.

<u>Lab Objectives</u>

The overarching goal of the lab component is to advance current knowledge on cluster formation and evolution by tackling some of the aspects associated with cluster micro-topography. The specific objectives of the laboratory study are:

1. To identify the bed shear stress range in which clusters form from a non-clustered bed and subsequently the stress values at which clusters disintegrate;
2. To quantitatively describe the spacing characteristics and orientation of clusters with respect to flow characteristics;
3. To quantify the effects clusters have on the mean bedload rate in unsteady flow conditions;
4. To assess the effects of clusters on the pulsating nature of bedload.

<u>Field Objectives</u>

A field component has been added to the ongoing laboratory studies to compare the results from the laboratory flume with processes in natural streams. The main objectives for the field component of the project are:

1. To characterize the cluster bedform morphologies in natural streams and compare with the morphologies produced in the laboratory for uniform and non-uniform grain sizes.
2. To identify the field geomorphic settings conducive to creating and maintaining cluster bedforms similar to those formed in the laboratory.
3. To characterize the hydraulic parameters, such as velocity, shear stress and near-bed turbulence, necessary to form, maintain and disaggregate sediment clusters.
4. To determine the fate of individual sediment particles within and outside clusters during bed-mobilizing events.

Methodology

<u>Lab Methodology</u>

This research addresses two aspects associated with cluster development and evolution, namely, cluster microform geometric characteristics and the effects of clusters on bed stability and the statistical properties of the instantaneous bedload rate. These aspects were investigated in a laboratory flume with the use of uniform-size spherical glass particles to eliminate effects due to particle protrusion, size, shape, specific gravity and sediment gradation on cluster development.

Knowledge in cluster microtopography was further advanced by investigating two main experimental scenaria, referred to as test series A and B. All runs in test series A were initiated from a non-clustered bed since the objective of this scenario was to determine the flow conditions under which clusters form and record their spacing and orientation once a developed cluster bed is formed. Test series B, on the other hand, simulate conditions where clusters preexisted in the surface layer due to their establishment from a precursor event. A subset of a test series B, referred to as test series B-NC, was performed without the presence of clusters, to discriminate the effects of flow on bedload characteristics.

Several established experimental techniques (such as video camera, photoshop software) were employed to measure the instantaneous bedload rate, map the geometric characteristics of clusters and provide localized information about the interaction of clusters and the transported material. In addition, statistical tools (such as MINITAB) were used to develop autoregressive (ARIMA) models for predicting the instantaneous bedload rate for both test series A and B. The ARIMA models provide unique information about the mean statistical properties of bedload and allow a quantitative comparison between test series B and B-NC. The ARIMA analysis was complemented with a change-point analysis to identify the effects of clusters on bedload transport.

Field Methodology

The procedures to set up the first cluster monitoring site in Year 1 involved 1) identifying and marking the clusters, 2) describing and photographing each cluster, 3) surveying cluster locations, 4) surveying channel cross sections, 5) installing stage monitoring instrument, 6) measuring flow velocity at known stage. After each flow event that is large enough to entrain and transport gravel on the bed (i.e. spring snow melt), the change in the channel bed will be re-photographed and documented. Anticipated results include (1) comparison of the form and spacing of sediment clusters in the field and lab, (2) calculation of the bed shear stress values necessary to form, maintain and break apart the cluster bedforms in the field and lab, and (3) further understanding of the role of geomorphic channel form in the formation of sediment clusters.

A total of 77 clusters were identified and marked at Site 1 on the gravel bar and adjacent shallow stream bed in an area measuring approximately 20 meters x 5 meters. All of the clusters involved 3 or more particles. At some point all clasts are interacting to some degree with the adjacent sediment particles, only the clusters with obvious anchor particle(s) protruding above the average channel bed were marked. Each cluster number was written on the anchor clast in a subtle location on the downstream side with permanent marker.

Two photographs were taken of each cluster using digital camera. A ruler scale and number of the cluster written on masking tape was included in each photo (not always possible for submerged clusters). All photos were taken with the bottom of the photo toward the bank and the top oriented toward the stream.

-Photo 1: Widest angle setting on camera from a consistent height (same scale for all clusters).

-Photo 2: Zoom in on cluster to fill field of view (scale varied for different clusters).

For each cluster, the following characteristics were recorded to supplement the photographs:

a. Cluster number
b. Length of cluster
c. Width of cluster
d. Shape of cluster: triangle (with either upstream or downstream tail), diamond, ring, line, or rectangle.
e. Orientation of cluster relative to flow direction
f. Measurement of long, intermediate and short axis of anchor clast(s)
g. Orientation of anchor clast relative to flow direction
h. Number of particles in cluster
i. Approximate d50 of non-anchor clasts in cluster
j. Additional comments

The center point of each cluster was surveyed using a total-station laser theodolite in preparation for creating a detailed map of cluster location and spacing. The survey instrument station location was chosen at a point that had a clear view of the entire cluster site and channel cross sections and is not likely to be inundated or eroded away during high flows. The surveying station was monumented with a permanent stake in the ground, and several additional survey benchmarks were surveyed and monumented. The exact survey grid can be reoccupied and cluster locations resurveyed to monitor any changes in cluster locations.

Three channel cross-sections were surveyed at the upstream, downstream and middle of the gravel bar under study. The end points of each cross-section were monumented with stakes. The surveyed cross-sections will be used in flow modeling to determine discharge at the site.

A stage monitoring instrument and data recorder made by Global Water Instruments were installed to record the peak stage. The stage monitor was installed on the right bank of cross section 2, across the river from Cluster Site 1. This bank is vertical, which allows the monitor casing to be anchored to the bank. The pressure transducer was positioned below the water level, and the cable leading to the data logger was fed through electrical conduit pipe with 2 elbows that curved up and over the top of the bank. The pipe was anchored to fence posts that were pounded into the side and top of the bank. Velocity and stage at the time of the installation were recorded. Because the stage recorder is located right on a surveyed channel cross section, the stage can be directly related to water depth over the cluster site. The instrument will automatically record the stage every 30 minutes for up to several months. This instrument will be retrieved after the peak flow has occurred in mid- to late June, to avoid vandalism during the high-use summer season. The instrument will be reinstalled in late fall and left in place over the winter.

Principal Findings and Significance

<u>Lab Studies</u>

A major contribution of the WSU research team is a detailed documentation of the evolutionary cycle of clusters, i.e. formation through disintegration, during the rising limb of a hydrograph and identification of the bed shear stress condition that partial or complete break-up of individual clusters commences. This condition is defined as the threshold or critical condition for partial or complete cluster disintegration.

Figure 1 provides a unique depiction of the instantaneous bedload rate q_b time series. The bedload rate time series, expressed in kg/m/s, is shown with the solid pulsating line enriched with square symbols. The thick solid line, showing in Figure1 in the form of a stepwise function, indicates the feed rate of sediment at different stress increments.

Figure 1 also offers a descriptive overview of the cumulative effects that clusters and flow may have on the pulsating nature of bedload. It is observed that at stresses less than $2.25\,\tau^*_{cr}$ the disbandment of a whole cluster is rare, rather particles were removed from individual cluster as they went through their evolutionary cycle with respect to shape and size. At stresses equal to or greater than $2.25\,\tau^*_{cr}$, partial or complete disintegration of individual clusters occurs causing significant spikes in bedload transport. These spikes are identified in Figure 1 as the black circles capping the significant peaks in the time series and the stress condition of $2.25\,\tau^*_{cr}$ is considered here as the critical stress condition for cluster stability. For stress conditions ranging between $2.5\,\tau^*_{er}$ and $3.0\,\tau^*_{er}$ complete cluster breakup occurs throughout each of the stress increments resulting in elimination of organized cluster topography. The elimination of organized topography commences at $2.5\,\tau^*_{cr}$, however, some individual clusters persist until $3.0\,\tau^{*\sim}_{cr}$

Based on the above observations one can suggest that the instantaneous bedload transport of glass spheres through a clustered area can be classified into three phases, namely phase I, phase II, and phase III (Figure 1). Phase I corresponds to a stress range varying between $1.5\,\tau^*_{cr}$ and $1.75\,\tau^*_{cr}$ (8.5-70.5min); the peaks in bedload rate within phase I are smaller comparatively to the peaks appearing in phases II and III. Phase II corresponds to a stress increment of $2.0\,\tau^*_{or}$ to $2.25\,\tau^*_{cr}$ (71-125.5min) and constitutes the transition or buffer region between phase I and III; in phase II, the commencement of complete or partial disintegration of individual clusters occurs. Finally, phase III occurs for a bed shear stress greater or equal to $2.5\,\tau^*_{cr}$ (126-162.5min). In phase III, complete cluster disintegration transpires and causes significant fluctuations in the bedload transport rate.

Field Studies

Site Selection

One site was selected for field study, on the American River. Field reconnaissance was conducted on several tributaries in the Yakima River drainage basin on the East slopes of the Cascade Mountains in Fall, 2002 and early Spring, 2003. The goal of the reconnaissance was to identify gravel-bed streams draining the Cascade Mountains that best matched the criteria for site selection, including evidence of gravel clusters, lithology, grain size, gradient, discharge, accessibility for monitoring. Using maps and aerial photos, four rivers in the Yakima watershed were chosen for detailed field reconnaissance: the American River, Little Naches River, Taneum Creek and Teanaway River. Cluster bedforms were found on the American River and Teanaway River. All of these rivers are unregulated and therefore have a greater chance of bed-mobilizing high-flow events. The American River was deemed the most promising location to set up the first field monitoring site for this project based on the following attributes:

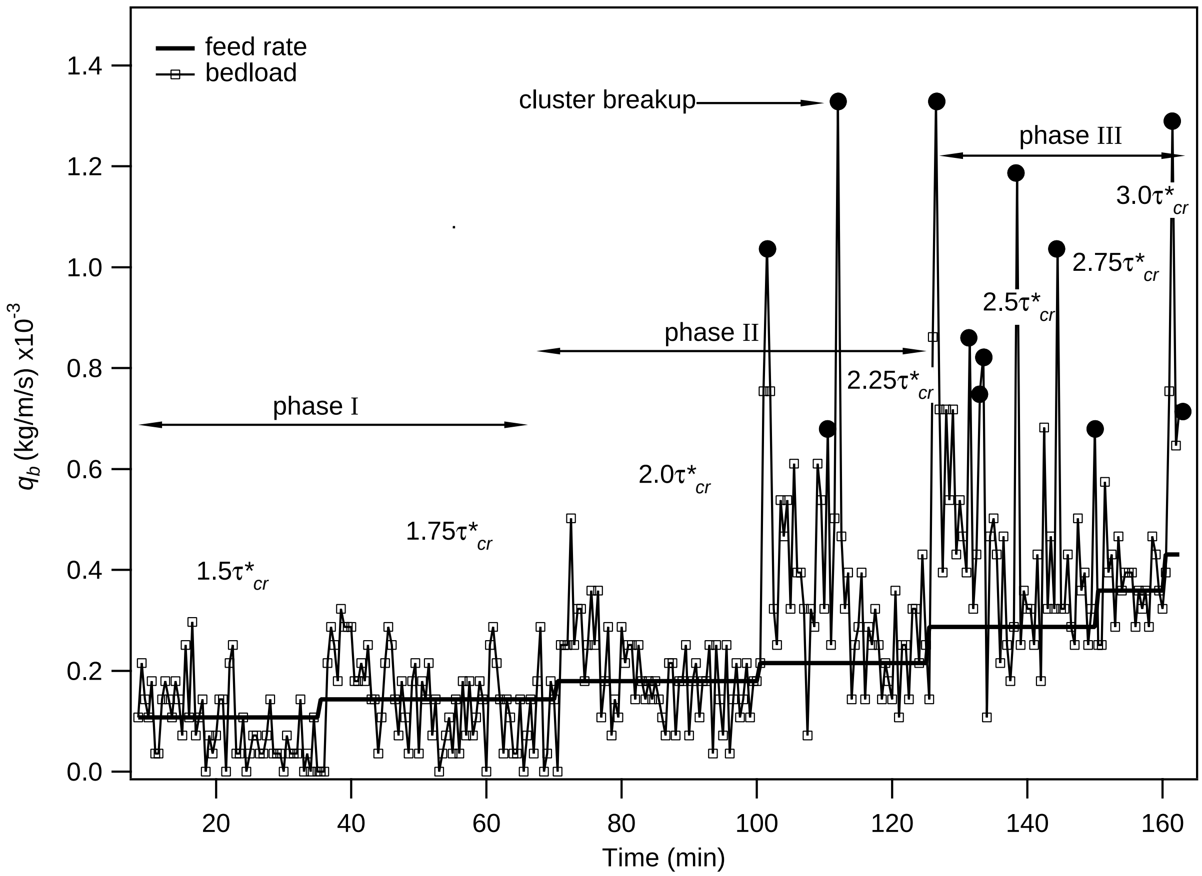


Figure 1. Bedload time series for cluster response to inflow hydrograph (test series B). In phase I ($1.25\tau^*_{cr}$ to $1.75\tau^*_{cr}$), clusters act as a sink to incoming particles so that the mean transport rate is lower than the mean feed rate. In phase II ($2.0\tau^*_{cr}$ to $2.25\tau^*_{cr}$), the buffer region, clusters do not affect the mean transport rate so that the bedload rate is equal to the feed rate. Phase III ($\geq 2.5\tau^*_{cr}$), depicts the region of bed shear stress where clusters act as sediment sources and not only add to the pulsating nature of bedload but also increase the mean transport rate so that it is greater than the feed rate.

- A well-developed suite of gravel clusters
- Watershed is relatively undisturbed by human activities such as logging, roads or mining.
- It is one of only 3 real-time USGS gaging stations (American River near Nile, Washington) with online access in the upper Yakima basin. Although the gaging station is several miles downstream from the cluster study site, it allows for remote monitoring of the hydrograph for timing and relative size of peak discharges.
- The study site near Pleasant Valley campground is also included in a recent study of geomorphic and hyporheic characteristics of salmon spawning habitat, conducted by Brooke Asbury, a graduate student at Central Washington University. The proximity of the two studies will broaden the potential applications of the current study by allowing a comparison or even an extension of the study on salmon habitat.
- Most reaches of the river are readily accessible in late spring through fall and are on U.S. Forest Service land.

Site Description

Cluster Site 1 on the American River is a gravel bar and adjacent channel bottom on the left bank of the river immediately downstream of the Pleasant Valley Campground at 46˚ 56' 45" N. Lat., 121˚ 19' 10" W. Long. The site is ~15 km upstream of the USGS gaging station on the American River at the junction with the Bumping River (USGS Amer. R. nr Nile, WA). The river at Site 1 is ~15 meters wide, highly sinuous, with a moderate gradient. The valley floor at this site is ~1.75 km wide. About 5 km downstream, the river enters the narrow, steep canyon that characterizes the lower reach of the American River. The gravel bar is on the downstream inside bank of a bend in the channel. The bar is partly to totally submerged during annual peak flows and is exposed during lower flows. The gravel bar contains numerous gravel clusters of 3 or more clasts, which become more sparsely scattered in the main flow channel.

Summary of Field Studies

As mentioned above, 77 clusters were identified and described at American River Site 1. The cluster morphologies fell into 6 forms: triangle (with either upstream or downstream tail), diamond, ring, line, or rectangle (Table 1). Two clusters were not described.

TABLE 1. Cluster morphologies at American River Site 1.

Triangle up	Triangle dn	Diamond	Ring	Line	Rectangle	Total
22	3	7	4	31	8	75

The line shape, consisting of an anchor clast with 2 or more imbricated clasts directly upstream or downstream of it, was the most common. The triangle shape consists of an anchor clast with the long axis transverse to the flow and an accumulation of smaller clasts either upstream or downstream. The triangle shape with an upstream tail of imbricated particles was the second most common. The other shapes all occurred at a much lower abundance. The diamond shape consists of one or more anchor clasts transverse to the flow with an accumulation of smaller clasts both upstream and downstream. The ring and rectangle shapes consist of multiple clasts that form either a ring or rectangle shape and collectively serve as an anchor against which smaller clasts accumulate.

The spacing of the clusters appeared to be more dense on the gravel bar than in the adjacent low-flow channel, but that relation has not yet been quantified at this site. Further field studies this summer at lower flows when a greater portion of the channel bed is exposed will seek to verify this initial observation. This pattern is supported by observations on other rivers, in which clusters are more common on gravel bars where the sediment is subject to fewer flows that are able to mobilize bed material, rather than in the thalweg channel where the sediment is better sorted (Ian Reid, written communication 2003; Hassan, & Reid, 1990).

References

Hassan, M.A. & Reid, I., 1990, The influence of microform bed roughness elements on flow and sediment transport in gravel bed rivers. Earth Surface Processes & Landforms 15, 739-750.

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:	1/1/1997
End Date:	1/1/1997
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

Problem and Research Objectives

Agricultural application of artificially fixed N to crops has perturbed the global N cycle to an unprecedented degree since the second World War. Among the most serious consequences of this perturbation 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. In this context Congress has mandated the EPA to implement the TMDL (Total Maximum Daily Load) program and it is estimated that around 40,000 TMDLs will be required nationwide. Given the magnitude of this undertaking, it is clearly important to develop sound scientific basis for TMDL determination. This in turn means understanding 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 (a) expanding our ongoing study of field-scale processes to include undrained settings, and (b) 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. We are taking this approach to address the following research objectives:

a. ***Observe geochemical and isotopic composition of surface and subsurface water at the field scale.***
b. ***Develop isotope hydrograph separation (IHS) models for a succession of catchment-to-basin watershed scales.***
c. ***Compare IHS with geochemical hydrograph separation (GHS) models to identify processes and pathways of water and NO_3 delivery to streams.***
d. ***Examine scaling trends of IHS and GHS models.***

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 ammonia 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. At the undrained field, selected parallel instrumentation will be installed in fall 2003. Subsequently, we plan to collect multiple 1.5-m deep core samples in each of the fields, for detailed determination of ^{18}O and NO_3 depth distributions and their spatial variation, at least twice (to assess seasonal variation).

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

Water year 2002-2003 was devoted to maintenance and refinement of surface-water flow logging and monitoring, and to development of sampling and analysis techniques, particularly for our new tracer ^{18}O. In water year 2003-2004 we continued sampling and gauging these surface-water flow stations. During this period we have also:

--expanded our routine sampling to include nests of replicated pore-water samplers at both drained and undrained locations (with aliquots collected and analyzed for ^{18}O)

--acquired (on loan from the USGS) and pilot-tested automated precipitation and stream-water samplers for study of field-scale hydrologic events during the coming water year

--established methods for routine calculation of N discharge at various watershed (including field) scales, and begun to study temporal patterns mass-discharge and their scaling

--begun (qualitatively only) to compare ^{18}O and nitrate temporal patterns in field discharge.

Figure 1 shows nitrate mass discharge from the tile drain at the drained location called “Area A”. The figure also shows the water discharge and nitrate concentration data on which the mass discharge values are based. The temporal concentrations patterns are grossly similar to those observed by USGS colleagues at Hooper, 80 km downstream, but the peak magnitudes are several times larger. Most of the variance in the mass discharge is due to water discharge; our calculations indicate factor-of-five variation in the cumulative mass discharges among the three full water years shown. We plan to do parallel analyses on patchier surface-discharge data from the undrained location.

Figure 2 shows an example of soil-water (lysimeter) ^{18}O data. The “U” shapes of the trends for each water year also appear in the datasets for the undrained location (data not shown). We hypothesize that isotopically less negative values are due to some combination of crop growth and seasonal variation of ^{18}O in precipitation. We will test these ideas by comparing nitrate and ^{18}O trends during events at different times of the next water year.

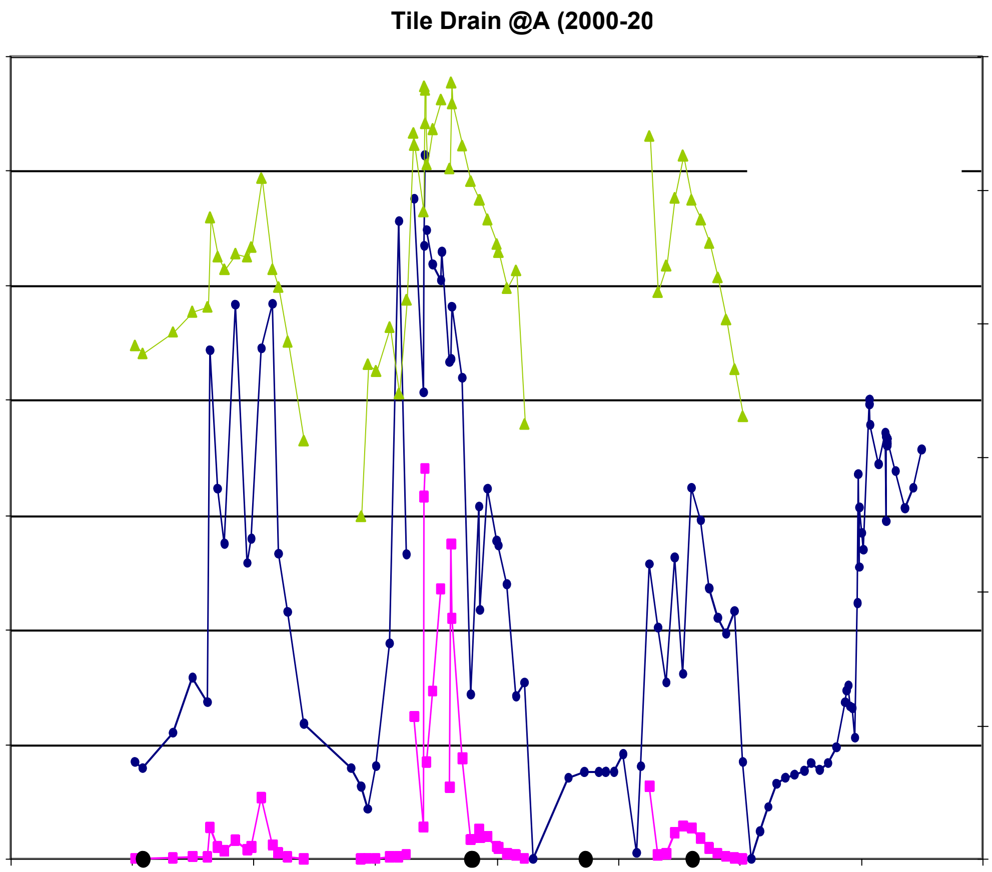


Figure 1. Nitrate concentration, water, and N mass discharges for the period of record at the drained location. Note log scale for water discharge

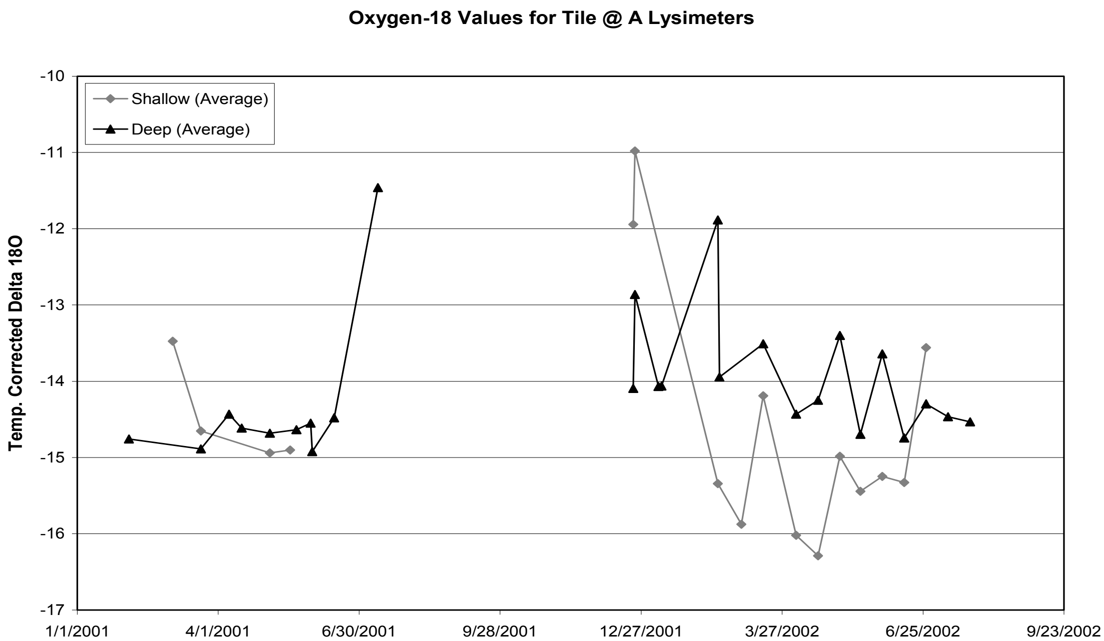


Figure 2. Oxygen-18 concentrations (per mil) in soil-water (lysimeter) samplers at the drained location for the first two water years. Up to three samplers yield water at each depth; averages are shown.

Information Transfer Program

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2002WA4B
Start Date:	3/1/2003
End Date:	2/28/2004
Funding Source:	104B
Congressional District:	Washington Fifth
Research Category:	None
Focus Category:	Management and Planning, Education, None
Descriptors:	None
Principal Investigators:	Michael Ernest Barber

Publication

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

After the February 2002 regional water quality conference, a considerable amount of effort went into uploading the proceedings onto our Web site and analyzing the responses to program questionnaires in order to improve our next conference. Planning began immediately for the next conference on TMDL implementation. This conference was held on October 29-30, 2003 in conjunction with the Washington State Department of Ecology and the U.S. Environmental Protection Agency, with a pre-conference workshop on TMDL's held on October 28, 2003.

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

Meetings with the Spokane/Rathdrum Prairie aquifer committee were attended to discuss Idaho and Washington Water Institute involvement with a potential project near Spokane.

The Director and the Program Director for Water and Wastewater met with several representatives from the Washington Department of Ecology and the Washington Department of Health to discuss research and educational needs associated with water reclamation in the state. Subsequently, a number of phone meetings and electronic correspondence have furthered the discussion.

The Director has participated as a committee member in the planning of the 2004 UCOWR conference.

Our Web site has undergone a major upgrade. 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 and is current and the look of the page is up to date. This year we began the process of making research reports available for download via PDF format rather than mailing of paper copies.

Our database of interested stakeholders is constantly being updated. Currently, over 2,200 names are included.

A variety of other activities were conducted during the year such as a) addressing questions related to the Eastern Washington Stormwater Manual, b) presentations to watershed groups, c) service in response to telephone and e-mail requests from users, and d) attendance at extension and agency meetings.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	4	1	0	0	5
Masters	3	7	0	0	10
Ph.D.	2	2	0	0	4
Post-Doc.	0	0	0	0	0
Total	9	10	0	0	19

Notable Awards and Achievements

In 2003, Principal Investigator Richelle Allen-King was selected as the Henry Darcy Distinguished Lecturer by the National Ground Water Association. At that time, Dr. Allen-King was faculty in the Geology Department at Washington State University and was also a program director with the State of Washington Water Research Center.

Her Darcy presentation "Ground and Surface Water Contributions to Chemical Mass Discharge: Considering the Problem at Field and Basin Scales: was presented by invitation to audiences at more than two dozen academic and research institutions, national and internationally. Results from research projects funded through the 104B and 104G programs formed the basis for this presentation.

Publications from Prior Projects

1. 1996WA102G ("Effectiveness of Irrigation District Conservation Oriented Pricing Programs") - Articles in Refereed Scientific Journals - Huffaker, Ray G. and Norman K. Whittlesey, 2003, A Theoretical Analysis of Economic Incentive Policies Encouraging Agricultural Water Conservation, International Journal of Water Resources Development, 19(1):37-53.
2. 1996WA102G ("Effectiveness of Irrigation District Conservation Oriented Pricing Programs") - Other Publications - Huffaker, Ray G., 2003, The linkage between irrigation effectiveness and water conservation: what new water managers should know, Invited presentation to the Water Resources Seminar Hazards of Practicing Your Trade, Tips for New Water Managers, Colorado State University, October 2003.
3. 1996WA102G ("Effectiveness of Irrigation District Conservation Oriented Pricing Programs") - Other Publications - Huffaker, Ray G., 2003, The agricultural water conservation morass, presented at the Principal Paper Session, Western Agricultural Economics Association Annual Meeting, Denver, Colorado, July 11-15, 2003.
4. 1997WA104G ("A Problem-solving Tool for Mitigating the Impact on Water Quality of Management Practices in Small Rural Watersheds") - Articles in Refereed Scientific Journals - Wang, G.T., S. Chen, J. Boll, and V.P. Singh, 2003, Nonlinear Convection-diffusion Equation with Mixing-cell

Method for Channel Flood Routing, Journal of Hydrologic Engineering, 8(5):259-265.

5. 1997WA104G ("A Problem-solving Tool for Mitigating the Impact on Water Quality of Management Practices in Small Rural Watersheds") - Articles in Refereed Scientific Journals - Wang, G.T., S. Chen, and J. Boll, 2003, A Semi-analytical Solution of the Saint-Venant Equations for Channel Flood Routing, Water Resources Research, 39(4):1076-1085.
6. 1997WA104G ("A Problem-solving Tool for Mitigating the Impact on Water Quality of Management Practices in Small Rural Watersheds") - Dissertations - Brooks, Erin S., 2003, Distributed Hydrologic Modeling of the Eastern Palouse, Ph.D. dissertation, Department of Biological and Agricultural Engineering, University of Idaho, Moscow, Idaho.
7. 1997WA103G ("Impact of Climatic Variations on Flood Magnitude and Frequency in Three Hydroclimatic Regions of the Western United States") - Book Chapters - Hosman, K.J., L.L. Ely, and J.E. O'Connor, 2003, Holocene Paleoflood Hydrology of the Lower Deschutes River, Oregon, "In" G.E. Grant and J.E. O'Connor, eds., Geology, Geomorphology, and Hydrology of the Deschutes River, Oregon, Water Science and Application Series, Volume 7, American Geophysical Union, Washington, DC, pp. 121-146.
8. 1997WA103G ("Impact of Climatic Variations on Flood Magnitude and Frequency in Three Hydroclimatic Regions of the Western United States") - Book Chapters - Miller, J.R., P.K. House, D. Germanoski, R.J. Tausch, and J.C. Chambers, 2004, Fluvial Geomorphic Responses in Central Nevada to Holocene Climatic Disturbances, "In" J.C. Chambers and J.R. Miller, eds., Great Basin Riparian Ecosystems: Ecology, Management and Restoration, Island Press, Washington, DC, 320 pp.
9. 1997WA103G ("Impact of Climatic Variations on Flood Magnitude and Frequency in Three Hydroclimatic Regions of the Western United States") - Conference Proceedings - Ely, L.L., J.E. O'Connor, and P.K. House, 2003, Proceedings of the Third International Paleoflood Conference, Hood River, Oregon, August 1-7, 2003, Nevada Bureau of Mines and Geology, 43 pp.
10. 1999WA0014G ("A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery") - Articles in Refereed Scientific Journals - Wang, G., S. Chen, and J. Boll, 2003, A Semi-analytical Solution of the Saint-Venant Equations for Channel Flood Routing, Journal of Water Resources Research, 39(4):1076-1085.
11. 1999WA0014G ("A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery") - Articles in Refereed Scientific Journals - Wang, G., S. Chen, J. Boll, and V.P. Singh, 2003, Non-linear Convective-diffusion Equation with Mixing Cell Method for Channel Flood Routing, Journal of Hydrological Engineering, 8(5):259-265.
12. 1999WA0014G ("A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery") - Water Resources Research Institute Reports - Mancilla, G., S. Chen, and G. Wang, 2004, A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery, State of Washington Water Research Center, Washington State University, Pullman, Washington, Water Research Center Report No. WRR-16, 33 pp.
13. 1999WA0014G ("A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery") - Other Publications - Chen, Shulin and M. Khalid Alvi, 2003, The effect of frozen soil depth on winter infiltration hydrology of Pataha Creek Watershed (Poster), presented at the ASAE Annual International Meeting, July 27-30, 2003, Las Vegas, Nevada, Poster No. 139, Paper No. 032160.
14. 1999WA0014G ("A Watershed Scale Study on No-till Farming Systems for Reducing Sediment Delivery") - Other Publications - Fu, G., S. Chen, and D.K. McCool, 2003, Soil erosion and its response to no-till practice estimated with ArcView GIS, presented at the ASAE Annual International Meeting, July 27-30, 2003, Las Vegas, Nevada, Paper No. 032288.
15. 1999WAB-01 ("Mechanisms of Pesticide Transport to Surface Water at the Field Scale in a

Dryland-Agriculture Region") - Other Publications - Allen-King, R.M., 2003, Ground and surface water contributions to chemical mass discharge: considering the problem at the field and basin scales. National Ground Water Association's 2003 Henry Darcy Distinguished Lecture was presented by invitation to audiences at more than two dozen academic and research institutions, nationally and internationally during the year. The presentation included data collected for this project.

16. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - 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 Sciences, Washington State University, Pullman, Washington, 131 pp.
17. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - Dissertations - 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.
18. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - Conference Proceedings - Allen-King, R.M., 2003, Ground and surface water contributions to chemical mass discharge: field to basin scales (Keynote), "in" Proceedings of the 4th Symposium of the Hydrogeology of Washington State, April 8-10, 2003, Tacoma, Washington, p. 1, http://www.ecy.wa.gov/events/hg/abstracts2003.pdf
19. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - Conference Proceedings - Simmons, A.N., R.M. Allen-King, C.K. Keller, J.L. Smith, and T. VanBiersal, 2003, Dissolved pesticide mass discharge in a semi-arid dryland agricultural watershed at the field and basin scale (Abstract), "in" Proceedings of the 4th Symposium of the Hydrogeology of Washington State, April 8-10, 2003, Tacoma, Washington, p. 78, http://www.ecy.wa.gov/events/hg/abstracts2003.pdf
20. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - Conference Proceedings - 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" Proceedings of the Annual Meeting of the Geological Society of America, November 2-5, 2003, Seattle, Washington, Abstracts with Programs, 34(7):316.
21. 1999WA0013G ("Surface and Subsurface Transport Pathways of Non-point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale") - Other Publications - The results from this project form the core of one of the two 2003 Distinguished Darcy Lectures "Ground and Surface Water Contributions to Chemical Mass Discharge: Considering the Problem at Field and Basin Scales," presented by Distinguished Darcy Lecturer Dr. Richelle Allen-King. This Darcy lecture was presented by invitation to audiences at more than two dozen academic and research institutions, nationally and internationally. The presentation included data collected for this project.
22. 2000WAC-04 ("Evaluating Water Policy Affecting Fish Habitat, Hydrology, and Irrigated Agriculture in the Snake River Basin") - Articles in Refereed Scientific Journals - Miller, S.A., G.S. Johnson, D.M. Cosgrove, and R. Larson, 2003, Regional Scale Modeling of Surface and Ground Water Interaction in the Snake River Basin, Journal of the American Water Resources Association, 39(3):517-528.
23. 2000WA4G ("Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the Yakima River Basin") - Water Resources Research Institute Reports - Leib, B.G., and R.G. Stevens, 2003, Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the

Yakima River Basin, State of Washington Water Research Center, Washington State University, Pullman, Washington, State of Washington Water Research Center WRR-17, 6 pp.

24. 2000WA4G ("Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the Yakima River Basin") - Other Publications - Strausz, D.A., B.G. Leib, and C.A. Redulla, 2003, PAM and erosion control practices for rill irrigated fields, Extension Fact Sheet, Washington State University.
25. 2000WAWA-05 ("Modeling Winter Hydrology and Erosion in the Northwest Wheat and Range Region") - Conference Proceedings - Wu, J.Q., and W.J. Conroy, 2003, WEPP (Water Erosion Prediction Project): a process-based watershed runoff and erosion model for TMDL development, "in" Proceedings, Getting It Done: The Role of TMDL Implementation in Watershed Restoration, October 29-30, 2003, Stevenson, Washington, State of Washington Water Research Center, Pullman, Washington. Available at http://www.swwrc.wsu.edu/conference2003/proceedings.html
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29. 2000WAWA--05 ("Modeling Winter Hydrology and Erosion in the Northwest Wheat and Range Region") - Other Publications - Wu, J.Q., 2003, Modeling hydrology and erosion under winter climatic conditions of the Pacific Northwest: modifying WEPP, Presented at the Western Regional Research Project W-188 Technical Committee Annual Meeting, Las Vegas, Nevada, January 6-8, 2003.
30. 2000WAWA-05 ("Modeling Winter Hydrology and Erosion in the Northwest Wheat and Range Region") - Other Publications - Wu, J.Q., W.J. Elliot, and S. Dun, 2003, Modification of the subsurface flow routines in the WEPP (Water Erosion Prediction Project) model, Presented at the 2003 ASAE Meeting, Las Vegas, Nevada, July 27-30, 2003.
31. 2001WA781B ("Biodegradation of Non-Point Source Pollutants in Soap Lake, Washington") - Articles in Refereed Scientific Journals - Alva, V.A., B.M. Peyton, 2003, Phenol and Catechol Biodegradation by the Haloalkaphile Halomonas campisalis: influence of pH and salinity, Environmental Science and Technology, 37(19):4397-4402.
32. 2001WA781B ("Biodegradation of Non-Point Source Pollutants in Soap Lake, Washington") - Dissertations - Alva, V., 2003, Biodegradation of Phenol and Metabolic Intermediates by the Haloalkaliphile Halomonas campisalis in Saline and Alkaline Conditions, Ph.D. dissertation, Department of Chemical Engineering, Washington State University, Pullman, Washington, 208 p.
33. 2001WA1041B ("Dye Tracers for Vadose Zone Hydrology") - Articles in Refereed Scientific Journals - Flury, M., and N.N. Wai, 2003, Dyes as Tracers for Vadose Zone Hydrology, Reviews of Geophysics, 41(1):1002, doi (digital object identifier): 10.1029/2001RG000109.
34. 2002WA15B ("Development of a Comprehensive Monitoring Protocol to Characterize the Concentration and Associated Health Risk of Salmonid Pathogens Suspended in Water") - Water Resources Research Institute Reports - Call, D.R., R.H. Hotchkiss, K.D. Cain, and F.J. Loge, 2003,

Development of a Comprehensive Monitoring Protocol to Characterize the Concentration and Associated Health Risks of Salmonid Pathogens Suspended in Water, State of Washington Water Research Center, Washington State University, Pullman, Washington, State of Washington Water Research Center Report WRR-14, 9 pp.

35. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Water Resources Research Institute Reports - Flury, M., C.O. Stockle, and R.M. Allen-King, 2003, Facilitated Transport of Pesticides by Organic Colloids, State of Washington Water Research Center, Washington State University, Pullman, Washington, State of Washington Water Research Center Report WRR-13, 25 pp.
36. 2002WA16B ("Reactive Transport of Reducible Metal Ions: Reaction Kinetics, Column Experiments, and Transport Modeling") - Articles in Refereed Scientific Journals - Viamajala, S., B.M. Peyton, and J.N. Petersen, 2003, Modeling Chromate Reduction in Shewanella oneidensis MR-1: development of a novel dual-enzyme kinetic model, Biotechnology and Bioengineering, 83:790-797.
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41. 1999WAB-02 ("The Role of Turbulence and Sediment Availability in Sediment Erosion Processes") - Articles in Refereed Scientific Journals - Hunt, A. and A.N. Papanicolaou, 2003, Tests of Predicted Downstream Transport of Clasts in Turbulent Flow, Advances in Water Resources, 26(11):1205-1211.
42. 1999WAB-02 ("The Role of Turbulence and Sediment Availability in Sediment Erosion Processes") - Articles in Refereed Scientific Journals - Papanicolaou, A.N. and S.A. Schuyler, 2003, Cluster Evolution and Flow-frictional Characteristics under Different Sediment Availabilities and Specific Gravity, Journal of Engineering Mechanics, ASCE, 129(10):1206-1219.
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45. 1999WAB-02 ("The Role of Turbulence and Sediment Availability in Sediment Erosion Processes") - Conference Proceedings - Strom, K., A.N. Papanicolaou, and M. Odeh, 2003, Monitoring the evolution of cluster microforms in gravel-bed streams, "in" T.L. Wahl, T.B. Vermeyen, K.A. Oberg, and C.A. Pugh, eds., Hydraulic Measurements and Experimental Methods 2002, Proceedings of the Speciality Conference, sponsored by Environmental and Water Resources Institute of American Society of Civil Engineers and the International Association of Hydraulic Engineering and Research, Estes Park, Colorado, July 28-August 1, 2002. [CD Version]