State of Washington Water Research Center

Annual Technical Report

FY 2000

Introduction

The State of Washington Water Research Center is committed to:

1. Engage state university faculty in a meaningful discussion of water-related issues with state and federal agencies and the general public, and to 2. Foster relevant university research, education, and outreach activities that provide solutions to these issues.

To accomplish these goals, the Center has developed a dynamic web page and an electronic newsletter, and has intensified its efforts to reach out to agencies, organizations, and faculty throughout the state. To promote research and outreach, the Center was organized into five program areas: Watershed Management, Water Resources and Biotic Systems, Groundwater systems, Irrigated Systems, and Outreach and Education. These programs have helped to prepare several multidisciplinary research proposals and provide better links between faculty and the Center. The Center has also been involved in international research and educational activities.

It is within this overall context that the USGS-funded project activities reported in this document must be inserted. These projects provide a solid core to the diverse efforts of the Center. Water quality continues to be the major issue of concern in the state, magnified by impacts on the habitat of several endangered species of salmonids and a major drought. Compliance with the Clean Water Act and the Endangered Species Act is and will be an important driver of the activities of the Center in the future.

Research Program

Basic Information

Title:	Surface and Subsurface Transport Pathways of Non-Point Agricultural Pollutants: Analysis of the Problem Over Four Decades of Basin Scale
Project Number:	S-01
Start Date:	9/1/1999
End Date:	5/31/2002
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Nitrate Contamination, Groundwater
Descriptors:	Agriculture, Contaminant transport, Fertilizers, Groundwater Hydrology, Groundwater Quality, Herbicides, Isotopes, Leaching, Nitrogen, Nutrients, Organic Compounds, Pollutants, Rivers, Runoff, Solute Transport, Unsaturated Flow, Water Wuality
Lead Institute:	Washington State University
Principal Investigators:	Richelle Allen-King, Andy Bary, Markus Flury, Michael barber, C. Kent Keller, Jeffrey L. Smith

Publication

1. Van Biersel, Thomas, Richelle Allen-King, C. Kent Keller, Jeffrey Smith, and Amy Simmons, 2000, Non-Point Pesticide Transport to Surface and Ground Water at the Field and Basin Scale: an Update. October 2000, 3rd Symposium on the Hydrogeology of Washington State, Tacoma, Washington. Published Abstract.
2. Allen-King, Richelle, Thomas Van Biersel, C. Kent Keller, and Jeffrey Smith, 2000, Non-Point Pesticide Loading of Surface Water at the Field and Basin Scale, November, 2000 Meeting Geological Society of America, Reno, Nevada, Abstract 51761.
3. Van Biersel, Thomas, Richelle Allen-King, Jeffrey Smith, and C. Kent Keller, 2000, Field Scale Tracer and Pesticide Transport Through Unsaturated Cultivated Loess, December, 2000 Meeting Am. Geophys. Union, San Francisco, California, Abstract H22C-07.
4. Schaumloffel, J.C., R.M. Allen-King, A. Simmons, and D. Talmage. 2000. A Rapid, Simplified SPME Procedure for the Determination of Moderately Hydrophobic Agricultural Chemicals in Runoff. ACS National Meeting, Washington, D.C., August 20-24, 2000. Published Abstract.

PROJECT SUMMARY

The overall goal of the proposed project is to determine whether combinations of geochemical tracers can be used to identify and quantify the contributions of various surface and groundwater transport pathways draining agricultural regions at the watershed scale. Our approach is to characterize selected hydrochemical features - the geochemical "fingerprint" - of each pathway, and to "trace" these features to surface water draining the watershed. The supporting objectives of the work include:

1. To test the multiple chemical tracer approach by measuring field-scale contributions to local watershed drainage from fields with a predominantly groundwater or surface flow pathway;
2. To determine whether chemical tracer analysis can be used to quantify temporal, particularly seasonal, variability in the components of flow and transport.

This project will test these ideas by comparing direct measurements of the mass discharge components of a target nutrient (N as nitrate) and hydrophobic pesticides (triallate, lindane) moving from fields to independent estimates obtained from multiple tracers in a typical agricultural setting near Pullman, WA. Because we have selected multiple environmental tracers ($\delta^{18}O$, dissolved silica and electrical conductivity as a proxy for total dissolved solids) with different hydrologic signatures, we anticipate the ability to separate pathways representing a spectrum of residence times.

The study monitors soil pore water and drainage (water quality and quantity) from topographically-defined fields and from the watershed along Missouri Flat Creek (MFC) and its tributaries at approximately decadal scale increases. Fields selected for intensive instrumentation include those which have ephemeral streams (surface runoff is the dominant outflow) and artificial subsurface drainage (tile drained, "groundwater" is the primary outflow). By this approach, agricultural chemicals and tracer masses can be quantified at multiple watershed scales.

The multiple tracer approach allows identification and quantitation of the complex dynamic flow system within the Palouse soils. For example, pore-water concentration patterns for nitrate, triallate and the geochemical tracers indicate a seasonal shift from vertical flow during soil wetting to primarily lateral flow and transport when the low slope position soils become seasonally saturated.

Our current understanding is that the hydrophobic pesticides are transported to the Palouse River (via Missouri Flat Creek) by a predominantly surface pathway at the field scale. Similarly, mass balances imply that a substantial flux of triallate reaches surface water by this route. Interestingly, the pesticide concentration trends (first-order decay for triallate and relatively constant for lindane) are simple in the field-scale (~7 ha) watershed drainage, as reflected by the concentration in the ephemeral stream. Widely varying concentration patterns at much larger basin scales appear to result from variable mass discharges apparently attributable to highly variable water discharge. These observations have important implications to estimates of seasonal mass transport from fields. Further, if particle-bound transport is important, current mass discharge estimates based on dissolved-phase samples may severely underestimate total mass discharge from the basin. This aspect of the work will receive further attention during the coming year of study.

While the data suggest a surface route for most pesticide transport, low level triallate detections throughout the water year cannot be attributed to concurrent surface runoff when it does not occur. These observations may imply the existence of a second pathway or mechanism by which pesticides occur in the river, either shallow ground water discharge or particle-born pesticides stored within discharge channels are consistent with observations.

Nitrate concentrations suggest transport predominantly by the subsurface (ground water) pathway, as indicated by the generally elevated nitrate concentration at depth in soil pore-water at instrumented fields and the elevated concentration (up to 22 mg/l) in the monitored tile drain. Mass balance calculations imply that a substantial flux of nitrate reaches surface water by a shallow ground water pathway.

Nitrate and pesticide concentrations in the river water are affected by the dynamic hydrology occuring within the soils. Additionally, there is clearly a relationship between the timing of application and precipitation that effects discharge concentrations. These are important factors to incorporate into models which “upscale” watershed concentration patterns to predict downstream river concentrations.

Results from surface water sampling along MFC and its tributaries indicate the presence of triallate (up to 0.151 µg/L), lindane (up to 0.280 µg/L) and nitrate (up to 34 mg/L) above regulatory criteria, at, or near, the monitored farm. Further along MFC, the concentrations decreased to below ecological standards, except at a sampling point directly downstream from an agrochemical storage facility. Diminished concentrations are attributable to dilution and potentially favorable dissipation processes and will be further investigated during the coming year.

This project is in the initial year of multi-year effort. At this point, effort has been focussed principally on intensive monitoring. Data interpretation and modeling have yet to be completed with the data. Additionally, a drought occurred during the year of intensive monitoring on this project. Many (most) of the new pore water samplers installed never produced water because of the unusually dry soil conditions and river sampling was limited because discharge is currently at approximately 10% of last year. Therefore, conclusions from this year of work are considered preliminary. The study will continue targeted monitoring, budget permitting, into the subsequent year to pursue the stated project goals.

INTRODUCTION

The quantity and quality of this Nation's water resources are strongly affected by agriculture, because areally widespread cultivation affects both the physical and chemical regimes within which water moves from atmospheric to exploitable surface and subsurface reservoirs. In large parts of the country, surface waters and some proportion of interconnected ground waters are polluted badly enough that they are unfit for human use and impact aquatic ecosystems downstream. These effects of modern agriculture are a clear threat to its viability, both because society increasingly holds water polluters to account, and because the pollution itself is lost ag-production input. At the planetary scale and over the long term, optimally targeted use of agrochemicals will be required to conserve nutrient capital and protect progressively scarce water resources in the face of increasing human population. And movement of chemicals from fields, to streams and shallow aquifers, cannot be controlled by management practices, unless it is understood.

At root, agrochemical pollution effects may be understood as consequences of the pathways by which meteoric water moves across and through fields to surface and shallow ground waters. The flow-rate and hydrogeochemical features of these pathways (i.e. physical and chemical hydrology) control water and contaminant mass discharges to surface and ground waters. Understanding the hydrologic "pieces" (pathways) and how they "fit together" (their relative contributions to aggregate discharges) is thus key to assessing measures that might be used to prevent or ameliorate this pollution.

Pesticide concentrations exceeding available regulatory criteria have been reported by the U.S. Geological Survey (USGS) in the Palouse River (Greene et al., 1996, and Wagner and Robert, 1998). The Palouse River drainage basin encompasses approximately 650,000 ha, predominantly (~80%, Williamson et al., 1998) under agricultural use, and drains into the Snake River, which is widely used for recreational purposes and drains into the Columbia River.

GOALS

The overarching goal of the project is to understand the contributions of surface and subsurface hydrologic components to non-point chemical loading of surface water, at field and basin scales, in a semi-arid dryland agricultural setting. An important contribution of this study is that it uses geochemical tracers (including stable isotopes) to quantify the sources of water discharge at multiple watershed scales. This work builds on previous and on-going, primarily basin-scale study, conducted by USGS researchers as part of the NAWQA program. It will be of use to USGS researchers in assessing methodologies for scale-up from field to large-basin watershed area. The improved understanding of hydrologic transport pathways gained will be used to assess the impact of current agricultural practices on the chemical loading of the shallow ground water system.

The specific objectives of the study are:

1. to quantify field-scale occurrence and movement of an herbicide (triallate), an insecticide (lindane) and a nutrient (nitrate) at selected field-sites and concurrently trace transmission to local drainage ways;

2. to separate hydrographs of local- to basin-scale surface-water flows into their surface, soil-water, and ground water components, using measured compositions of multiple, independent chemical and isotopic tracers (SiO_2, electrical conductivity, $\delta^{18}O$);
3. to test the ability of the resultant models to explain observed nitrate and triallate concentrations in surface water associated with each watershed scale;
4. to use the understanding gained to estimate the effects of non-point chemical application on the shallow ground water resource at field and basin scales;
5. to use solute transport models of different levels of complexity (screening, management, and research models) to study the transport of the agrochemicals.

These objectives are met through sample collection (Table 1), the analysis of triallate, lindane and nitrate concentrations, and water discharges in surface runoff, soil solution, ground water, tile drain water and concurrent drainage for three particular fields. ‘Upscaling’ of the mixing model relationships developed at the field scale will be tested through monitoring of discharge at watershed scales up to the river-basin scale (Table 2) at regular intervals over a water year. The resulting conceptual framework, based as it is on “off-the-shelf” solute analyses and simple mathematics, can be readily tested and adapted in other regions. Because the approach relies strongly on comparisons between artificially drained and undrained fields, our work will also provide a significant step to compare the importance of these pathways to regional-scale water quality effects in a semi-arid area. Because the study focuses on the processes that control transport, the information gained will provide insights on the fate of other chemicals with similar physicochemical properties. We anticipate that the methods developed will be useful in other basins studied in the USGS NAWQA program.

TABLE 1. Samples collected June 2000-present.

		Sample Collected			
		Location	# of Samples	From	To
CRF	Area A	P-6	1	2/19/01	2/19/01
		SC-3	8	10/27/00	4/16/01
		SC-5	5	2/19/01	4/16/01
		SC-8	1	3/21/01	3/21/01
		SC-9	2	10/27/00	4/16/01
		SS-1	3	3/3/01	4/8/01
		SS-2	4	3/3/01	4/16/01
		SS-4	3	3/21/01	4/16/01
		SS-5	3	3/21/01	4/16/01
		SS-7	4	2/19/01	4/16/01
		SS-8	2	2/19/01	3/21/01
CRF	Area C	SC-10	6	2/6/01	4/16/01
		SC-11	6	2/6/01	4/16/01
		SC-12	6	2/6/01	4/16/01
		SC-14	6	2/6/01	4/16/01
		SC-15	6	2/6/01	4/16/01
		SC-16	6	2/6/01	4/16/01
		SC-17	6	2/6/01	4/16/01
		SC-18	6	2/6/01	4/16/01
MFC		Rill @ C	6	2/5/01	4/12/01
		Trib @ B	5	2/3/01	4/9/01
		Tile @ A	11	10/6/00	4/16/01
		Culvert @ A	10	10/6/00	4/16/01
		Gray Rd	10	10/6/00	4/16/01
		McGreevy Rd	8	10/19/00	4/16/01
		Kitzmiller Rd	5	12/7/00	4/9/01
		State St.	10	10/5/00	4/16/01
ARS		LYS 2	8	6/1/00	4/12/01
		LYS 3	8	6/1/00	4/12/01
		LYS 4	12	6/1/00	4/12/01
		LYS 5	12	6/1/00	4/12/01
		LYS 6	16	6/1/00	4/12/01
		LYS 7	17	6/1/00	4/12/01
		LYS 8	18	6/1/00	4/12/01
		LYS 9	12	6/1/00	4/12/01
		Stream	5	6/1/00	4/12/01

Notes: CRF stands for Cunningham Research Farm (WSU owned farm); Area A is a tile-drained field and Area C a naturally drained field.
ARS stands for Agricultural Research Service (USDA operated farm)
MFC stands for Missouri Flat Creek
LYS are PVC capillary wick lysimeters
P are stainless steel pan lysimeters
SC are ceramic suction cup lysimeters
SS are stainless steel suction cup lysimeters

TABLE 2. Approximate watershed drainage area corresponding to each of the surface sampling sites.

Gaging Station ID	App. Watershed Area (ha)
ARS - Ephemeral Stream	7.5
MFC - Rill @ C	7
MFC - Tile @ A	19
MFC - Trib @ B	150
MFC - Culvert @ A	450
MFC - Gray	600
MFC - McGreevy	6,000
MFC - Kitzmiller	11,000
MFC - State	14,400
Palouse River @ Hooper	650,000*

Note: * value obtained from Williamson et al, 1998.

Materials and Methods

The research is conducted in the Palouse subunit of the former Central Columbia Plateau (now Central Columbia-Yakima, CCYK) unit of the National Water-Quality Assessment (NAQWA) program of the USGS. The field sites (Figure 1) selected are located near Pullman, WA, and include three topographically-defined fields – two monitored fields that develop ephemeral streams [U.S. Dept. of Agriculture (USDA) Agricultural Research Service Palouse Field Station (ARS), and WSU Cunningham Research Farm (CRF) Area C] and one tile-drained field (CRF Area A), all actively farmed by the USDA under no-till conditions. In the course of previous work (Allen-King et al., 2000; Van Biersel et al., 2000; Roberts, 1999) the ARS watershed was outfitted with surface-water gauging and sampling apparatus, a weather station, and depth profiles of ground water and unsaturated-zone water samplers, water content reflectometers, and thermocouples, installed laterally into undisturbed soils, via a trench (Roberts, 1999). Surface water is monitored at two ~annually farmed (disturbed) ephemeral streams (ARS Stream and MFC-Rill @ C), one (not disturbed) ephemeral tributary (MFC-Trib @ B), a tile drain (MFC-Tile @ A) and several gauging stations along Missouri Flat Creek (MFC) and its tributaries (Figure 1). MFC joins the South Fork of the Palouse River in Pullman, WA.

The agrochemicals monitored (triallate, lindane, and nitrate-N) were selected because of their importance in the local hydrologic system and potential to provide insights relevant to other systems. Both the herbicide triallate (S-(2,3,3-trichloroallyl) diisopropylthiocarbamate) and insecticide lindane (>99% gamma isomers of hexachlorocyclohexane, HCH) have been detected in the Palouse River at the Hooper monitoring station at significant concentrations. Triallate is the most heavily applied organic pesticide (on a mass per area basis) in the Palouse subunit. Both chemicals have relatively long field half-lives, are hydrophobic, moderately volatile. Chemical properties for both compounds suggest that they may be bioaccumulative. Process-based understanding of these chemicals is expected to yield insights applicable to other hydrophobic pollutants. Excess nitrogen can lead to eutrophication and oxygen depletion in streams and to health effects in water supplies – problems receiving consideration globally. Nitrogen-limited eutrophication has been identified for the South Fork of the Palouse River.

The agrochemical application and seeding schedule is presented in Table 3. Far-Go® (Monsanto) is incorporated in the soil in a granular form. Nitrate is applied in liquid form as ammonium nitrate. Lindane application is a by-product of seeding. Seeds used at the farms are coated with lindane (~0.00022 g/g seed). Actual application rate may range between 0.16 and 1.4 g of lindane per kg of seed (source: http://www.speclab.com/compound/c58899.htm), and is expected to be approximately 0.025 kg of lindane per ha of winter wheat.

TABLE 3. Agrochemical applications to study fields.

	Agrochemical Application			
	Triallate	Lindane/Seeding	N Fertilizer	KCl
ARS				
Fall 1999	East: 5 kg/ha West: 5 kg/ha	East: West: winter peas		
Winter 1999				
Spring 2000		East: spring barley West:	East: 113 kg/ha West:	
Summer 2000				
Fall 2000		East: winter peas West: winter wheat	East: West: 108 kg/ha	
Winter 2000				
Spring 2001				
CRF-Area A				
Fall 2000	1.7 kg/ha	Winter wheat	192 kg/ha	
Winter 2000				
Spring 2001				
CRF-Area C				
Fall 2000	1.7 kg/ha	Winter barley	192 kg/ha	
Winter 2000				
Spring 2001				108 kg/ha

Note: Triallate applied as granular Far-Go® and reported as kg of active ingredient.
Lindane application is approximately 0.025 kg/ha for winter wheat.

Samples for pesticides (triallate and lindane), EC (electrical conductivity), silica, nitrate and $\delta^{18}O$ determinations are collected from subsurface lysimeters and surface water gauging stations at approximately two-week intervals. Surface water sample collection/filtration methods are consistent with recommended USGS methods (Shelton, 1994). A water sample from the Palouse River at Hooper is obtained from the USGS on a monthly basis for $\delta^{18}O$ analysis.

The subsurface water samples are collected at the ARS site using low-tension capillary wick (CAPS) lysimeters (Figure 2a) located at depth of ~15, 84 and 112-cm. The 15-cm depth represents the bottom of the no-till drill penetration, and 84 and 112-cm depth represent the top and bottom of the E horizon, respectively (Roberts, 1999). The subsurface water samples are collected at the CRF-Area A site from stainless steel pan, stainless steel suction cup and ceramic suction cup lysimeters (Figure 2b) located at depth of ~25, 45 and 85 cm. The selection of these depth are based on the depth of the plow layer (~25 cm) and water table (~100 cm). The soils at CRF-Area A are recently deposited (<50 years) up-slope alluvium. CRF-Area C ceramic suction-cup lysimeters are installed at the same depth as those at CRF-Area A.

(a) (b)

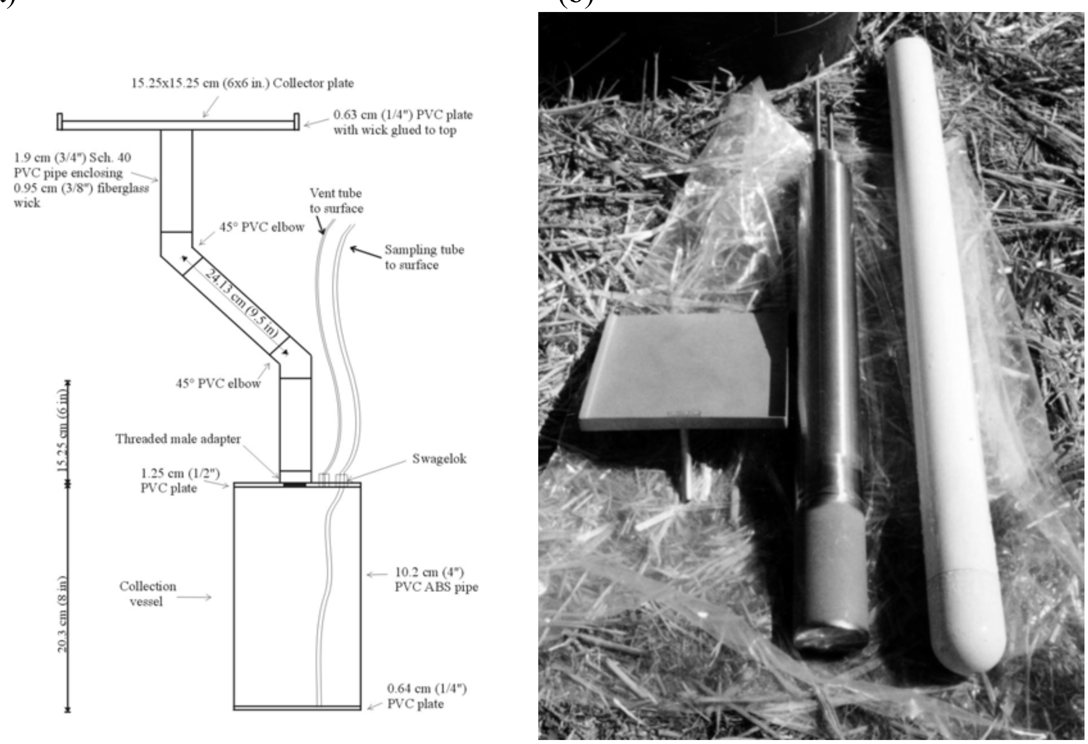


Figure 2. Types of subsurface water samplers. (a) Diagram of ARS capillary wick lysimeter. (b) Photograph of CRF (from left to right) stainless steel pan, stainless steel suction cup and ceramic suction cup lysimeters

The EC is measured in the lab, directly after sample return using a temperature compensated probe (Orion®). Samples for pesticide analyses are passed through a through a pre-baked, in-line, glass fiber membrane (0.7-µm pore size) in a stainless steel holder during field collection directly into a 160 ml borosilicate glass vial, sealed with a PTFE lined silicone septa, and stored refrigerated until analysis. Pesticide samples are analyzed for triallate and lindane using solid-phase microextraction (SPME) and gas chromatography with electron capture detection according to the method developed by our group (Schaumloffel et al., 2000). Samples for nitrate, silica and $\delta^{18}O$ analysis are filtered a second time with a 0.2-µm cellulose nitrate membrane filter. Samples for nitrate analyses are preserved frozen until analyzed at the USDA-ARS lab at WSU using a continuous flow analyzer. Samples for silica and $\delta^{18}O$ are stored at room temperature, in the dark. Silica is analyzed at WSU using a spectrophotometric technique (APHA et al., 1981). The $\delta^{18}O$ is determined by CO_2 equilibration (Epstein and Mayeda, 1953) and reported with respect to VSMOW. Turbidity is measured in the laboratory, directly after sample return, using a Hach ® 2100P portable turbidimeter.

Surface discharge is quantified at the field-scale, using either 2" or 6" Parshall flumes (CRF), or a V-notch weir (ARS). The flumes are equipped with a stilling well and the head is continuously recorded using, a pressure transducer. Surface discharge at the gauging stations along Missouri Flat Creek (MFC) and one of its tributaries is continuously measured at two corrugated culverts and three highway bridges equipped with pressure transducers (Figure 1). The tile drain located at CRF-Area A is gauged manually and with a tipping bucket assembly. Data for all continuously monitored locations are being collected to establish rating curves.

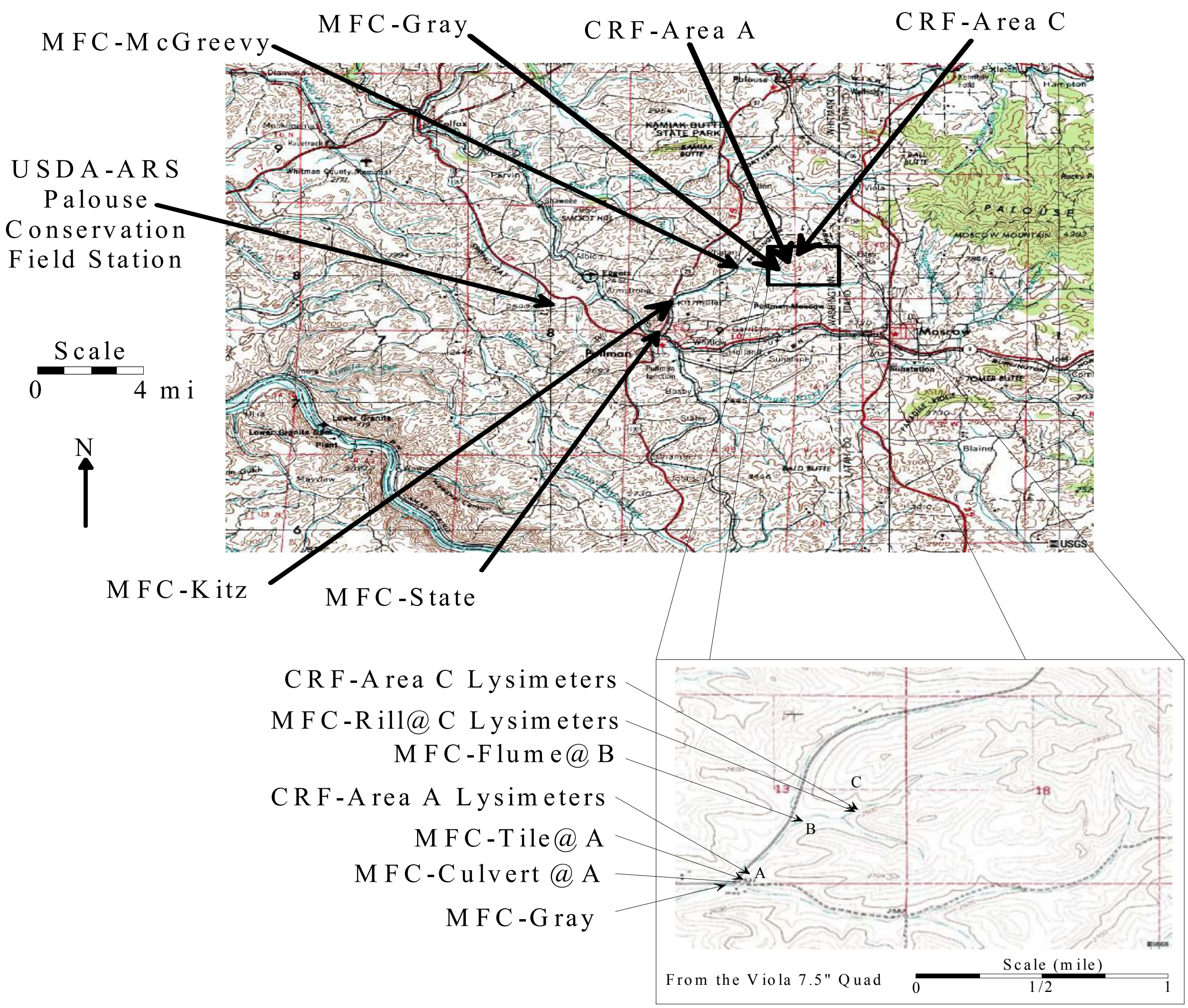


Figure 1. Location Map (source: http://terraserver.homeadvisor.msn.com/default.asp)

Soil conditions are monitored at each of the fields. Soil water content and temperature are continuously recorded by dataloggers, with the exception of soil temperature at ARS, which is monitored manually. In addition, ground water levels are monitored manually at several piezometers on a biweekly basis.

Weather data, including, at a minimum, air temperature, solar radiation, and precipitation, is continuously collected at ARS and CRF. In addition, a composite precipitation sample is collected monthly at CRF-Area A for $\delta^{18}O$ analysis.

In addition to tracer-based modeling, the predictive capabilities of several other transport-model based techniques will be tested against system response. The spatial information for the distribution of the soil units in the study area was obtained from the Soil Survey Geographic database (SSURGO). These data are available in digital format up to the county level. A Digital Elevation Model (DEM) for the study area was obtained from the USGS. The data have been transformed from the SDTS standard format into ArcView format and are now being merged together with the attribute data to compile a complete digital map for the study area. Three models were selected. These are (1) CHAIN_2D, a research model (Simunek and Van Genuchten, 1994); (2) PRZM-2, a management model; and (3) SCI-GROW, a screening model. The EPA uses both PRZM-2 and SCI-GROW models for pesticide registration purposes. Model testing for CHAIN-2D and PRZM-2 has started and the required input parameters are presently being obtained from the Soil Survey Manual (Soil Survey Staff, 1983).

The DEM will be used to calculate several topographic functions (e.g. elevation, slope, aspect, and solar radiation) that will be used with the other chemical and physical properties to evaluate the effect of the spatial variability found within the field and between field and basin scales on transport processes. We will calibrate and validate the models at the field and basin scales using data generated by this project. The performance of the three selected models will be tested and evaluated considering the amount of required data input. The effect of uncertainty in data overlay maps especially for the delineation of the soil map units and the subsequent effect on solute transport will also be determined.

SUMMARY OF ACTIVITIES DURING THIS YEAR

During the past year, effort has been concentrated in the following areas:

1. continued monitoring of the previously instrumented field (ARS);
2. addition of lindane to standard organic analysis method;
3. instrumentation (piezometers, lysimeters, water content reflectometers and temperature probes) of two additional fields (CRF-Area A and CRF-Area C);
4. installation of eight (8) flow gauging stations (two ephemeral streams, one tile drain, two culverts on the MFC tributaries and three bridge locations on MFC);
5. installation of a weather station, including collection of rainwater samples;
6. compilation of a complete digital map for the study area.

The fieldwork began in June, 2000. Monitoring of the ARS field (Figure 1) that had previously been instrumented at its outflow (Robert, 1999), commenced in fall 1999. Stream gauging started during the summer of 2000 along Missouri Flat Creek and its tributaries (Figure 1). Because of the ongoing drought and consequent low flow this year, rating curve data are limited for this year.

The water year (defined as August though July) 1999-2000 provided a relatively continuous set of water samples for the ARS field. The severity of the winter and the early onset of the current on-going drought, have limited the number of samples for the current water year (2000-2001). A table of samples collected since June, 2000, is attached (Table 1).

<u>RESULTS TO DATE</u>

Preliminary stream discharges are presented in Figures 3 and 4. Surface water flow is intermittent. Peak flow is usually observed during spring.

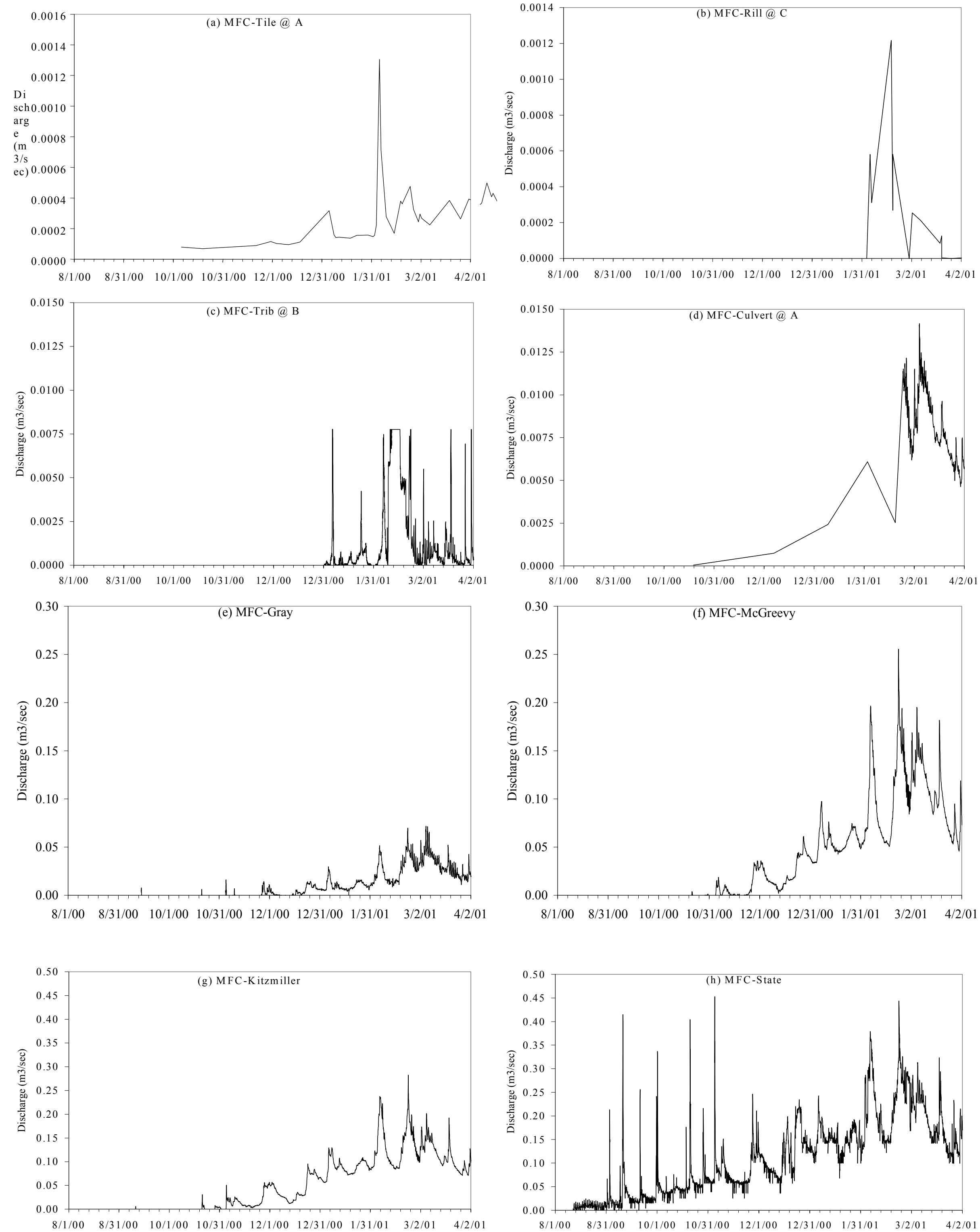


Figure 3. Discharge measured at the drain tile, and Missouri Flat Creek and its tributaries.

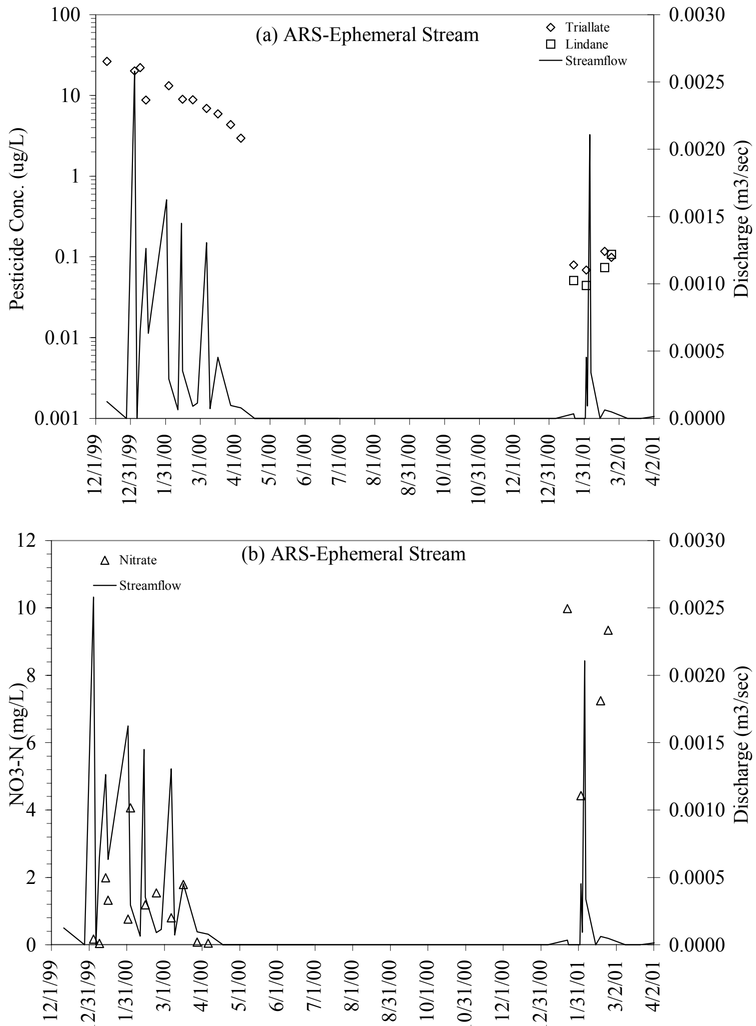


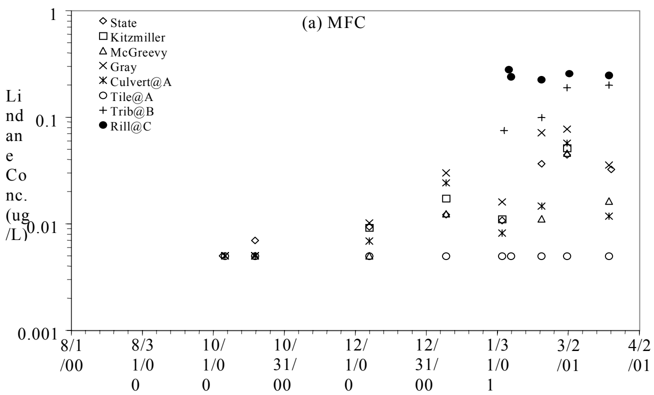
Figure 4. Pesticide (a) and nitrate (b) concentrations in the ARS ephemeral stream. Nitrate concentration is lower during 1999-2000 because there was no fall application, compared to 2000-2001 when N fertilizer was applied in October, 2000. Triallate concentration is ~ 50 fold greater than that observed by the USGS in the Palouse River at Hooper during the same period.

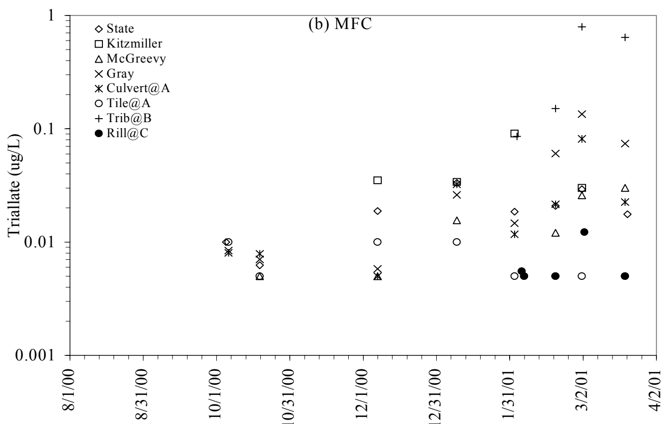
Pesticide Concentrations

The maximum triallate concentration measured in the ARS ephemeral stream (26.3 μg/L, Figure 4a) is much greater than the annual maximum concentration observed in stream flow in the Palouse River at Hooper (< 1 μg/L). This ARS stream concentration is approximately two orders of magnitude greater than the Canadian aquatic chronic standard (CACS) of 0.24 μg/L. The triallate concentrations in the ephemeral stream (Figure 4a) have been declining following a first-order trend since November, 1999 (the month of Far-Go® application), and are within an order of magnitude of a recent observation in the Palouse River at Hooper (0.035 μg/L on 2/6/01). The ephemeral stream lindane concentration is similar to the triallate concentration during the 2000-2001 water year, despite differences in application (Figure 4a).

The relatively monotonic, first-order decline in triallate concentration with time in the ARS stream despite highly variable flow suggests that temporal concentration variability observed in the Palouse River at Hooper may result principally from flow variation within and/or between fields. This observation provides key information for the modeling. This hypothesis will be examined during the subsequent year.

The triallate concentration in the unplowed ephemeral stream at the CRF (during this first year following application) is much lower, ~0.1 to 1 µg/L (Trib @ B, Figure 5b), compared to the ARS ephemeral stream during the first year after application. Interestingly, triallate has not been detected in the plowed ephemeral stream at CRF (Rill @ C), and the reasons underlying this unexpected outcome are currently under study.





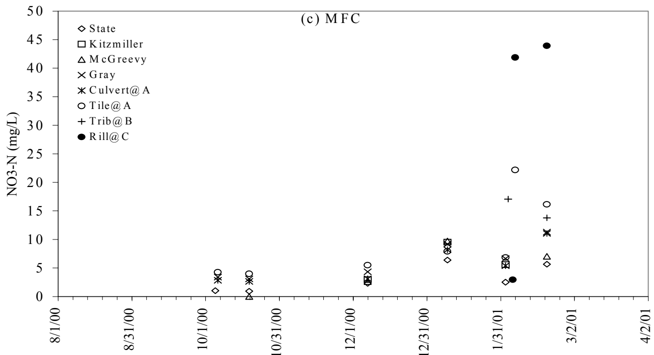


Figure 5. Lindane (a), triallate (b) and nitrate (c) concentrations in Missouri Flat Creek and its tributaries. Note triallate detection limit is 0.005 □g/L, except between 6/2000 and 1/2001 during which it was 0.010 □g/L. Lindane detection limit was 0.005 □g/L.

Triallate and lindane concentration trends along Missouri Flat Creek and its tributaries (Figure 5a, b) generally: increase with increase in seasonal discharge (Figure 3), and decrease with increasing drainage area (Table 2). Neither compound was detected in the tile drain. The triallate concentrations only exceed the CACS during the month of February at MFC-Trib @ B. The observed trends are consistent with a primary source of pesticide that originates from field runoff each year. The exceptions that cannot be explained by this process are the October detections of triallate at a few of the MFC sampling locations (Figure 5b). These detections occurred nearly two months preceding discharge from any of the ephemeral streams (ARS, MFC-Rill @ C and MFC-Trib @ B). Another transport mechanism must explain detections in those samples.

The highest lindane concentration reported to date is 0.280 µg/L at MFC-Rill @ C. The lindane concentration in samples collected from MFC-Rill @ C, MFC-Trib @ B, and the ARS ephemeral stream February samples are at or above the USEPA’s Title 4 Subchapter D Part 131 Freshwater Criteria Continuous Concentration (CCC) of 0.08 µg/L. (The CCC is the highest concentration of a pollutant to which aquatic life can be exposed for an extended period of time (4 days) without deleterious effects.)

The triallate concentration pattern in pore water at the ARS provides information on the physics of the hydrologic system as well as information on pesticide transport. Triallate was detected in lysimeters at all depths as the ARS field soil wetted following application (Figure 6) demonstrating chemical transport to as much as ~1.2 m depth. Because triallate was not applied to this field during the three years prior to the present study (at minimum) to our knowledge, and because of the much lower response during the second season after application, the pattern indicates mass movement from near surface to > 1 m depth within a very short time after application, almost certainly by a preferential flow path. The intermittent detections between all the lysimeters irrespective of depth is consistent with transport associated with mobile particles, whose movement is enhanced during intermittent wetting. After approximately early February 2000, the concentration pattern observed in the lysimeters changed - higher concentrations (~0.1-1.0 µg/L) were present in the shallow lysimeters and concentrations declined towards the detection limit and remained low in pore water from the middle and deep lysimeters (Figure 6). The variability between replicate lysimeters at the same depth also diminished at the same point in time. The relatively abrupt transition in the concentration patterns with time and depth will be discussed later in the report.

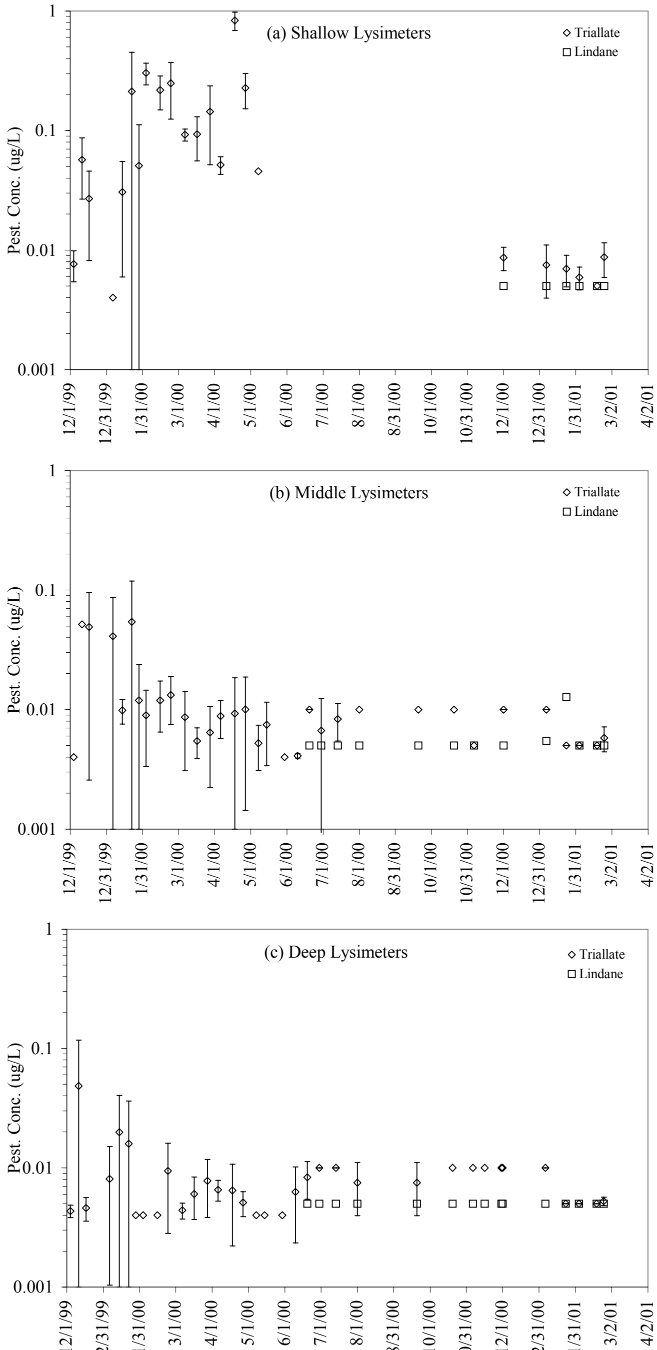


Figure 6. Pesticide concentrations at ARS in (a) shallow (18 cm), (b) middle (83 cm) and (c) deep (118 cm) lysimeters. Error bars indicate one standard deviation between pore water results of replicate lysimeters at a particular depth and indicate spatial variability (rather than analytic error). Note triallate detection limit is 0.005 µg/L, except between 6/2000 and 1/2001 during which it is 0.010 µg/L. Lindane detection limit is 0.005 µg/L.

Because of the drought, few of the lysimeters produced water at the CRF. The limited samplers from which pore water could be obtained indicate a triallate concentration at or slightly above the detection limit (Figure 7b). Lindane results were similar with exceptional higher concentration noted during Februrary to early March (Figure 7a). The samples described were collected from the ceramic suction cup lysimeters. Because of drought conditions, we have been unable to compare the response of the different lysimeter types, as planned.

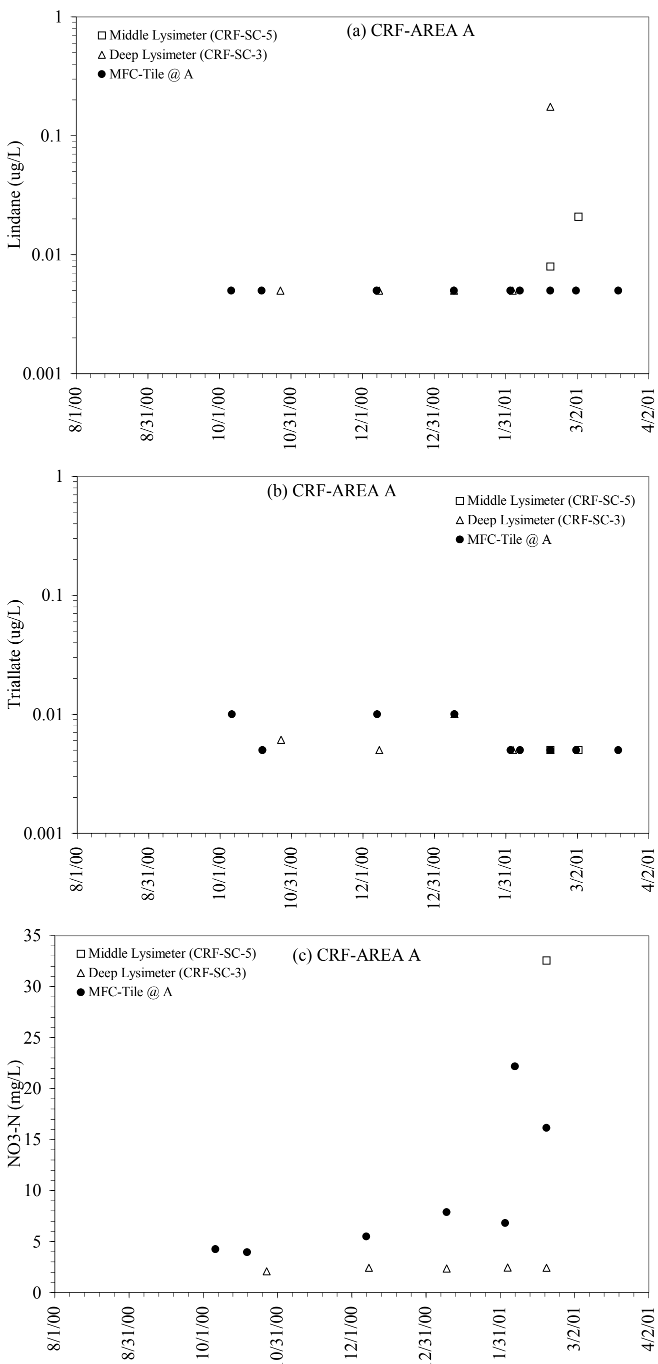
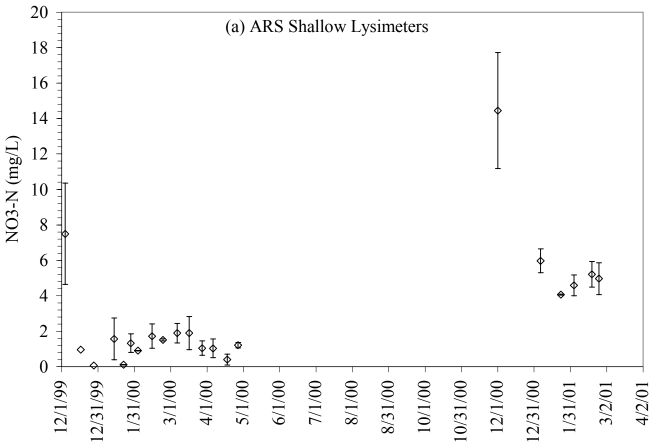


Figure 7. Lindane (a), triallate (b) and nitrate (c) concentrations at CRF-Area A Field (tile-drained) in CRF-SC-5 (middle lysimeter at 45 cm) and CRF-SC-3 (deep lysimeter at 85 cm) ceramic-cup suction lysimeters. Note triallate detection limit was 0.010 g/L on 1/9/2001.

Nitrate Concentrations

Nitrate concentrations in stream flow show distinctly different patterns compared to the pesticides (Figures 4b and 5c). At the local watershed scale at the ARS, the winter nitrate concentration in 1999/2000 is a little lower than those observed for Hooper, and a little greater in 2000/2001, probably due to the Fall 2000 application timing. At the CRF, nitrate concentrations for the local watershed scale represented by MFC-Rill @ C and –Trib @ B are much greater than those observed at the ARS field, up to 44 mg-N/L following the winter thaw. Interestingly, the nitrate concentration observed in tile discharge (MFC-Tile @ A) also increased substantially following the winter thaw (late January, Figure 5c). Increased nitrate concentration at the stations draining larger portions of the MFC watershed appear to increase (compared to fall) prior to the winter thaw. The timing of the increased nitrate concentration at these locations may correspond more closely to the timing of increased discharge in the tile drain, than to increases in both water discharge and nitrate concentration that occurred coincident with the winter thaw. Concentrations in the samples collected in MFC-Rill @ C (up to 44 mg-N/L), MFC-Trib @ B (up to 33.8 mg-N/L) and MFC-Tile @ A (up to 22.7 mg-N/L) were above the MCL (10 mg/L).

Data from the CRF and ARS lysimeters (Figures 7c and 8) and several recent reports show that pore water below the root zone from a number of different local field sites also contains nitrate at a concentration comparable to that detected in local stream discharge (Geyer et al., 1992; Schultheis, 2000; Kafka, 1995). Furthermore, soil core data (not shown) show a large reservoir of N stored in the soil (Geyer et al., 1992; O'Brien et al., 1996; Kafka, 1995; Smith, unpublished data). The ARS lysimeter data also appear to respond dynamically to the winter thaw, discussed further below.


(a) ARS Shallow Lysimeters
NO3-N (mg/L)
0
2
4
6
8
10
12
14
16
18
20
12/1/99
12/31/99
1/31/00
3/1/00
4/1/00
5/1/00
6/1/00
7/1/00
8/1/00
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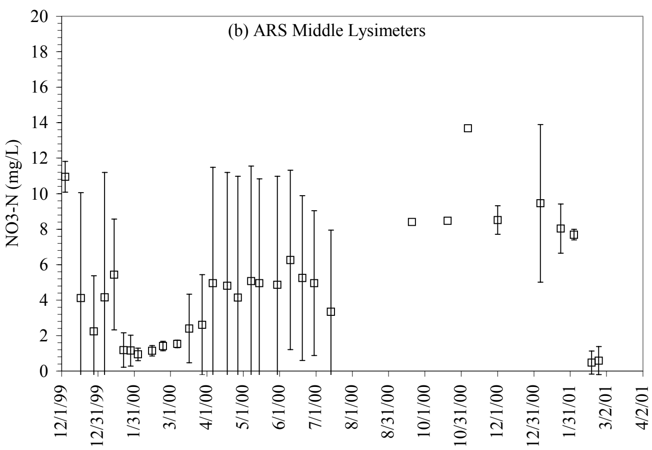
3/2/01
4/2/01


(b) ARS Middle Lysimeters
NO3-N (mg/L)
0
2
4
6
8
10
12
14
16
18
20
12/1/99
12/31/99
1/31/00
3/1/00
4/1/00
5/1/00
6/1/00
7/1/00
8/1/00
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3/2/01
4/2/01

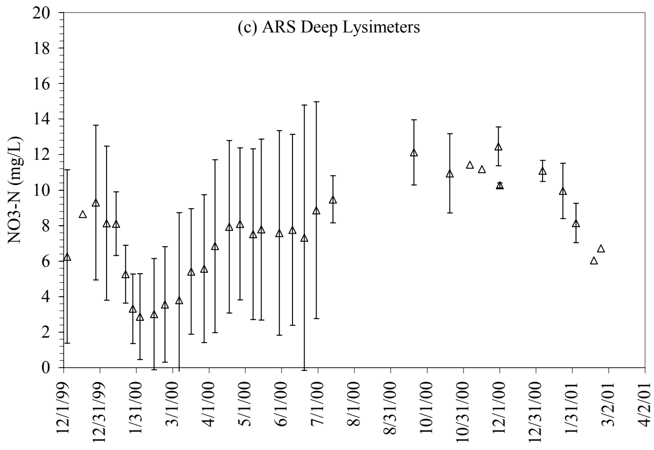
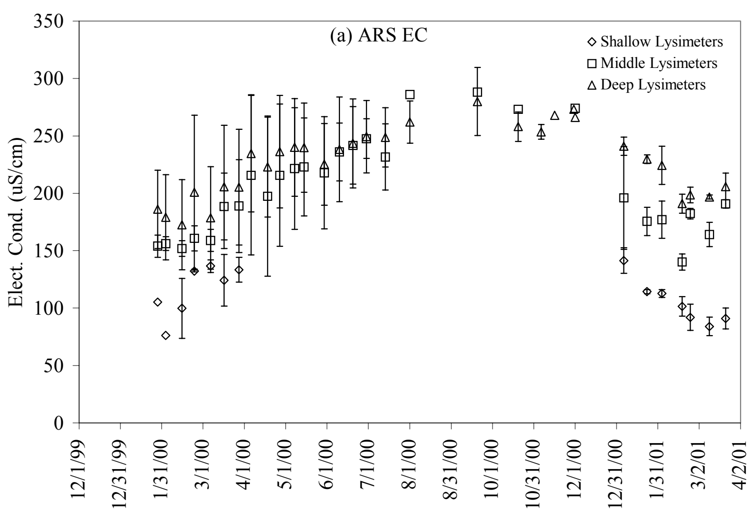


Figure 8. Nitrate concentrations at ARS in (a) shallow (18 cm), (b) middle (83 cm) and (c) deep (118 cm) lysimeters. Error bars indicate one standard deviation of pore water results from replicate lysimeters at a particular depth and indicate spatial variability (rather than analytic error).

Environmental Tracers

At the field scale, the ARS EC and dissolved silica (Figure 9a, b) indicate a decline in concentration during the fall as the soil wets and a slow increase following a minimum in late January to early February, corresponding to a brief thaw, in each of the two monitored water years. In general, pore water increases in both EC and silica with depth in the system. At CRF field A, the silica trend described for the ARS is observed, however, the limitations resulting from drought impacts are obvious (e.g. ~10% of pore water samplers functioning) (Figure 10). Temporal trends cannot be observed in the Area C data because of the limited number of results available at this time (Figure 11). The EC is generally greater at CRF than at ARS.



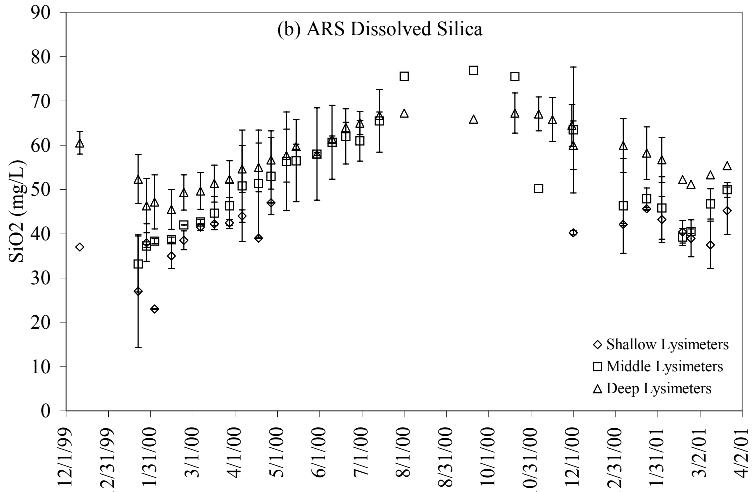
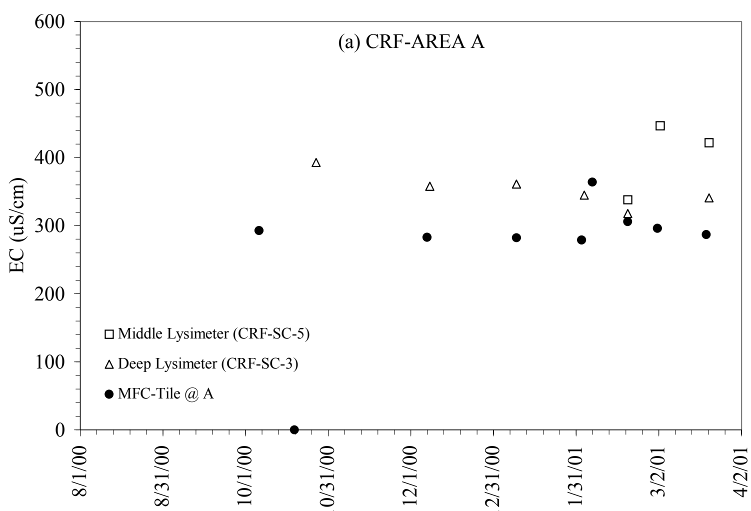


Figure 9. Environmental tracer [(a) electrical conductivity, and (b) dissolved silica (as SiO_2)] concentration in soil pore-water at ARS. Error bars indicate one standard deviation of pore water results from replicate lysimeters at a particular depth and indicate spatial variability (rather than analytic error).



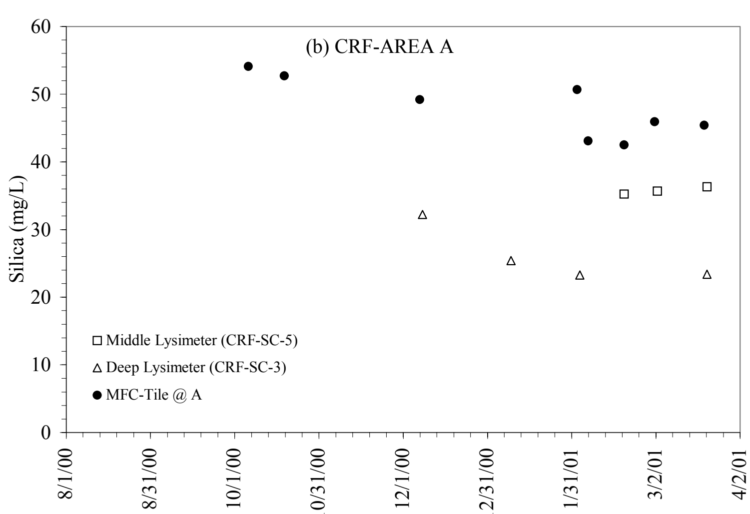


Figure 10. Environmental tracer [(a) electrical conductivity and (b) dissolved silica (as SiO_2)] concentration in soil pore-water at CRF-Area A Field (tile-drained) in CRF-SC-5 (middle lysimeter at 45 cm) and CRF-SC-3 (deep lysimeter at 85 cm) ceramic-cup suction lysimeters.

In comparison, the dissolved silica concentrations in surface water (Figures 9, 11 and 12) exhibit an overall decline with time that appears to be associated with increased flow (Figure 3). As a group, the EC concentrations in surface waters are relatively uniform with time (Figure 12a). The tile drain usually has the greatest silica concentration at a particular sampling time compared to the other surface waters shown on Figure 12b. The silica concentration in the ephemeral streams (ARS, MFC-Rill @ C, MFC-Trib @ B) are generally at the low end of the range.

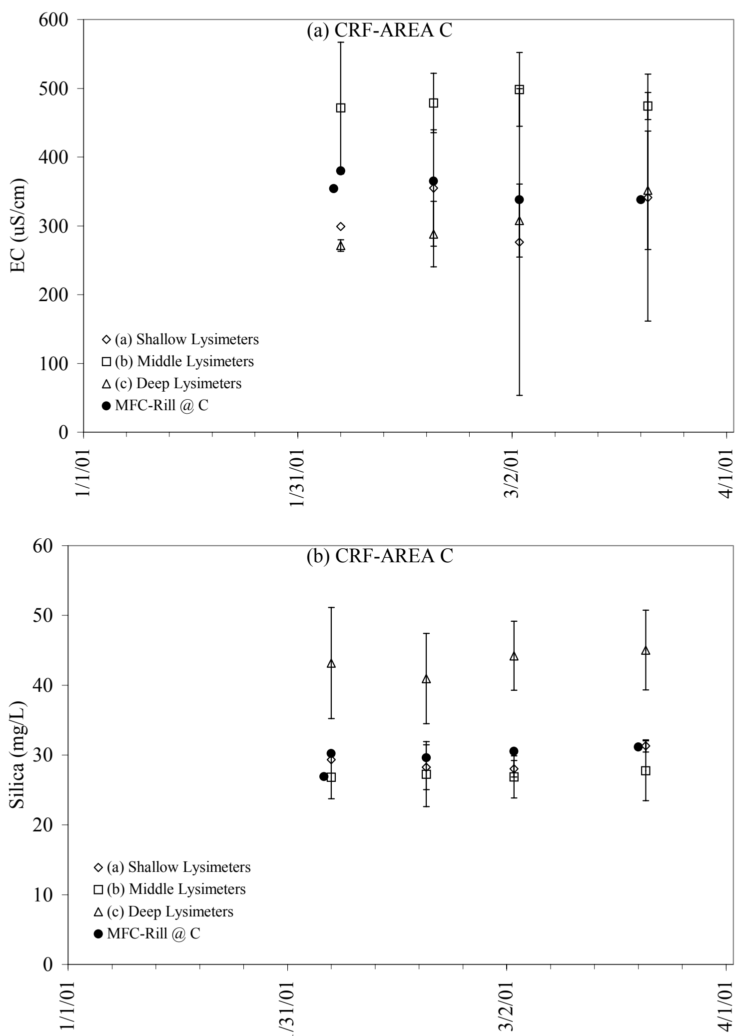


Figure 11. Environmental tracer [(a) electrical conductivity and (b) dissolved silica (as SiO_2)] concentration in soil pore-water at CRF-Area C. All results are from ceramic suction-cup lysimeters

with the exception of the Rill @ C, which is the emphemeral stream that develops on this field. Error bars indicate one standard deviation of pore water results from replicate lysimeters at a particular depth and indicate spatial variability (rather than analytic error).

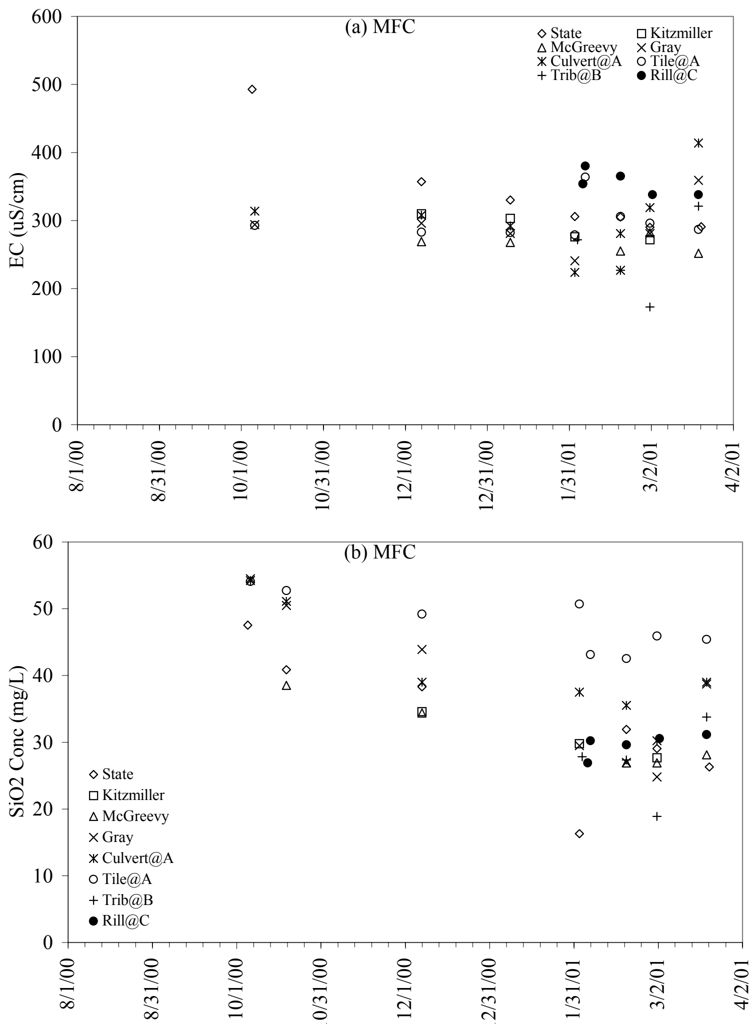


Figure 12. Environmental tracer [(a) electrical conductivity and (b) dissolved silica (as SiO_2)] concentration in Missouri Flat Creek and its tributaries.

While silica and EC provide positive evidence of transmission through soil or ground water indicating longer residence times, stable oxygen isotope measurements are investigated with a goal to constrain residence times for waters in the shallow/fast flowing compartments of the system. The stable isotopic composition of precipitation varies seasonally by more than 15 ‰ in $\delta^{18}O$ (Larson et al., 2000). Preliminary analyses of ARS samples (Figure 13) indicate the pore water from shallow lysimeters exhibits a seasonal evolution from colder (lighter) to warmer (heavier) precipitation and increased mixing (resulting in more stable values in the subsurface). The surface water data set indicates a dynamic system dominated by storms. In contrast to the two above, the deeper pore waters (from deep lysimeters) show more stable ^{18}O ratio throughout the year that are consistent with shallow ground water values (Larson et al., 2000). The depression of approximately 1‰ $\delta^{18}O$ in early February is approximately coincident with the silica and EC minima for the same samples.

We hypothesize that this ~-1 ‰ shift is attributable to rapid vertical movement associated with the early winter thaw. Additional samples, including precipitation samples and Palouse River at Hooper samples, will be analyzed later this summer.

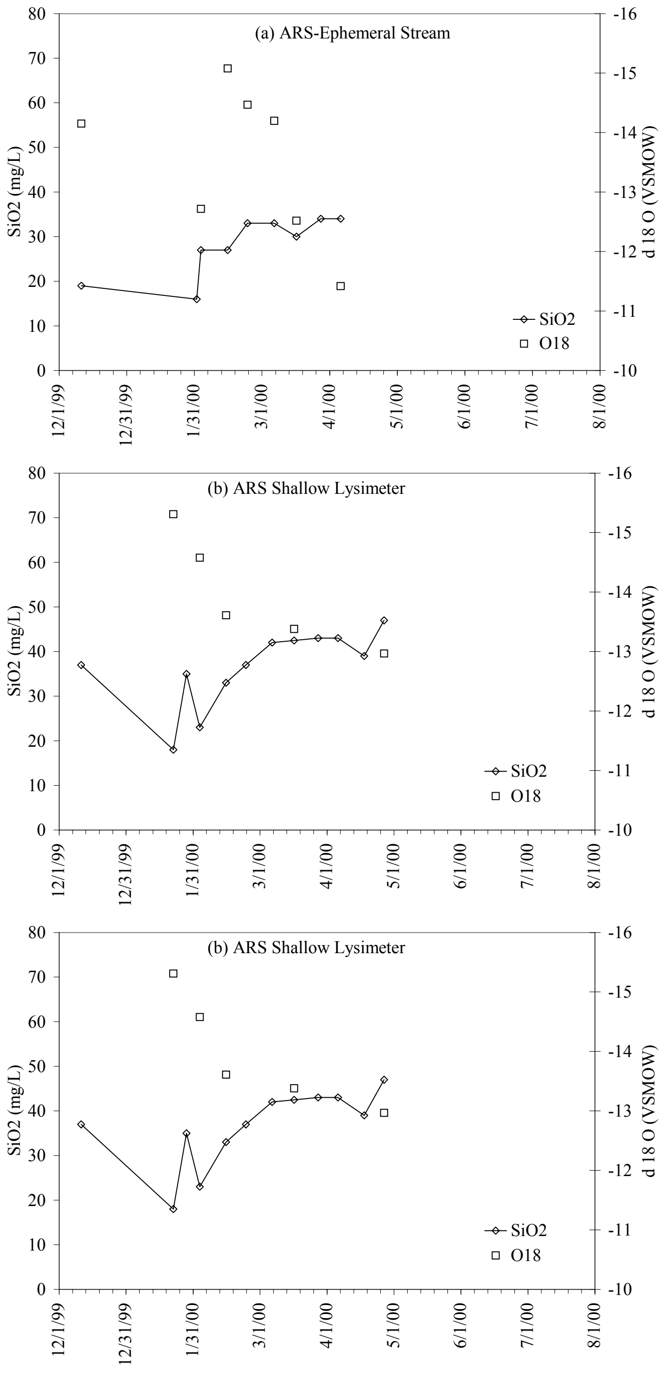


Figure 13. Environmental tracer [dissolved silica (as SiO_2) and $\delta^{18}O$ in (a) the Ephemeral stream, (b) a shallow lysimeter (ARS-LYS #2) and (c) two deep lysimeters (ARS-LYS #7 and #9)] concentration in representative soil pore-waters and surface runoff at ARS.

Discussion

Temporal Pore-water Concentration Dynamics

Preliminary comparisons between potential tracers and nutrient concentrations suggest a high correlation in field-scale data. Both dissolved silica and EC (representing total dissolved solids) are generally expected to increase with mineral weathering in soil. At the field scale, we find a positive correlation between dissolved silica and EC and a general trend of increasing content with depth (Figure 14a), supporting the notion that dissolved silica and EC contain information about residence time in the soil system. The relation between dissolved silica and nitrate at the field scale indicates that the two parameters are apparently uncorrelated in water with relatively short residence time (EC <175 µS/cm) and containing low nitrate as typified by the ephemeral stream and shallow lysimeter samples (Figure 14b). However, dissolved silica and nitrate are positively correlated suggesting a mixing relation for most middle and deep lysimeter samples (EC >175 µS/cm; Figure 14b) during the 1999-2000 water year. (Note that application of nitrogen to the field combined with few samples analyzed to date from middle and deep pore-water samplers causes the dissolved silica-nitrate relation to be poorly defined for the 2000-2001 water year at the present time. Data not shown). Because the subsurface lysimeter nest is located at a toe-slope field position, nitrate resident in shallow soils throughout the field may contribute to the deeper nitrate pool detected in the middle and deep lysimeters.

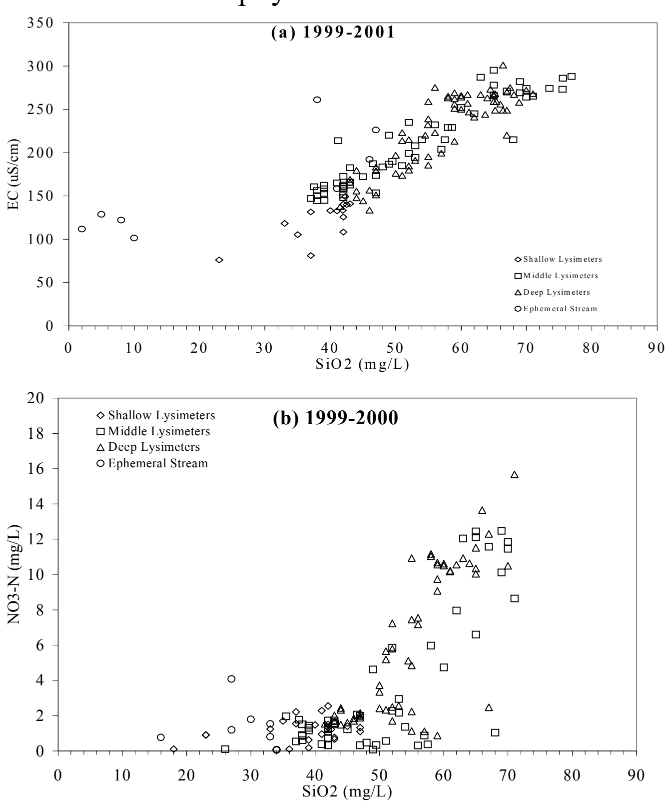


Figure 14. Comparison of field tracers in soil pore water and surface runoff at the ARS field. (a) comparison of EC and dissolved silica for the period 1999-2001, and comparison of nitrate and dissolved silica (as SiO_2) for the period (b) 1999-2000 and (c) 2000-2001.

There is an observed positive correlation between soil EC and soil nitrate in Palouse surficial deposits (Smith, unpublished data). Comparison of EC and nitrate in lysimeter samples collected at ARS and CRF-Area C indicate that this correlation is also present in pore water collected from the middle and deep lysimeters (Figure 15). This relationship is not observed in ephemeral stream data for the same fields (data not shown).

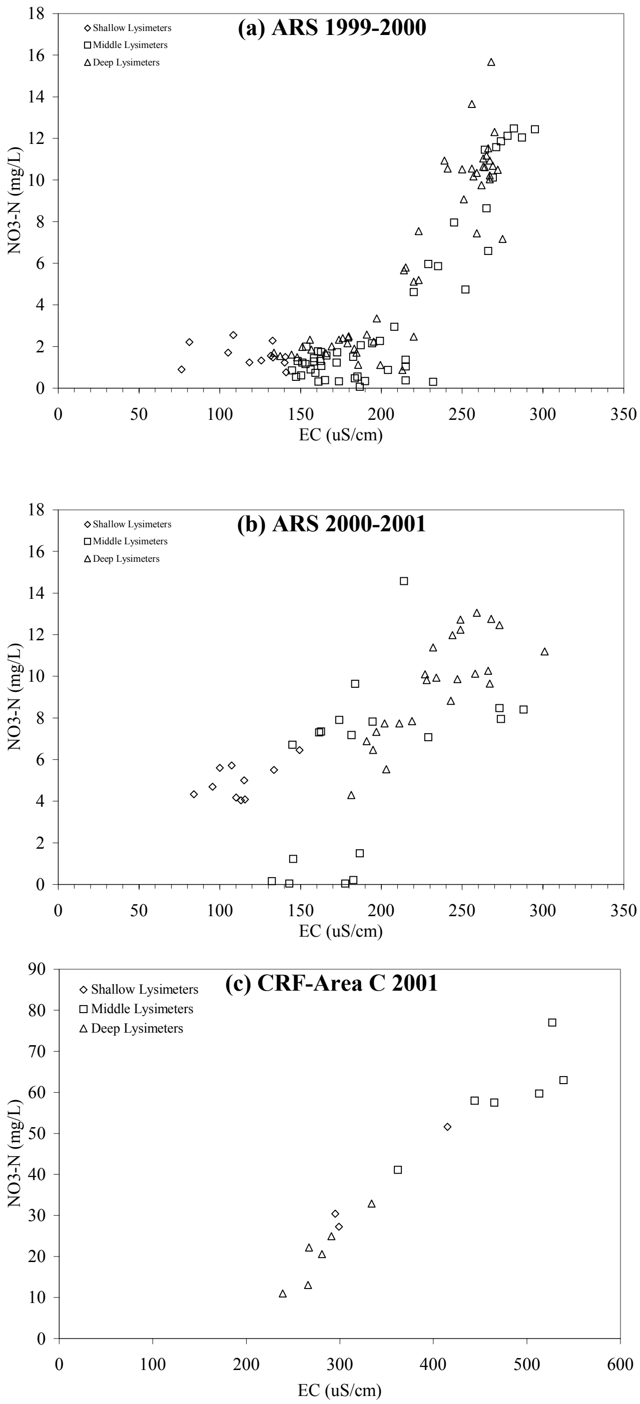


Figure 15. Comparison of EC and nitrate in soil pore water at the monitored fields: (a) ARS for the period 1999-2001, (b) ARS for the period 1999-2000, and (c) CRF-Area C for period 2000-2001.

The concentration patterns for the pesticides strongly suggest transport along preferential flowpaths, as one might expect in a loess soil (e.g. Flury, 1996, Barbash and Resek, 1996; Tsuboyama et al., 1994). Triallate is detected in pre water from all of the middle and deep lysimeters within the first few samplings. Although the concentrations are low compared to those detected in samples from the shallow lysimeters later in the year, they are clearly greater than the detection limit (~5 to 10 fold). Early arrival of triallate is consistent with movement though preferential flow paths and with extensive work by others describing the movement of hydrophobic compounds through structured soils (e.g. Shipitalo and Edwards, 1996; Flury et al., 1995; Flury et al., 1998; Clendening et al., 1990; Flury, 1996; Li and Ghodrati, 1997). Palouse soils become extremely wet, near saturation, between late fall and early summer (e.g. Bacon, 1997), allowing these preferential pathways (i.e. macropores) to become active preferential flow paths. Furthermore, because of relatively high sorption (compared to more soluble compounds), triallate may also be subject to particle-assisted transport. Colloid transport is favored during intermittent soil wetting (El Farhan et al., 2001). Masse et al. (1998) found that pesticide migration was greater under no-till cultivation than under conventional tilling. The soil conditions at the ARS field during November 1999-January 2000 are consistent with and favor particle-associated vertical movement of triallate through preferential flow paths during wetting.

The presence of triallate soon after application during wet years provides evidence that water and solutes can be transported rapidly deeper within the system, but because of reaction, the triallate chemical signature does not allow estimation of the mass of water moved by this pathway. The signature observed for the other tracers suggests that they can provide this information. By ~late January of each of the two study years, the nitrate, EC and silica concentrations (Figures 8 and 9) in the middle and deep lysimeter pore water declined by ~>30% at the ARS field. Although the decline varied among lysimeters at each depth, the covariance of all three (Figures 14 and 15) implies influx to depth of water with a relatively low residence time. During early February, 2001, the relatively sharp decline in tracer concentration corresponded to several pieces of physical evidence that corroborate a flush of relatively low residence time water entering deeper portions of the subsurface: the shallow soil temperature increased (>0.5 ^{o}C), the shallow water table rose ~ 9 cm, and there was a large precipitation event which occurred coincident with temperatures above freezing for approximately 2 days. More limited direct physical evidence for the winter thaw in 2000 suggests consistent behavior between the two years. A coincident subtle decrease in δ^{18}O in the deep lysimeter pore water is also consistent with vertical movement of warmer water (e.g. ephemeral stream <-13 ‰ δ^{18}O).

Steadily increasing pore water nitrate, silica and EC concentrations following the early winter thaw were due either to a progressive exchange and weathering, or to mixing and gradual displacement of the earlier influx by upslope pore waters. Correlations between EC, silica, and nitrate concentrations are consistent with the latter. The pattern of pore water triallate occurrence suggests a change from non-equilibrium preferential vertical transport (before ~February 2000) to saturated, predominantly lateral transport along during soil horizons following the "flush." This interpretation is further corroborated by the stream hydrograph patterns.

Tracers in Stream Waters

Turbidity was collected as a surrogate for suspended solids content at the surface water sampling sites. A preliminary comparison of the pesticide and turbidity data (Figure 16a, b) suggests that there may be positive correlation for some of the sampling sites along the river (e.g. triallate at MFC-Trib @ B, MFC-Gray and MFC-McGreevy), but not at all sampling stations. In particular, the trends for MFC-State and MFC-Kitzmiller demonstrate that a simple correlation is not sufficient to explain the observed concentration patterns.

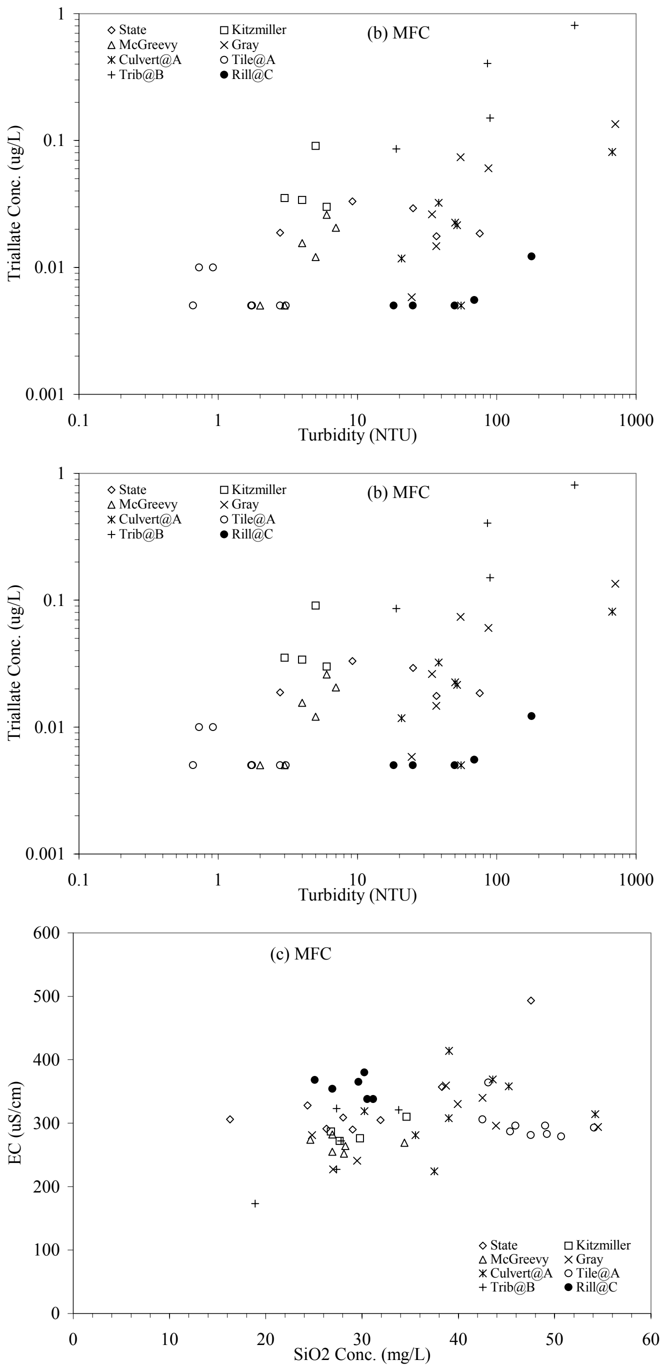


Figure 16. Comparison of field tracers in surface water at MFC. Comparison between (a) lindane or (b) triallate with turbidity, and (c) comparison between EC and dissolved silica (as SiO_2).

Stream chemistry for the range of drainage-scales studied does not show a simple correlation between EC and dissolved silica concentration (Figure 16c). For each sampling location, there appears to be greater variability in silica concentration than EC. The observed patterns also suggest that a combination of temporally variable system hydrology and chemistry must be considered to interpret the signal. The planned modeling activities during the next year will make use of this data to test our hypotheses about groundwater and surface runoff contributions to stream flow.

Mass Discharge and Stream Water Concentration Patterns

The annual triallate mass discharge following the fall application for the ARS field is much greater than that reported for the watershed as a whole (Figure 17a). These data suggest that surface runoff from fields, which are not tile drained, may be a critical pathway for non-point pesticide transport to surface water in this region. Because water discharge from the ARS ephemeral stream is discontinuous, triallate mass discharge is much greater on high compared to low flow days. Furthermore, the highest concentrations of triallate observed in the Palouse River co-occur with high total suspended solids. The above observations strongly suggest that the majority of hydrophobic compound transport can be explained by a surface flow pathway and imply that particle-assisted transport is important. Differences in discharges and maximum concentrations between the field and basin scales are consistent with dilution by a source of water (such as ground water discharge via tile drainage) with lower concentration. Preliminary data for the 2000-2001 water year (Figure 17b) indicate a similar pattern, with the exception that triallate mass flux is much reduced because no additional application was made. The concentration patterns observed in MFC and its tributaries are consistent with most mass entering the drainage system at the field annually.

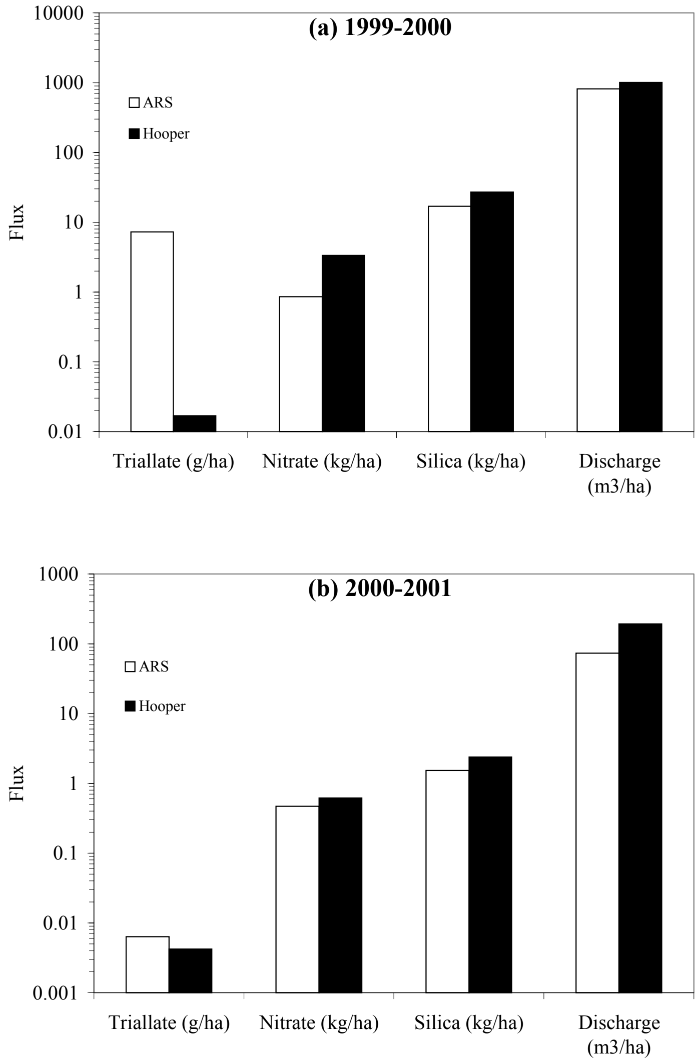


Figure 17. Mass discharge normalized by drainage area (flux) at the field (ARS) and river (Palouse River, Hooper) -watershed scales for the (a) 1999-2000 and (b) 2000-2001 (preliminary/incomplete data) water years. Note the factor of ten difference in the vertical axis between the figures. Discharges are much lower during the 2000-2001 water year primarily because of the drought (rather than incomplete water year). Field data from current work. Palouse River, Hooper estimates bases on USGS NAWQA data.

While the mass discharge for triallate is sufficient to explain mass discharge at the much larger basin scale (e.g. Hooper), the duration of the discharge hydrograph is not. The ephemeral streams (ARS, MFC- Rill @ C, and MFC-Trib @ B) produce water intermittently during only a few months (approximately 4.5 months and < 4 months during 1999-2000 and 2000-2001, respectively). Albeit at a low concentration, triallate was detected in MFC and tributary samples prior to observed flow in ephemeral streams during the 2000-2001 water year. These results suggest that in order to explain the duration of the triallate hydrograph, an additional discharge mechanism must supply mass to the downstream locations. Two possible mechanisms include: particle-bound residues stored in the near-field portion of the watershed drainage system between years, or, material dissolved in tile drainage. Results to date suggest that the former may be more likely.

The surface pathway appears to be strongly affected by application timing of agrochemicals (i.e. soil moisture and temperature, and duration prior to incorporation), stream discharge, and weather (i.e. air temperature and precipitation). This observation is based on a comparison of the agrochemical concentration observed at the field-scale in the streams at the ARS site last year (triallate up to 26.3 μg/L) and at the CRF site this year (triallate up to 0.012 μg/L). Similarly, nitrate concentrations observed at the ARS site were low in 2000 (<1 - 4 mg/L) versus 2001 (4 - 10 mg/L). Fertilizer was not applied on the field in the fall of 1999, instead applications were made during the spring and fall of 2000. Nitrate concentrations at the field-scale increase with increasing discharge, versus at the watershed scale where there is a decreasing tendency at peak flow.

During the 1999-2000 water year, ARS surface runoff accounts for only approximately 25% of the total nitrate flux detected at the watershed scale (Figure 17a). Similarly, silica and water discharge are underestimated. Although simplistic, these observations suggest that the system contains a large subsurface reservoir of nitrate that is supplied at relatively constant concentration to the stream by the watershed during the wet season, regardless of river stage. This concept is consistent with relatively high nitrate concentration (and mass discharge) observed in the tile drainage during the 2000-2001 water year and substantiated by a number of additional measurements and recent reports by our group (e.g. Schultheis et al., 1999; Schultheis, 2000). More rigorous mass discharge analysis for the watershed scales of study will be pursued as the study proceeds.

Summary of Key Points and Continuing Work

The Palouse hydrologic system provides the opportunity to assess surface flow and ground water contributions to non-point pollutant occurrence at the watershed scale. Pesticides define watershed-scale high surface flows and offer a large dynamic range of analysis (>4 orders of magnitude). Geochemical tracers (EC/Si) define ground water flow paths. Stable oxygen isotopes help to resolve flow paths representing intermediate residence times. The combined use of these tracers allows identification and quantitation of the complex dynamic flow system within the Palouse soils. For example, pore-water concentration patterns for nitrate, triallate and the geochemical tracers indicate complex patterns of vertical and lateral flow occur seasonally. Additional targeted analyses and quantitative approaches to interpret the data will be pursued during the coming year.

During the remaining portion of the project, selected monitoring of the instrumented reservoirs will be continued (budget permitting). *To our knowledge, this project will provide the first comprehensive test of the application of multiple tracers to evaluate and quantify watershed flowpaths in a any region outside the mid-continental U.S.* The resulting conceptual framework , based as it is on “off-the-shelf” solute analyses and simple mathematics, can be readily tested and adapted in other regions. The improved understanding of hydrologic transport pathways gained will be used to assess the conceptual model, thus contributing a tool to for watershed planning. The data collected will further be used to test more complex models that “upscale” the various runoff contributions to surface waters. The results of this study will be of use to USGS researchers in assessing methodologies for scale-up from field to large-basin watershed area. Because the approach relies strongly on comparisons between artificially drained and undrained fields, our work will also provide a significant step to compare the importance of these pathways to regional-scale water quality effects in a semi-arid area. Our study will also focus attention on the importance of temporal system dynamics.

ACKNOWLEDGEMENTS

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TABLE 1. Samples collected June 2000-present.

		Sample Collected			
		Location	# of Samples	From	To
CRF	Area A	P-6	1	2/19/01	2/19/01
		SC-3	8	10/27/00	4/16/01
		SC-5	5	2/19/01	4/16/01
		SC-8	1	3/21/01	3/21/01
		SC-9	2	10/27/00	4/16/01
		SS-1	3	3/3/01	4/8/01
		SS-2	4	3/3/01	4/16/01
		SS-4	3	3/21/01	4/16/01
		SS-5	3	3/21/01	4/16/01
		SS-7	4	2/19/01	4/16/01
		SS-8	2	2/19/01	3/21/01
CRF	Area C	SC-10	6	2/6/01	4/16/01
		SC-11	6	2/6/01	4/16/01
		SC-12	6	2/6/01	4/16/01
		SC-14	6	2/6/01	4/16/01
		SC-15	6	2/6/01	4/16/01
		SC-16	6	2/6/01	4/16/01
		SC-17	6	2/6/01	4/16/01
		SC-18	6	2/6/01	4/16/01
MFC		Rill @ C	6	2/5/01	4/12/01
		Trib @ B	5	2/3/01	4/9/01
		Tile @ A	11	10/6/00	4/16/01
		Culvert @ A	10	10/6/00	4/16/01
		Gray Rd	10	10/6/00	4/16/01
		McGreevy Rd	8	10/19/00	4/16/01
		Kitzmiller Rd	5	12/7/00	4/9/01
		State St.	10	10/5/00	4/16/01
ARS		LYS 2	8	6/1/00	4/12/01
		LYS 3	8	6/1/00	4/12/01
		LYS 4	12	6/1/00	4/12/01
		LYS 5	12	6/1/00	4/12/01
		LYS 6	16	6/1/00	4/12/01
		LYS 7	17	6/1/00	4/12/01
		LYS 8	18	6/1/00	4/12/01
		LYS 9	12	6/1/00	4/12/01
		Stream	5	6/1/00	4/12/01

Notes: CRF stands for Cunningham Research Farm (WSU owned farm); Area A is a tile-drained field and Area C a naturally drained field.
ARS stands for Agricultural Research Service (USDA operated farm)
MFC stands for Missouri Flat Creek
LYS are PVC capillary wick lysimeters
P are stainless steel pan lysimeters
SC are ceramic suction cup lysimeters
SS are stainless steel suction cup lysimeters

TABLE 2. Approximate watershed drainage area corresponding to each of the surface sampling sites.

Gaging Station ID	App. Watershed Area (ha)
ARS - Ephemeral Stream	7.5
MFC - Rill @ C	7
MFC - Tile @ A	19
MFC - Trib @ B	150
MFC - Culvert @ A	450
MFC - Gray	600
MFC - McGreevy	6,000
MFC - Kitzmiller	11,000
MFC - State	14,400
Palouse River @ Hooper	650,000*

Note: * value obtained from Williamson et al, 1998.

TABLE 3. Agrochemical applications to study fields.

	Agrochemical Application			
	Triallate	Lindane/Seeding	N Fertilizer	KCl
ARS				
Fall 1999	East: 5 kg/ha West: 5 kg/ha	East: West: winter peas		
Winter 1999				
Spring 2000		East: spring barley West:	East: 113 kg/ha West:	
Summer 2000				
Fall 2000		East: winter peas West: winter wheat	East: West: 108 kg/ha	
Winter 2000				
Spring 2001				
CRF-Area A				
Fall 2000	1.7 kg/ha	Winter wheat	192 kg/ha	
Winter 2000				
Spring 2001				
CRF-Area C				
Fall 2000	1.7 kg/ha	Winter barley	192 kg/ha	
Winter 2000				
Spring 2001				108 kg/ha

Note: Triallate applied as granular Far-Go® and reported as kg of active ingredient.
Lindane application is approximately 0.025 kg/ha for winter wheat.

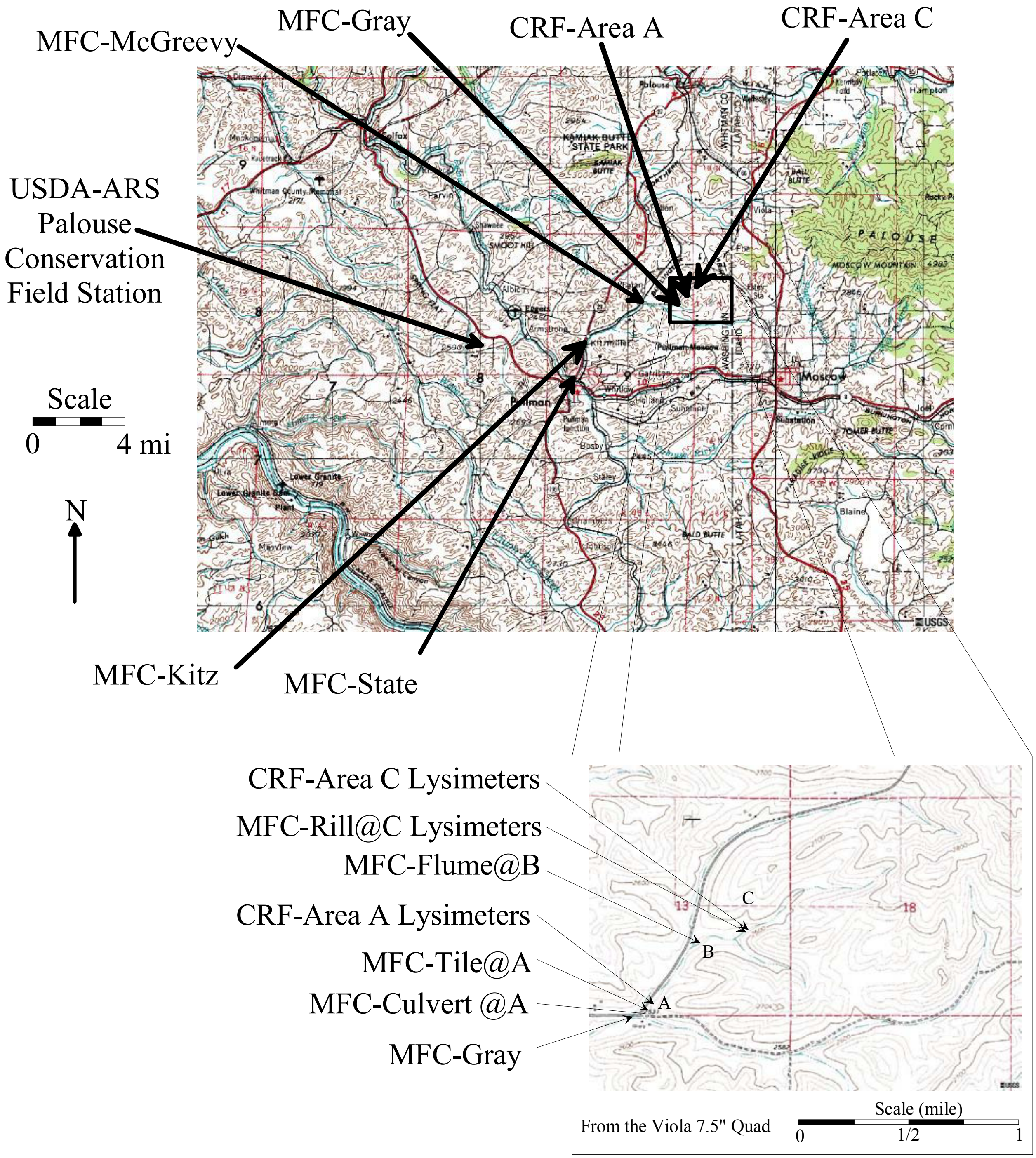
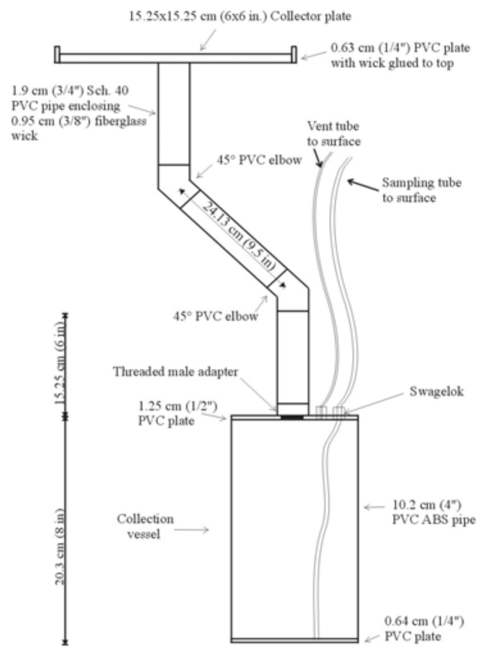


Figure 1. Location Map (source: http://terraserver.homeadvisor.msn.com/default.asp).



(a)

(b)

Figure 2. Types of subsurface water samplers. (a) Diagram of ARS capillary wick lysimeter. (b) Photograph of CRF (from left to right) stainless steel pan, stainless steel suction cup and ceramic suction cup lysimeters

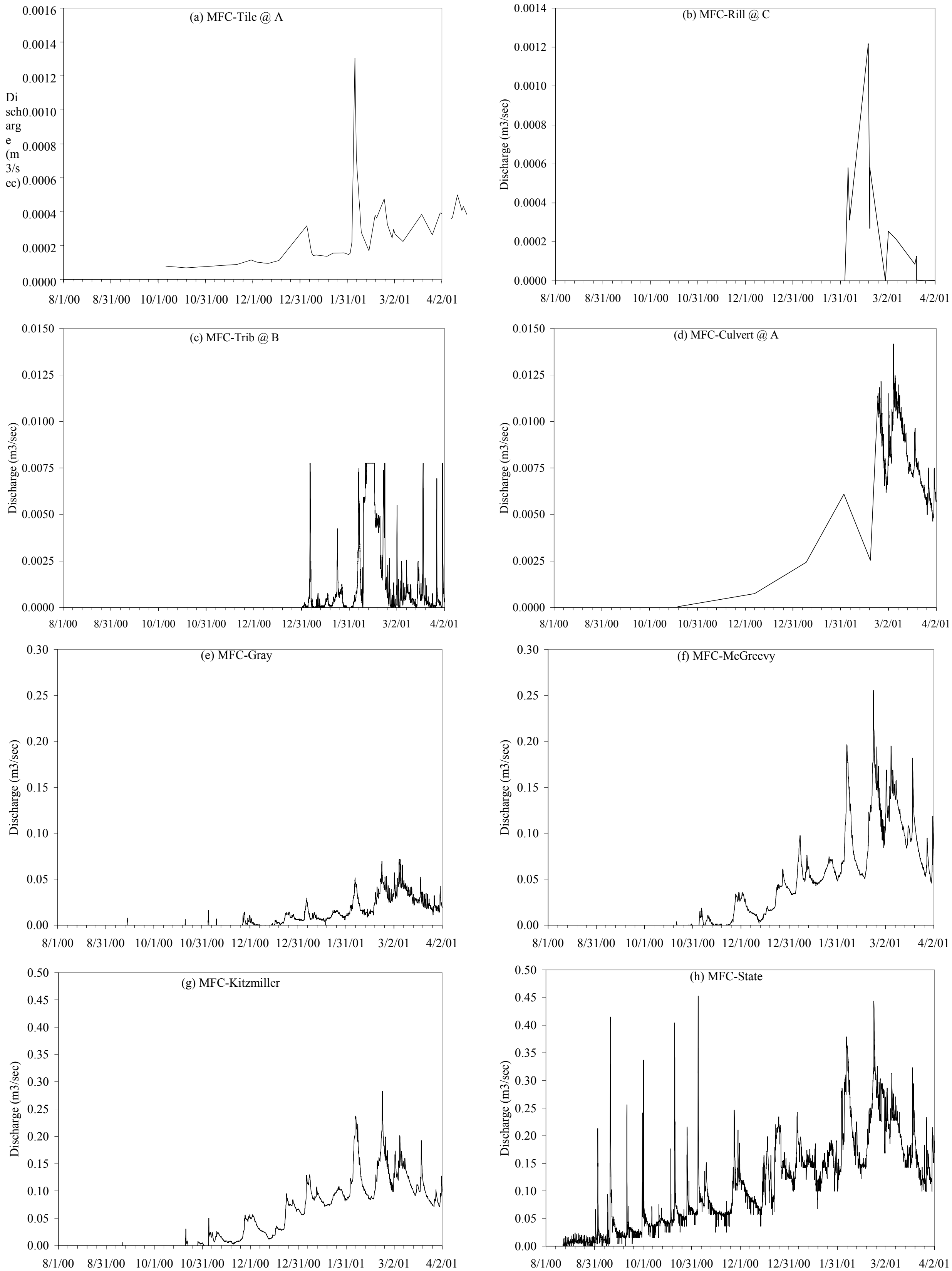
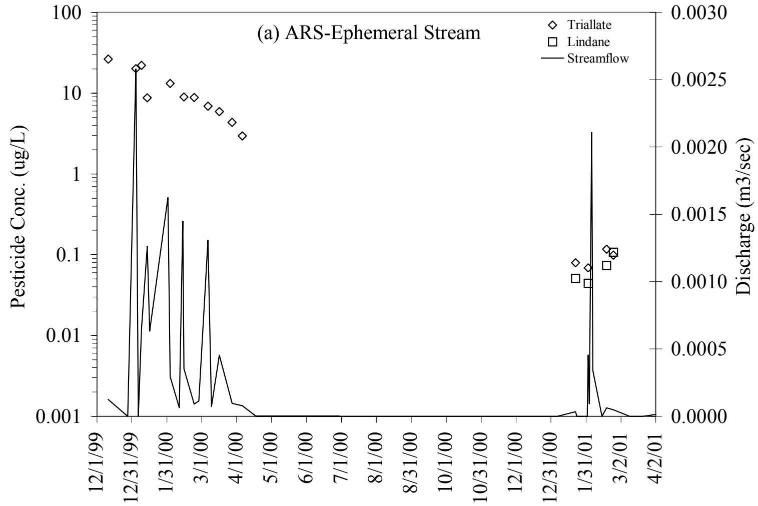
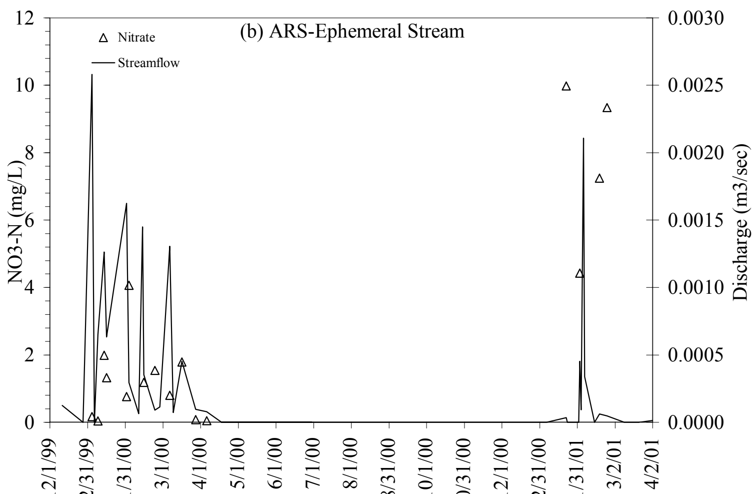


Figure 3. Discharge measured at the drain tile, and Missouri Flat Creek and its tributaries.



(a)



(b)

Figure 4. Pesticide (a) and nitrate (b) concentrations in the ARS ephemeral stream. Nitrate concentration is lower during 1999-2000 because there was no fall application, compared to 2000-2001 when N fertilizer was applied in October, 2000. Triallate concentration is ~ 50 fold greater than that observed by the USGS in the Palouse River at Hooper during the same period.

Pesticide Concentrations

The maximum triallate concentration measured in the ARS ephemeral stream (26.3 μg/L, Figure 4a) is much greater than the annual maximum concentration observed in stream flow in the Palouse River at Hooper (< 1 μg/L). This ARS stream concentration is approximately two orders of magnitude greater than the Canadian aquatic chronic standard (CACS) of 0.24 μg/L. The triallate concentrations in the ephemeral stream (Figure 4a) have been declining following a first-order trend since November, 1999 (the month of Far-Go® application), and are within an order of magnitude of a recent observation in the Palouse River at Hooper (0.035 μg/L on 2/6/01). The ephemeral stream lindane concentration is similar to the triallate concentration during the 2000-2001 water year, despite differences in application (Figure 4a).

The relatively monotonic, first-order decline in triallate concentration with time in the ARS stream despite highly variable flow suggests that temporal concentration variability observed in the Palouse River at Hooper may result principally from flow variation within and/or between fields. This observation provides key information for the modeling. This hypothesis will be examined during the subsequent year.

The triallate concentration in the unplowed ephemeral stream at the CRF (during this first year following application) is much lower, ~0.1 to 1 µg/L (Trib @ B, Figure 5b), compared to the ARS ephemeral stream during the first year after application. Interestingly, triallate has not been detected in the plowed ephemeral stream at CRF (Rill @ C), and the reasons underlying this unexpected outcome are currently under study.

Triallate and lindane concentration trends along Missouri Flat Creek and its tributaries (Figure 5a, b) generally: increase with increase in seasonal discharge (Figure 3), and decrease with increasing drainage area (Table 2). Neither compound was detected in the tile drain. The triallate concentrations only exceed the CACS during the month of February at MFC-Trib @ B. The observed trends are consistent with a primary source of pesticide that originates from field runoff each year. The exceptions that cannot be explained by this process are the October detections of triallate at a few of the MFC sampling locations (Figure 5b). These detections occurred nearly two months preceding discharge from any of the ephemeral streams (ARS, MFC-Rill @ C and MFC-Trib @ B). Another transport mechanism must explain detections in those samples.

The highest lindane concentration reported to date is 0.280 µg/L at MFC-Rill @ C. The lindane concentration in samples collected from MFC-Rill @ C, MFC-Trib @ B, and the ARS ephemeral stream February samples are at or above the USEPA's Title 4 Subchapter D Part 131 Freshwater Criteria Continuous Concentration (CCC) of 0.08 µg/L. (The CCC is the highest concentration of a pollutant to which aquatic life can be exposed for an extended period of time (4 days) without deleterious effects.)

The triallate concentration pattern in pore water at the ARS provides information on the physics of the hydrologic system as well as information on pesticide transport. Triallate was detected in lysimeters at all depths as the ARS field soil wetted following application (Figure 6) demonstrating chemical transport to as much as ~1.2 m depth. Because triallate was not applied to this field during the three years prior to the present study (at minimum) to our knowledge, and because of the much lower response during the second season after application, the pattern indicates mass movement from near surface to > 1 m depth within a very short time after application, almost certainly by a preferential flow path. The intermittent detections between all the lysimeters irrespective of depth is consistent with transport associated with mobile particles, whose movement is enhanced during intermittent wetting. After approximately early February 2000, the concentration pattern observed in the lysimeters changed - higher concentrations (~0.1-1.0 µg/L) were present in the shallow lysimeters and concentrations declined towards the detection limit and remained low in pore water from the middle and deep lysimeters (Figure 6). The variability between replicate lysimeters at the same depth also diminished at the same point in time. The relatively abrupt transition in the concentration patterns with time and depth will be discussed later in the report.

Because of the drought, few of the lysimeters produced water at the CRF. The limited samplers from which pore water could be obtained indicate a triallate concentration at or slightly above the detection limit (Figure 7b). Lindane results were similar with exceptional higher concentration noted during Februrary to early March (Figure 7a). The samples described were collected from the ceramic suction cup lysimeters. Because of drought conditions, we have been unable to compare the response of the different lysimeter types, as planned.

Nitrate Concentrations

Nitrate concentrations in stream flow show distinctly different patterns compared to the pesticides (Figures 4b and 5c). At the local watershed scale at the ARS, the winter nitrate concentration in 1999/2000 is a little lower than those observed for Hooper, and a little greater in 2000/2001, probably due to the Fall 2000 application timing. At the CRF, nitrate concentrations for the local watershed scale represented by MFC-Rill @ C and –Trib @ B are much greater than those observed at the ARS field, up to 44 mg-N/L following the winter thaw. Interestingly, the nitrate concentration observed in tile discharge (MFC-Tile @ A) also increased substantially following the winter thaw (late January, Figure 5c). Increased nitrate concentration at the stations draining larger portions of the MFC watershed appear to increase (compared to fall) prior to the winter thaw. The timing of the increased nitrate concentration at these locations may correspond more closely to the timing of increased discharge in the tile drain, than to increases in both water discharge and nitrate concentration that occurred coincident with the winter thaw. Concentrations in the samples collected in MFC-Rill @ C (up to 44 mg-N/L), MFC-Trib @ B (up to 33.8 mg-N/L) and MFC-Tile @ A (up to 22.7 mg-N/L) were above the MCL (10 mg/L).

Data from the CRF and ARS lysimeters (Figures 7c and 8) and several recent reports show that pore water below the root zone from a number of different local field sites also contains nitrate at a concentration comparable to that detected in local stream discharge (Geyer et al., 1992; Schultheis, 2000; Kafka, 1995). Furthermore, soil core data (not shown) show a large reservoir of N stored in the soil (Geyer et al., 1992; O'Brien et al., 1996; Kafka, 1995; Smith, unpublished data). The ARS lysimeter data also appear to respond dynamically to the winter thaw, discussed further below.

Environmental Tracers

At the field scale, the ARS EC and dissolved silica (Figure 9a, b) indicate a decline in concentration during the fall as the soil wets and a slow increase following a minimum in late January to early February, corresponding to a brief thaw, in each of the two monitored water years. In general, pore water increases in both EC and silica with depth in the system. At CRF field A, the silica trend described for the ARS is observed, however, the limitations resulting from drought impacts are obvious (e.g. ~10% of pore water samplers functioning) (Figure 10). Temporal trends cannot be observed in the Area C data because of the limited number of results available at this time (Figure 11). The EC is generally greater at CRF than at ARS.

In comparison, the dissolved silica concentrations in surface water (Figures 9, 11 and 12) exhibit an overall decline with time that appears to be associated with increased flow (Figure 3). As a group, the EC concentrations in surface waters are relatively uniform with time (Figure 12a). The tile drain usually has the greatest silica concentration at a particular sampling time compared to the other surface waters shown on Figure 12b. The silica concentration in the ephemeral streams (ARS, MFC-Rill @ C, MFC-Trib @ B) are generally at the low end of the range.

While silica and EC provide positive evidence of transmission through soil or ground water indicating longer residence times, stable oxygen isotope measurements are investigated with a goal to constrain residence times for waters in the shallow/fast flowing compartments of the system. The stable isotopic composition of precipitation varies seasonally by more than 15 ‰ in $\delta^{18}O$ (Larson et al., 2000). Preliminary analyses of ARS samples (Figure 13) indicate the pore water from shallow lysimeters exhibits a seasonal evolution from colder (lighter) to warmer (heavier) precipitation and increased mixing (resulting in more stable values in the subsurface). The surface water data set indicates a dynamic system dominated by storms. In contrast to the two above, the deeper pore waters (from deep lysimeters) show more stable ^{18}O ratio throughout the year that are consistent with shallow ground water values (Larson et al., 2000). The depression of approximately 1‰ $\delta^{18}O$ in early February is approximately coincident with the silica and EC minima for the same samples. We hypothesize that this ~-1 ‰ shift is attributable to rapid vertical movement associated with the early winter thaw. Additional samples, including precipitation samples and Palouse River at Hooper samples, will be analyzed later this summer.

DISCUSSION

Temporal Pore-water Concentration Dynamics

Preliminary comparisons between potential tracers and nutrient concentrations suggest a high correlation in field-scale data. Both dissolved silica and EC (representing total dissolved solids) are generally expected to increase with mineral weathering in soil. At the field scale, we find a positive correlation between dissolved silica and EC and a general trend of increasing content with depth (Figure 14a), supporting the notion that dissolved silica and EC contain information about residence time in the soil system. The relation between dissolved silica and nitrate at the field scale indicates that the two parameters are apparently uncorrelated in water with relatively short residence time (EC <175 μS/cm) and containing low nitrate as typified by the ephemeral stream and shallow lysimeter samples (Figure 14b). However, dissolved silica and nitrate are positively correlated suggesting a mixing relation for most middle and deep lysimeter samples (EC >175 μS/cm; Figure 14b) during the 1999-2000 water year. (Note that application of nitrogen to the field combined with few samples analyzed to date from middle and deep pore-water samplers causes the dissolved silica-nitrate relation to be poorly defined for the 2000-2001 water year at the present time. Data not shown). Because the subsurface lysimeter nest is located at a toe-slope field position, nitrate resident in shallow soils throughout the field may contribute to the deeper nitrate pool detected in the middle and deep lysimeters.

There is an observed positive correlation between soil EC and soil nitrate in Palouse surficial deposits (Smith, unpublished data). Comparison of EC and nitrate in lysimeter samples collected at ARS and CRF-Area C indicate that this correlation is also present in pore water collected from the middle and deep lysimeters (Figure 15). This relationship is not observed in ephemeral stream data for the same fields (data not shown).

The concentration patterns for the pesticides strongly suggest transport along preferential flowpaths, as one might expect in a loess soil (e.g. Flury, 1996, Barbash and Resek, 1996; Tsuboyama et al., 1994). Triallate is detected in pre water from all of the middle and deep lysimeters within the first few samplings. Although the concentrations are low compared to those detected in samples from the shallow lysimeters later in the year, they are clearly greater than the detection limit (~5 to 10 fold). Early arrival of triallate is consistent with movement though preferential flow paths and with extensive work by others describing the movement of hydrophobic compounds through structured soils (e.g. Shipitalo and Edwards, 1996; Flury et al., 1995; Flury et al., 1998; Clendening et al., 1990; Flury, 1996; Li and Ghodrati, 1997). Palouse soils become extremely wet, near saturation, between late fall and early summer (e.g. Bacon, 1997), allowing these preferential pathways (i.e. macropores) to become active preferential flow paths. Furthermore, because of relatively high sorption (compared to more soluble compounds), triallate may also be subject to particle-assisted transport. Colloid transport is favored during intermittent soil wetting (El Farhan et al., 2001). Masse et al. (1998) found that pesticide migration was greater under no-till cultivation than under conventional tilling. The soil conditions at the ARS field during November 1999-January 2000 are consistent with and favor particle-associated vertical movement of triallate through preferential flow paths during wetting.

The presence of triallate soon after application during wet years provides evidence that water and solutes can be transported rapidly deeper within the system, but because of reaction, the triallate chemical signature does not allow estimation of the mass of water moved by this pathway. The signature observed for the other tracers suggests that they can provide this information. By ~late January of each of the two study years, the nitrate, EC and silica concentrations (Figures 8 and 9) in the middle and deep lysimeter pore water declined by ~>30% at the ARS field. Although the decline varied among lysimeters at each depth, the covariance of all three (Figures 14 and 15) implies influx to depth of water with a relatively low residence time. During early February, 2001, the relatively sharp decline in tracer concentration corresponded to several pieces of physical evidence that corroborate a flush of relatively low residence time water entering deeper portions of the subsurface: the shallow soil temperature increased (>0.5 ^{o}C), the shallow water table rose ~ 9 cm, and there was a large precipitation event which occurred coincident with temperatures above freezing for approximately 2 days. More limited direct physical evidence for the winter thaw in 2000 suggests consistent behavior between the two years. A coincident subtle decrease in δ^{18}O in the deep lysimeter pore water is also consistent with vertical movement of warmer water (e.g. ephemeral stream <-13 ‰ δ^{18}O).

Steadily increasing pore water nitrate, silica and EC concentrations following the early winter thaw were due either to a progressive exchange and weathering, or to mixing and gradual displacement of the earlier influx by upslope pore waters. Correlations between EC, silica, and nitrate concentrations are consistent with the latter. The pattern of pore water triallate occurrence suggests a change from non-equilibrium preferential vertical transport (before ~February 2000) to saturated, predominantly lateral transport along during soil horizons following the "flush." This interpretation is further corroborated by the stream hydrograph patterns.

Tracers in Stream Waters

Turbidity was collected as a surrogate for suspended solids content at the surface water sampling sites. A preliminary comparison of the pesticide and turbidity data (Figure 16a, b) suggests that there may be positive correlation for some of the sampling sites along the river (e.g. triallate at MFC-Trib @ B, MFC-Gray and MFC-McGreevy), but not at all sampling stations. In particular, the trends for MFC-State and MFC-Kitzmiller demonstrate that a simple correlation is not sufficient to explain the observed concentration patterns.

Stream chemistry for the range of drainage-scales studied does not show a simple correlation between EC and dissolved silica concentration (Figure 16c). For each sampling location, there appears to be greater variability in silica concentration than EC. The observed patterns also suggest that a combination of temporally variable system hydrology and chemistry must be considered to interpret the signal. The planned modeling activities during the next year will make use of this data to test our hypotheses about groundwater and surface runoff contributions to stream flow.

Mass Discharge and Stream Water Concentration Patterns

The annual triallate mass discharge following the fall application for the ARS field is much greater than that reported for the watershed as a whole (Figure 17a). These data suggest that surface runoff from fields, which are not tile drained, may be a critical pathway for non-point pesticide transport to surface water in this region. Because water discharge from the ARS ephemeral stream is discontinuous, triallate mass discharge is much greater on high compared to low flow days. Furthermore, the highest concentrations of triallate observed in the Palouse River co-occur with high total suspended solids. The above observations strongly suggest that the majority of hydrophobic compound transport can be explained by a surface flow pathway and imply that particle-assisted transport is important. Differences in discharges and maximum concentrations between the field and basin scales are consistent with dilution by a source of water (such as ground water discharge via tile drainage) with lower concentration. Preliminary data for the 2000-2001 water year (Figure 17b) indicate a similar pattern, with the exception that triallate mass flux is much reduced because no additional application was made. The concentration patterns observed in MFC and its tributaries are consistent with most mass entering the drainage system at the field annually.

While the mass discharge for triallate is sufficient to explain mass discharge at the much larger basin scale (e.g. Hooper), the duration of the discharge hydrograph is not. The ephemeral streams (ARS, MFC- Rill @ C, and MFC-Trib @ B) produce water intermittently during only a few months (approximately 4.5 months and < 4 months during 1999-2000 and 2000-2001, respectively). Albeit at a low concentration, triallate was detected in MFC and tributary samples prior to observed flow in ephemeral streams during the 2000-2001 water year. These results suggest that in order to explain the duration of the triallate hydrograph, an additional discharge mechanism must supply mass to the downstream locations. Two possible mechanisms include: particle-bound residues stored in the near-field portion of the watershed drainage system between years, or, material dissolved in tile drainage. Results to date suggest that the former may be more likely.

The surface pathway appears to be strongly affected by application timing of agrochemicals (i.e. soil moisture and temperature, and duration prior to incorporation), stream discharge, and weather (i.e. air temperature and precipitation). This observation is based on a comparison of the agrochemical concentration observed at the field-scale in the streams at the ARS site last year (triallate up to 26.3 μg/L) and at the CRF site this year (triallate up to 0.012 μg/L). Similarly, nitrate concentrations observed at the ARS site were low in 2000 (<1 - 4 mg/L) versus 2001 (4 - 10 mg/L). Fertilizer was not applied on the field in the fall of 1999, instead applications were made during the spring and fall of 2000. Nitrate concentrations at the field-scale increase with increasing discharge, versus at the watershed scale where there is a decreasing tendency at peak flow.

During the 1999-2000 water year, ARS surface runoff accounts for only approximately 25% of the total nitrate flux detected at the watershed scale (Figure 17a). Similarly, silica and water discharge are underestimated. Although simplistic, these observations suggest that the system contains a large subsurface reservoir of nitrate that is supplied at relatively constant concentration to the stream by the watershed during the wet season, regardless of river stage. This concept is consistent with relatively high nitrate concentration (and mass discharge) observed in the tile drainage during the 2000-2001 water year and substantiated by a number of additional measurements and recent reports by our group (e.g. Schultheis et al., 1999; Schultheis, 2000). More rigorous mass discharge analysis for the watershed scales of study will be pursued as the study proceeds.

Summary of Key Points and Continuing Work

The Palouse hydrologic system provides the opportunity to assess surface flow and ground water contributions to non-point pollutant occurrence at the watershed scale. Pesticides define watershed-scale high surface flows and offer a large dynamic range of analysis (>4 orders of magnitude). Geochemical tracers (EC/Si) define ground water flow paths. Stable oxygen isotopes help to resolve flow paths representing intermediate residence times. The combined use of these tracers allows identification and quantitation of the complex dynamic flow system within the Palouse soils. For example, pore-water concentration patterns for nitrate, triallate and the geochemical tracers indicate complex patterns of vertical and lateral flow occur seasonally. Additional targeted analyses and quantitative approaches to interpret the data will be pursued during the coming year.

During the remaining portion of the project, selected monitoring of the instrumented reservoirs will be continued (budget permitting). *To our knowledge, this project will provide the first comprehensive test of the application of multiple tracers to evaluate and quantify watershed flowpaths in a any region outside the mid-continental U.S.* The resulting conceptual framework , based as it is on “off-the-shelf” solute analyses and simple mathematics, can be readily tested and adapted in other regions. The improved understanding of hydrologic transport pathways gained will be used to assess the conceptual model, thus contributing a tool to for watershed planning. The data collected will further be used to test more complex models that “upscale” the various runoff contributions to surface waters. The results of this study will be of use to USGS researchers in assessing methodologies for scale-up from field to large-basin watershed area. Because the approach relies strongly on comparisons between artificially drained and undrained fields, our work will also provide a significant step to compare the importance of these pathways to regional-scale water quality effects in a semi-arid area. Our study will also focus attention on the importance of temporal system dynamics.

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Basic Information

Title:	Modeling Winter Hydrology and Erosion in the Northwest Wheat and Range Region (NWRR)
Project Number:	WA-05
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Water Quality
Focus Category:	Hydrology, Sediments, Models
Descriptors:	Agriculture, Management, Winter Hydrology, Soil Erosion, Climate, NWRR, Computer Models
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	Joan Q. Wu, Donald Klepper McCool, Jan Boll

Publication

1. Wu, J.Q., M.K. Place, D.K. McCool, and C.O. Cuhaciyan, Effects of freeze/thaw conditions on soil Strength, pp. 447-450, Proc. Soil Erosion Research for the 21st Century, January 3-5, Honolulu, HI, 2001.
2. Place, M.K., J.Q. Wu, C.O. Cuhaciyan, and D.K. McCool, The big freeze--and thaw, Resource, 11-12, Am. Soc. of Agric. Eng., St. Joseph, MI, December, 2000.
3. Cuhaciyan, C.O., J.Q. Wu, M.K. Place, D.K. McCool, C.R. Palmer, Design of a tilting flume for testing frozen soil erosion, ASAE Pap. 200009, Am. Soc. of Agric. Eng., St. Joseph, MI, 2000.

Problem and Research objectives:

Soil erosion by water from cropland is a major agricultural and environmental problem in the Northwestern Wheat and Range Region (NWRR) that covers northern Idaho, eastern Washington, and northeastern Oregon. The high erosion rate in this region is a result of a combination of winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and inadequate management practices. Soil erosion can reduce agricultural productivity, increase costs for road-side ditch cleaning and water conveyances and hydraulic structures maintenance, and adversely affect stream water quality and fish habitat. Models of different levels of sophistication have been developed for water erosion prediction. These models, however, are highly limited in their applicability for long-term, continuous simulation under the unique climatic conditions of the NWRR. On one hand, empirical models lack event-based or off-site erosion prediction capability and may require time-consuming, costly model calibration before use, and on the other, process-based models, such as the USDA's WEPP (Water Erosion Prediction Project) model (Laflen, 1991), cannot properly account for the NWRR's winter hydrology and erosion processes. The main purpose of this study is to elucidate the mechanisms by which soil freezing and thawing affect runoff and erosion through laboratory experimentation, and to adequately incorporate the identified effects into the WEPP model for use in determining long-term erosion and agricultural Best Management Practice (BMP)s. Specific objectives are to: (1) experimentally identify and mathematically formulate the mechanisms by which freezing and thawing of soils influence runoff and water erosion; (2) improve the winter hydrology and water erosion routines in the WEPP model by properly incorporating into it the relationships between soil freeze-thaw processes and erosion; and (3) evaluate selected, representative management practices and determine BMPs for the NWRR using the improved WEPP model.

Methodology:

<u>Experimental facility setup</u>

Criteria of flume redesign

In inspecting the experimental facilities, in particular the tilting flume, constructed and used in the precious laboratory erosion study by Van Klaveren and McCool (1993, 1998), we found that substantial improvement of these facilities was imperative. The titling flume was built at the USDA-ARS Palouse Conservation Field Station (PCFS) near Pullman, WA. Although successful, the design had limitations, including slow soil consolidation process, long freezing and thawing times, and poor flume material durability. Soil preparation prior to flow application and runoff testing is necessary to reconsolidate the soil to field conditions and simulate natural freezing and thawing. Therefore, emphasis was placed on identifying strategies and techniques for shortening the soil preparation process and accommodating existing technology and materials to enhance the durability of the flume.

Model design and testing

To reduce soil preparation times three approaches were adopted, including decreasing soil depth, changing the sub-soil porous material, and using ceramic materials for drainage. In the original design, a 10-cm pea gravel layer was placed underneath the soil layer to ease the tension application and drainage process. While the pea gravel can lead to rapid drainage, it certainly poses a limit on the range of tension that can be applied. To decrease freeze/thaw cycle times, two potential techniques were examined. First, newer brine chilling and air conditioning equipment was installed at the PCFS after the completion of the work by Van Klaveren and McCool (1993, 1998). This new equipment might be able to freeze soil at an improved rate and do so during warm summer months. Second, dry ice was assessed for its effectiveness as a cooling material. To test the validity of these strategies, a small scale model was built and a series of tests were implemented.

A soil consolidation model, consisting of a 50-L cooler equipped with a saturation and drainage system, an aluminum plate for supporting dry ice and producing radiative cooling, and a second cooler inverted over the plate, was designed and built. The model primarily served three purposes: to test a variety of porous materials and intakes that would be appropriate to be placed under the soil; to determine the minimal number of saturation and drainage cycles necessary to consolidate the soil to field conditions, and to assess the effectiveness of dry ice as a cooling agent. The porous materials tested were Palouse silt loam (fine silty, mixed mesic Pachic Ultic Haploxeroll) (Soil Survey Staff, 1973), three types of sand (one graded, 62–6,000 μm; one fine, well-sorted, 200 μm; and one medium, well-sorted, 600–800 μm), and pea gravel. The intakes tested were porous ceramic cylinders and a simple intake consisting of a tube notched and wrapped in a Scotchbrite pad. The simple intake was tested for use with all five porous materials, while the two ceramic cylinders of different dimensions were tested using only the graded sand.

In the work by Van Klaveren and McCool (1993, 1998), three saturation and drain cycles were applied as part of the soil preparation process. In this study, to determine the minimum number of cycles necessary to consolidate the soil to field conditions, soil samples were collected from the model after each cycle and dry bulk density (ρ_{dry}) was measured using the clod/paraffin method (Blake and Hartge, 1986). The rate and depth of which dry ice could freeze the soil were also tested using the model.

Flume redesign

There were two downfalls to the materials of the original flume. First, extensive contact of the flume with soil and water caused severe rotting of the 19 mm marine plywood which was the major component of the flume. Although the plywood had been sealed and coated, rotting was still prevalent. Second, the plywood flume had little ability to endure the impacts and abuses of removing the consolidated soil by shovel. Thus, soil removal was tedious and time consuming and preparing the flume for multiple soil testing would have been difficult. Using durable material to build the new flume was considered a priority. In addition, the new design should allow the flume to be cleaned and maintained easily, suitable for multiple soil testing. Another challenge was to enable the flume to withstand the extreme pressures caused by the expansion of the frozen saturated soil.

It was observed in the study by Van Klaveren and McCool (1993, 1998) that most rills, formed under three tested water flow rates of 2, 3, and 4 L/min, were no deeper than 100 mm, implying that a 150–200 mm deep soil layer should be sufficient. The thickness of the soil layer (656 mm) in the original flume may therefore be reduced in the new flume. However, a deeper soil layer becomes necessary if higher flow rates and different soil types, which can lead to deeper rills, are to be tested. An innovative approach would be to change the depth of the soil layer and the depth and types of the underlying porous media accordingly in different tests with different water flow and soil conditions.

<u>Experiment design</u>

The Palouse silt loam and the Walla Walla silt loam (coarse-silty, mixed, mesic Typic

Haploxeroll) will be tested in this study to obtain rill erodibility and critical shear stress values under unfrozen, frozen, and thawing conditions, and at different flow rates and soil water tensions. Both soils are typical of the NWRR and have been studied as benchmark soils and parameterized in the WEPP model. The test will be performed following a three-factor (soil type, flow rate, and soil water tension) factorial design with two replicates. Five-year climate files were generated using a random climate generator CLIGEN (Nicks et al., 1995) for Moscow, ID and Spokane, WA, in order to estimate peak and average rainfall intensities and thus the peak and average runoff rates. These estimates, together with those used in the study by Van Klaveren and McCool (1993, 1998), will serve as guidelines for designing water flow application rates. Following Van Klaveren and McCool (1993, 1998), we will apply three soil water tensions, 50, 150, and 450 mm, to simulate the soil water conditions in the wet winters in the NWRR. We anticipate that the new flume setup will lead to much shortened soil preparation and artificial freezing of the soil, and allow the completion of the factorial experiment that consists of numerous runs within a reasonable amount of time (about six months). Through the designed experiment, quantitative relationships between soil erodibility and critical shear stress and soil water tension would be established.

Principal Findings and Significance:

Model design and testing results

Fig. 1 shows the components of the soil consolidation model consisting of a 50-L cooler, a drainage intake, a 20-L carboy (used as a Marriott device), a 1-L Nalgene bottle, a 3-mm aluminum radiation plate, and a second cooler inverted atop the radiation plate. The first cooler was filled with 10 cm of underlying porous material (soil, sand, or gravel) followed by 19 cm of the tested soil. The Marriott device was used during saturation and the bottle was used to catch and measure drainage. During the soil freezing test, the radiation plate was set on the cooler followed by dry ice and the second, inverted cooler.

The cooler-based model functioned properly. It allowed for a sufficient depth of soil to be tested. The coolers come with a drain plug, providing easy external connection. They are sufficiently sturdy and are well insulated for freezing tests. The Marriott device allowed for easy head adjustment and determination of the volume entering into the cooler. Twenty liters of water would be more than enough to saturate the soil in the cooler. However, the water in the carboy is not all accessible given the design of the bottle. A larger volume carboy or a different shaped container would be necessary to avoid frequent refilling. The freezing apparatus performed adequately and allowed efficient freezing of the soil. The newer brine chilling equipment at the PCFS is yet to be tested, and the efficiency of both cooling strategies will be compared.

Tests of sub-soil porous media showed that as overall media diameter and therefore pore size increases so does the rate of drainage. The rate of saturation can also be increased when the saturation front is within the larger diameter porous media. When the saturation front comes into contact with the tested soil of finer texture the rate must be decreased to avoid air entry problem. The use of finer underlying porous media, including the Palouse silt loam it self, increases the time necessary to complete saturation and drainage cycles. The pea gravel was able to drain up to 10 times faster than the finer media. However, the fine materials allowed for better connectivity of the water column between the drainage system and the soil, and a tension up to twice the depth of the flume. The pea gravel only allowed tensions that were within the depth of the soil.

The ceramic cylinders increased the resistance of the system significantly and were not able to speed up the soil preparation process. To counteract the resistance effect, large head differences were necessary to allow the water to flow both into and out of the system. The difficulty came from change in the resistance of the ceramic cylinders with time, which may be due to the use of the hard tap water that could lead to deposits filling the micro-pores of the ceramic cylinders.

The bulk density tests consistently showed that soil consolidation mainly occurs during the first saturation process and the subsequent gravitational drainage. Wetting the soil a second time and increasing tension below the depth of the flume had caused little change in the elevation of the soil surface within the model. The average dry bulk density after one saturation and drain cycle for all model tests was determined to be 1.38 g/cm^3, which in fact exceeds the field measured mean value of 1.28 g/cm^3 for the Palouse silt loam (Van Klaveren and McCool, 1993).

Dry ice freezing was proved to be an adequate technique to rapidly freeze the testing soil to a large depth, thus reducing soil preparation time. However, using dry ice for multiple erosion tests with the full-scale flume may be costly. In addition, dry ice has a temperature much lower than what naturally occurs during winter in the NWRR. A soil freezing process that is too rapid may significantly affect the erosion test. Further investigation is thus needed to assess the suitability of dry ice as a cooling material.

Flume design results

Fig. 2 illustrates the new flume designed with a removable tub made of stainless steel (10 gage, 304L). Eventually, multiple tubs may be built which would allow a soil to be tested in the flume while other tubs were in the preparation process. Stainless steel was used to increase the flume longevity and allow shovels and picks to be used during tub cleaning without causing serious damage. A window was built in the side of the flume using a coated polycarbonate material (Tuffak CM-2) for its high resistance to abrasion, strength, and optical properties. The window will allow visual observation of saturation and drain progress, freeze and thaw progress, and possibly other processes.

The tub, sitting in a set of 19-mm thick plywood ribs, was kept similar in depth (50 mm shallower than the original) to accommodate different flow rates and soil types. The ribs help support the tub and increase the rigidity of the system. Automobile tires were cut into 230- by 380-mm sections and placed edgewise between the tub and ribs, allowing the tub to expand in a controlled manner during freezing and to return to its original dimensions after thawing.

A gate was designed that could be easily adjusted to match the elevation of the bottom of the forming rill. Such an adjustable gate is necessary to prevent water from pooling at the end of the flume while still supporting the soil during the soil preparation process. The challenge in designing the gate was that it had to be both adjustable and waterproof. To meet these criteria a gate made of 6.3-mm polypropylene was designed to slide freely between two stainless steel rails. Adjustments are made by a scissor jack placed on the floor and attached to the bottom of the polypropylene gate. The gate itself was cut with the same "v" notch shape as is used in the flow approach and created on the soil surface.

The radiation plate was re-examined. The old chilling brine was let out and new chilling brine added in. The flow approach was re-surfaced, and the air-conditioning system was also upgraded. The original catch basin, still in fine conditions, was left unchanged. Fig. 3 shows the complete flume assembly. Fig. 4 shows the actual flume after construction.

As the redesign and construction of the tilting flume (including a model design and testing) as well as the experiment design have consumed essentially the entire project time, the actual experiment and subsequent result analysis has been postponed. However, we were successful in our application for a three-year NSF IGERT (Integrative Graduate Education and Research Training) graduate fellowship to continually support this study. Currently, the IGERT student is testing the efficiency of the cooling plate. We expect to formally start the experiment runs in late May or early June. In addition to the IGERT fellowship, we have submitted two other proposals that are pending for the funding agencies' final decisions: Soil Erosion Testing Using a Tilting Flume: Teaching Material Development to the Verle Kaiser Conservation Endowment ($1,380), and Environmental and Economic Impacts of Conventional and Conservation Farming in the Northwestern Wheat and Range Region (NWRR) to the USDA NRICGP ($311,075). In summary, significant efforts have been devoted to the redesigning and construction of the laboratory facilities and equipment for soil erosion experimentation and great success has been achieved. Although certain activities set in the original work plan have to be postponed, we have been able to garner substantial funding to continuously support this study. Further, we have been seeking additional funds to largely expand and improve this study.

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Information Transfer Activities:

The following approaches were used to disseminating and transferring research information: (1) communications with USDA NRCS by Co-PI Don McCool, and with Washington State Water Research Center by PI Joan WU, (2) reporting research findings in scientific journals (one manuscript on the lab experimental design and results is in preparation), and (3) presentations made at multiple professional meetings, including the ASAE Pacific Northwest Region Meeting, September 21–23, 2000, Richland, WA, and the ASAE Soil Erosion Research for the 21st Century Symposium, January 3–5, 2001, Honolulu, HI.

Publications:

Wu, J.Q., M.K. Place, C.O. Cuhaciyan, and D.K. McCool, Design of a tilting flume for testing frozen soil erosion, *Appli. Eng. Agric*., 2001. (In preparation.)

Wu, J.Q., M.K. Place, D.K. McCool, and C.O. Cuhaciyan, Effects of freeze/thaw conditions on soil Strength, pp. 447–450, *Proc. Soil Erosion Research for the 21st Century*, January 3–5, Honolulu, HI, 2001.

Place, M.K., J.Q. Wu, C.O. Cuhaciyan, and D.K. McCool, The big freeze—and thaw, *Resource, 11–12*, Am. Soc. of Agric. Eng., St. Joseph, MI, December, 2000.

Cuhaciyan, C.O., J.Q. Wu, M.K. Place, D.K. McCool, C.R. Palmer, Design of a tilting flume for testing frozen soil erosion, *ASAE Pap*. 200009, Am. Soc. of Agric. Eng., St. Joseph, MI, 2000.

Students Supported (name; status; discipline)

Christopher O. Cuhaciyan: M.S. graduate student, Biological Systems Engineering Department.

Nathan E. Marsh: Undergraduate student, Mechanical Engineering Department.

Charles R. Palmer: Undergraduate student, Civil Engineering Department.

Maya K. Place: M.S. graduate student, Biological Systems Engineering Department.

The USGS funds were used to support Christopher, Nathan and Charles as student helpers for their contribution to the titling flume model design, construction and testing, and for their participation in the redesign and construction of the tilting flume. The funds were also used to purchase lab materials and supplies to facilitate Maya's experimental work which forms the major part of her M.S. thesis.

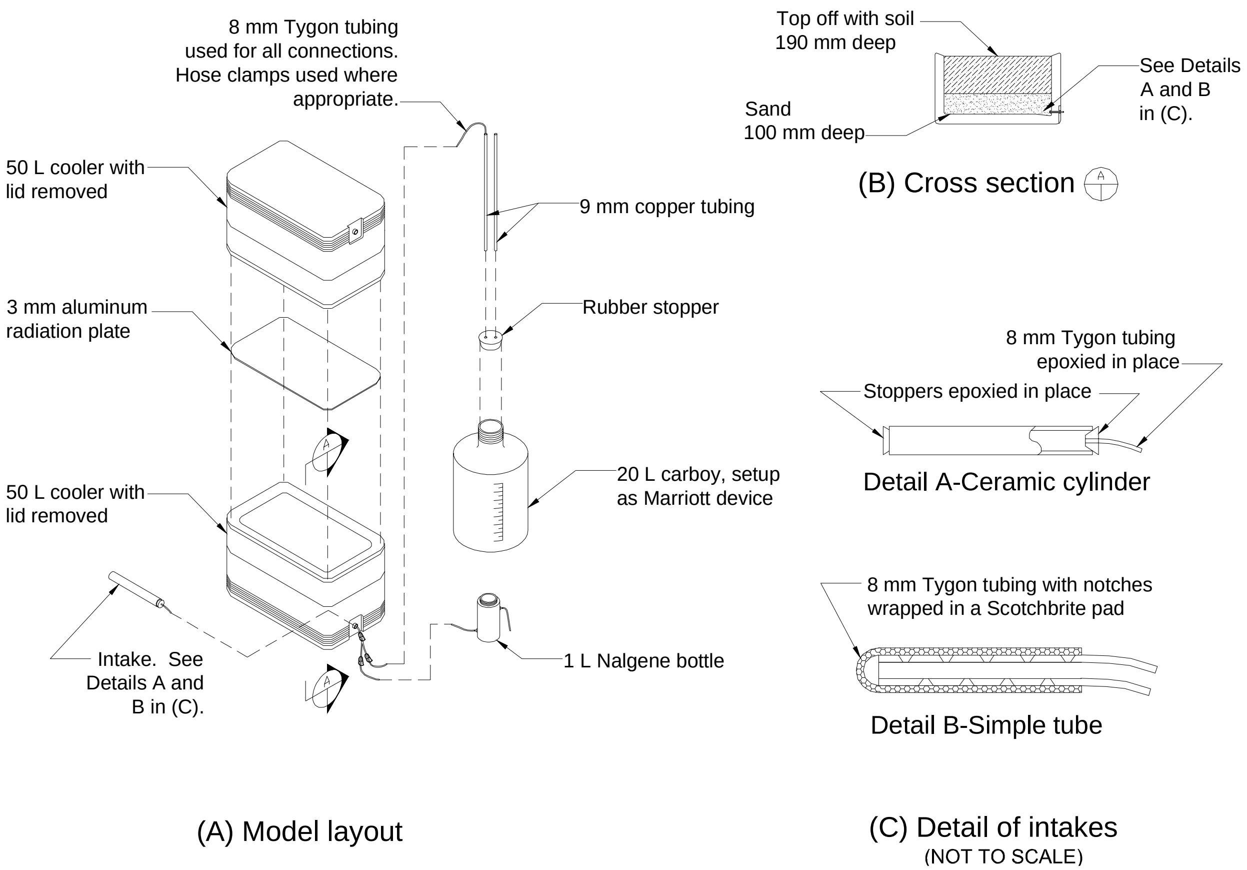


Fig. 1. Model layout

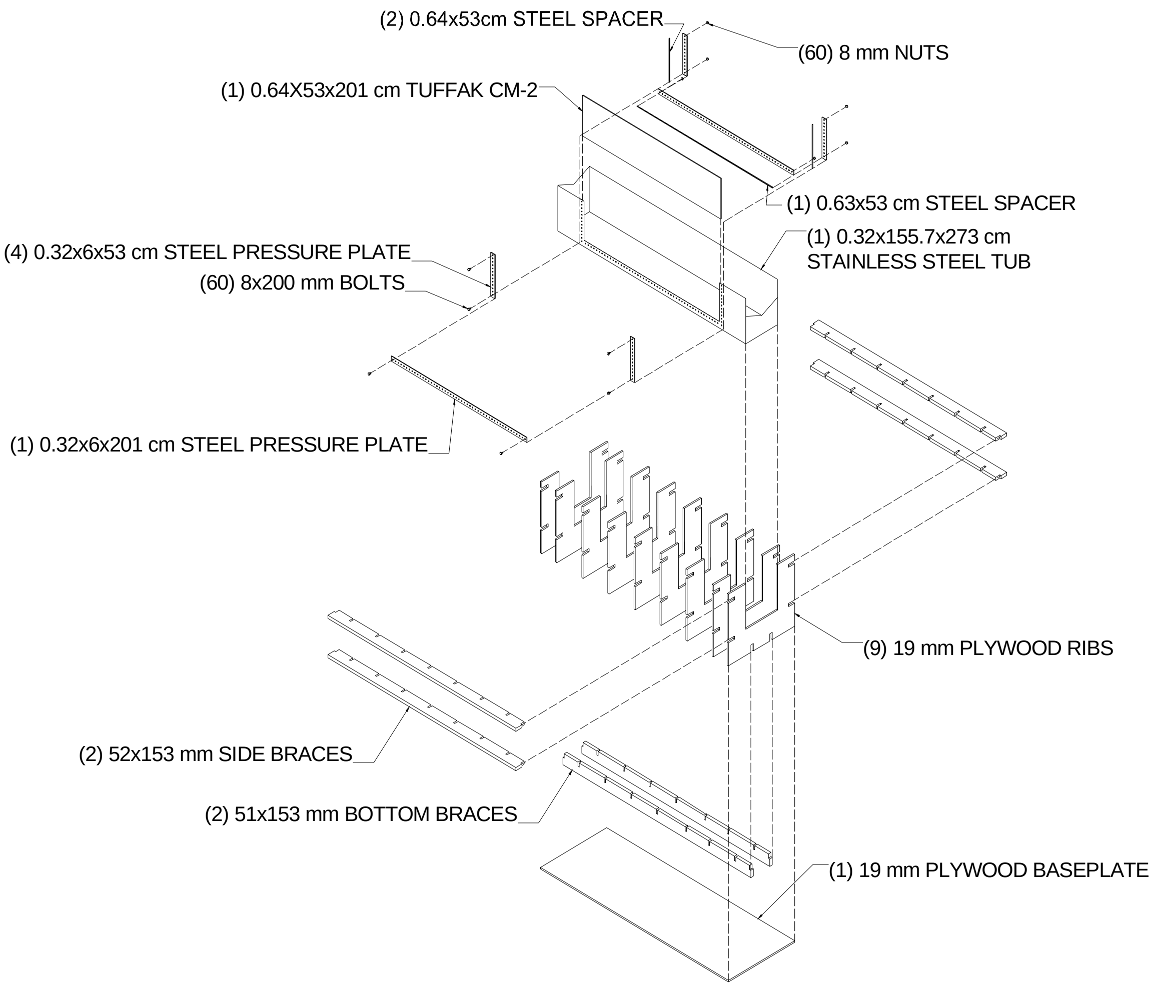


Fig.2. Flume layout.

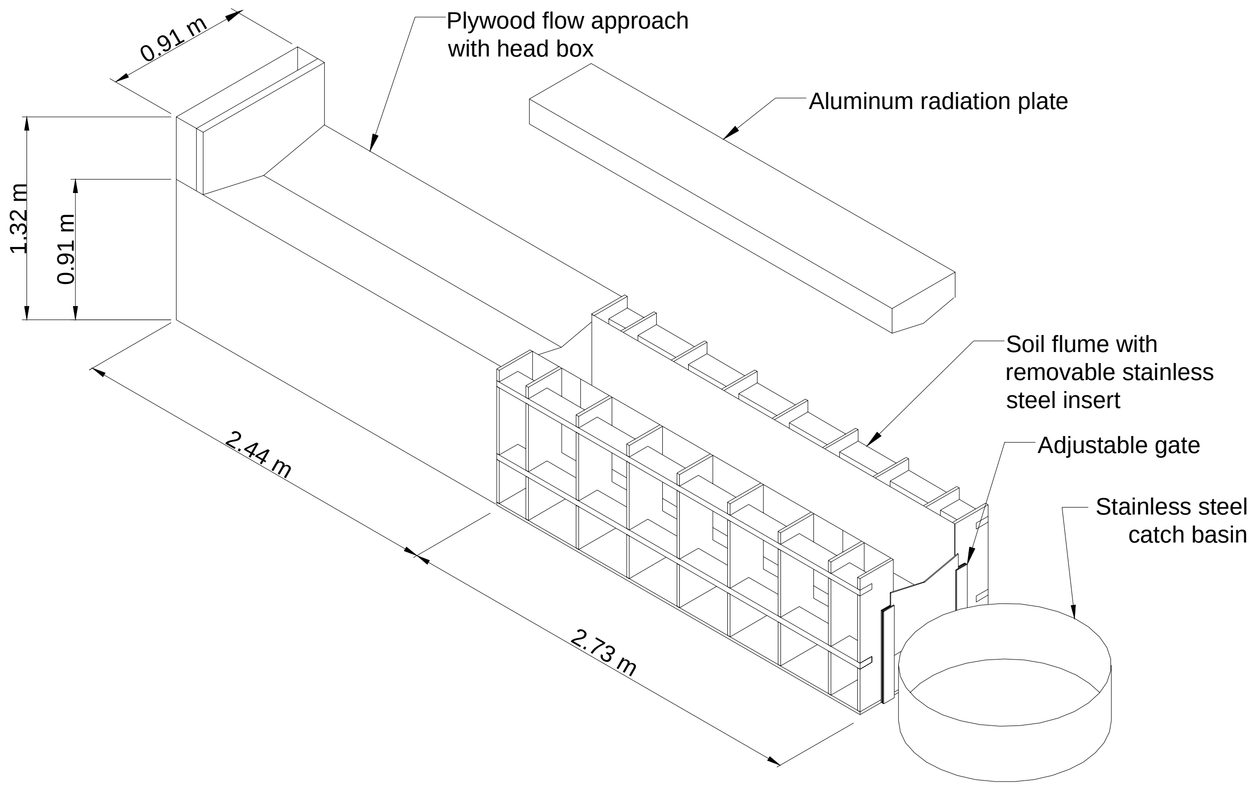


Fig. 3. Complete flume assembly.

Not pictured in the photo is the sediment catch basin to be connected to the flow exit gate (at the near end of the flume). The flow entrance (at the far end) was re-surfaced.

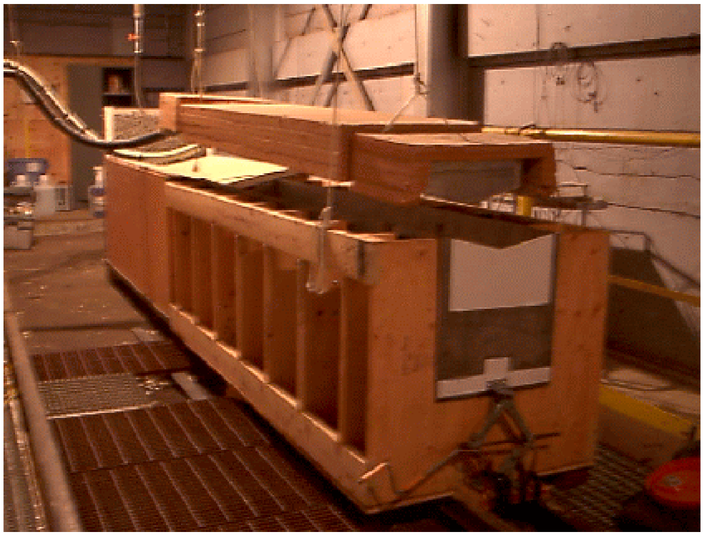


Fig. 4. The actual flume after construction.

Basic Information

Title:	A Watershed Scale Study on No-Till Farming Systems for Reducing Sediment Delivery
Project Number:	S-02
Start Date:	9/1/1999
End Date:	8/31/2002
Research Category:	Water Quality
Focus Category:	Sediments, Agriculture, Models
Descriptors:	Sediment delivery, best management practices, watershed, soil erosion, water quality, watershed management, runoff, conservation farming
Lead Institute:	None
Principal Investigators:	Shulin Chen, Rollin Hotchkiss, Darin Saul

Publication

1. Mancilla, G., and Chen, S. 2000. A Watershed Scale Study on No-Till Farming Systems for Reducing Sediment Delivery, First-year project report to the Pomeroy Conservation District. Department of Biological Systems Engineering, Washington State University, Pullman Washington
2. Wang, G.-D., S. Chen, and J. Boll. 2000. Integrated Watershed Modeling, Written for Distribution and Presentation at Watershed 2000, Hotel Vancouver, British Columbia, July 8-12, 2000

Problem and research objectives

This project addresses priority areas 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) has one of the highest soil erosion levels of the United States. Freezing and thawing cycles of the ground detach soil particles, making them easily transported by runoff. In addition, currently practiced farming systems tend to leave the soil unprotected to the rain energy. 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. No-till farming has been recommended to farmers as a conservation culture practice to reduce soil erosion. The effectiveness of this practice, however, has not been evaluated at a watershed scale. Clearly, this project fits the RFP in the area described as "Examination of the effectiveness of Best Management Practices (BMPs) at watershed scales of tens to hundreds of square miles."

Another important soil erosion-related issue is sediment delivery. One of the questions that farmers often ask is, "what is the percentage of eroded soil that ultimately ends up in streams?" For a large area in northern Idaho, eastern Oregon and eastern Washington, which is typified by steep rolling hills and freezing and thawing winter conditions, sediment delivery ratios have not been well studied. As a result, there is a lack of basic modeling tools for the purpose of planning, management, and policy development for these agricultural watersheds.

The objectives of this research are:

1. Compare soil loss from no-till and traditional farming fields;

Evaluate models for sediment delivery process under no-till and traditional farming conditions;

Develop a model for predicting sediment delivery of the entire watershed.

Methodology:

Runoff plot study

The purpose of the runoff study is to investigate the difference between no-till and conventional tillage systems in terms of amount of runoff produced for the same amount of rainfall. Less infiltration results in more runoff and higher erosion potential. For the study, which was conducted in both 1999-2000 and 2000-2001 winter seasons, one-square-meter runoff plots with borders and runoff collectors were installed in the fields of different precipitation areas.

The high precipitation area had the greatest number of installed plots on five sites: a forest site, two disked no-till sites, a no-till standing stubble site, and a planted no-till site. These sites are located in the Columbia Center/Mountain Road area of Garfield County. The intermediate precipitation area had plots installed on two sites: planted no-till and planted conventional tillage. A frost tube, manually-read precipitation gauge, and automated weather station operated by the conservation district were located adjacent to the sites. These sites are located in the Pomeroy Hill area of Garfield County. The low precipitation area had plots installed on three sites: planted no-till, planted conventional tillage, and planted chem-fallow. The sites were instrumented with frost tubes and manually-read precipitation gauges. These sites are located in the New York Gulch area of Garfield County.

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. Trips from Pullman to Garfield County were scheduled on precipitation event bases through web-based weather information sources and consultation with conservation district personnel.

Rill formation and sediment delivery study

Rill erosion is the main mechanism for soil loss in the study region. A comparative study of rill formation in different tillage systems was conducted to determine the field soil loss rate and sediment transport within the rill on the USDA Palouse Conservation Farm near Pullman, Washington, during the winter season (between December 2000 and April 2001). Water was applied at three different rates (4, 6 and 8 gpm), on 7.2 m^2 plots. Each plot supported one of the following four typical tillage systems: no-till, conventional tillage, chisel plow, or moldboard plow. Conditions of slope, orientation, and soil type were similar. The number and dimension of rills formed in each experiment, plus flow velocity and discharge, were determined. Therefore, effective comparisons between the different tillage systems are being made based on the number of rills generated, rate of soil loss, capacity for transporting sediments, random and oriented roughness, discharge, and flow velocity distributions.

Monitoring systems were implemented in the 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.

Hydrological and sediment delivery modeling

An integrated watershed hydrological model framework was developed that includes an overland flow model and a channel routing model. A sediment transport model is currently being developed for a subwatershed located near Pomeroy for predicting sediment delivery to the main channel. The model will be verified with the data from the sub-watersheds that were instrumented to collect the following data:

- Flow sequence in response to a storm, by flumes and flow meters;

- Rainfall intensity sequence, by a recording rain gage;

- Infiltration sequence, by taking the difference between rainfall and flow in the runoff plots;

- Sediment production sequence (transported by main channel), by automated samplers.

A process-based hydrologic modeling framework using Saint-Venant equations has been developed. Saint-Venant equations include a continuity equation and a momentum equation. For the study region, with low precipitation intensities, the momentum equation is replaced by the Chezy equation.

The continuity equation is represented as

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r - f$$

where the first term is the variation of the flow water depth ‘h’ with time ‘t’; the second term represents the variation of the flow rate ‘q’ with distance ‘x’; and the term of the right-hand side corresponds to the rainfall excess, represented as the difference between rainfall intensity ‘r’ and infiltration rate ‘f’.

The Chezy equation is represented as:

$$h = \left(\frac{q}{\alpha}\right)^{\frac{1}{\beta}}$$

in which $\alpha = Cs^{\frac{1}{2}}$; and $\beta = \frac{3}{2}$; and s = slope of channel, and C is a roughness coefficient.

The sediment transport model will be developed based on rill and interrill physical processes. Simulated rainfall will be used to derive equations for rill formation and sediment transport.

Principal findings and significance

Objective 1: Runoff produced in the 21 plots of all the wheat fields during the 1999-2000 winter season was about 18 percent of the total precipitation. The rest of the water is considered as infiltrated. The relatively small runoff produced could be due to the fact that most of the precipitation was as snow, with a long period of accumulation. Freezing was observed to cause soil cracking, enhancing infiltration of water while the snow was melting. Total solids concentrations in runoff were generally higher in conventional tillage fields, as was the total amounts of solids. This fact reveals that soil erosion is effectively reduced by no-till practice, even though the runoff differences between cropping practices were not evident. In only one pair of areas, the no-till practice showed more erosion than the conventional one. However, field observations indicated higher amounts of soil detachment and movement in the conventional field.

Data gathering and analysis of data continues for the 2000-2001 winter season; hence, the results are observational in nature as the report is written. Unfortunately, Garfield County experienced an exceedingly mild winter this season. Neither of the sub-watershed monitoring systems reported sufficient discharge to trigger water sampler operation. In fact, the sub-watershed monitoring system in the Linville Gulch area has yet to report any discharge at all.

The limited runoff data show that conventionally tilled fields generally discharged higher runoff volumes than no-tilled fields in a given precipitation zone. An interesting anomaly was observed in the high precipitation plots in that the planted no-till site had more runoff and was observed to have much more bulk water within the upper soil profile than adjacent no-till fields. In discussion with the farm owner, it was determined that this was the second no-till planting for this particular field and that these observations tend to be in keeping with other's observations that no-till fields behave in this manner through their first few crop cycles. This, of course, is more hearsay than science, but comes up in no-till conversations regularly.

Objective 2. The preliminary results of the experiments conducted during the 2000-2001 winter season at the USDA Palouse Conservation Farm show the importance of no-till system as an effective controller of rill formation and soil erosion. Applications of water of 4 and 6 gpm (which it would represent an effective rainfall of between 1 and 14 in/hour, a high rainfall intensity) did not produced any rill in no-till plots with at least 78 % of residue cover. On the other hand, rill formation was faster and usually in more quantity under conventional till plots. However, between 4 gpm and 8 gpm flow applications, the average number of rills generated under conventional practices varied between 2.5 and 3 rills in plots of 1.8 meters wide. More implications and relationships between the results are being developed.

Objective 3: An integrated watershed system modeling approach was used to simulate a large comprehensive watershed hydrological process. A large watershed can be geographically sub-divided into lower level sub-watersheds based on rainfall distribution and physical geographical conditions over the watershed. In the model developed, an implicit analytical solution of the kinematic wave equation was used to calculate outflow hydrographs of the lowest order's sub-watershed and small stream routing. A mixing cell method was used to transform the convection diffusion equation derived from complete Saint-Venant equation into a first-order nonlinear ordinary differential equation that is solved using the Runge-Kutta method, an approach for main channel routing. The parameters for the model don't need to be calibrated and are determined based on physical geographical conditions of a watershed. Validation and a full development of the hydrologic and sediment model will be postponed due to the lack of data. The reduced number of precipitation events during the last two winter seasons resulted no significant hydrologic response of the sub-watershed and practically no delivery of sediments to the main channel.

Basic Information

Title:	Integration of Surface Irrigation Techniques to Reduce Sediment and Nutrient Loading in the Yakima River Basin
Project Number:	S-03
Start Date:	9/1/2000
End Date:	8/31/2003
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
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	Brian G. Leib, Robert Stevens, Ariel Szogi

Publication

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 will be on inexpensive methods to further reduce sediment and nutrient loads from rill irrigation. Sediment loads will be 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 are being repeated at two locations during two growing seasons to create four replicates with significant field and year effects. Also, data collection will be repeated during each irrigation event (the number of irrigations are dependent on the crop and soil type). The treatments need to be large enough to allow approximately 50 furrows to flow into the tailwater ditch at one time. The treatments will be randomized within each field in each year.

Each treatment is being monitored for inflow, outflow, soil moisture, sediment load, and sediment concentration. Measured inflow to the furrows is important to insure that all treatments are subjected to the same erosive force. Inflows will be estimated by measuring the delivery pipe and percent opening of spigot valves that will be rated in the set-up. By comparing total inflow to total outflow, the proportion of water lost via run-off can be determined along with the average application depth. Outflow from each treatment will be measured by a flow meter that receives water from a collection sump and sump pump at a maximum rate of 2.0 gallons per minute per furrow.

Soil moisture will be monitored with the neutron probe and access tubes. There will be readings before and after each irrigation. Treatment will have two access tubes at both the head and tail of the field for a total of six tubes. This type of monitoring will help determine the timing of irrigations and the uniformity/depth of application. Average advance time will also be recorded.

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

After outflow is measured, the tailwater effluent will be delivered to a sediment trapping box. The slotted apple crates will be lined with filter fabric to retain sediment. The number of boxes will be large enough to trap a season's worth of sediment if the tailwater contains 1000 mg/l of sediment. The depth of sediment added to the boxes will be measured after each irrigation. Also, NTUs and suspended solids will be measured at periodic intervals during tailwater run-off to determine whether return flow water-quality standards are being met.

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

Principal findings and significance

Since 2001 will be the first field season for this project, there are no experimental findings at this time. The accomplishments to date are:

1. Formed a project management/oversight team comprised of members from a cross section of Tribal Offices and Government Agencies (see Information Transfer Section above).
2. Arranged for "on-farm" experiments/demonstrations on two cooperating farms. Colin Mears and Billy Korstad in the Wapato Irrigation District will be cooperating on a 40-acre, rill irrigated, grain corn field with 1300 foot runs and a 0.2% slope on the tailwater ditch. Ken Lewis of the Roza Irrigation District will be cooperating on a 30-acre, rill irrigated, Concord grape field with 800 foot runs and a 1.2% slope on the tail water ditch.
3. Personnel to conduct the field project have been hired. In addition to the students identified in the section above, Gary Matthews, Engineering Technician, has been retained to fabricate, install and maintain the monitoring equipment needed for this experiment.
4. Most of the materials and equipment needed to conduct the experiments have been purchased and/or fabricated. Once the cooperating producers form the tailwater ditches in their fields, the monitoring equipment will be installed and data collection will commence.
5. The Washington State University Water Quality and Waste Analysis Lab will be performing the certified analysis of water samples and a quality assurance program for the sampling protocol is being finalized.

Basic Information

Title:	A Problem-Solving Tool for Mitigating the Impact on Water Quality of Management Practices in Small Rural Watersheds
Project Number:	C-02
Start Date:	9/1/1997
End Date:	8/31/2000
Research Category:	Water Quality
Focus Category:	Hydrology, Management and Planning, Non Point Pollution
Descriptors:	Water Quality, Winter Hydrology, Decision Models, Watershed Management
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	Claudio Osvaldo Stockle, Shulin Chen, Donald Klepper McCool, Jan Boll

Publication

1. Brooks, E.S., D.K. McCool, and J. Boll. 2001. Determining erodibility parameters for a Palouse silt loam using runoff plot data, "in" International Symposium on Soil Erosion research for the 21st Century, American Society of Agricultural Engineers, January 3-5, 2001, Honolulu, Hawaii, pp. 591-594.
2. Wang, G., S. Chen, J. Boll, C.O. Stöckle and D.K. McCool. Modeling overland flow based on Saint-Venant equations using a discretized hillslope approach. Submitted to Water Resour. Res. (In review).
3. Stockle, C.O., R. Nelson, J. Boll, and S. Chen. 1999. Assessing Agricultural Water Management Using a Model for Small Rural Watersheds, ASAE Paper No. 992165, St. Joseph, MI., 1999.
4. Stockle, C.O., G. Bellocchi, and R. Nelson. 1998. Evaluation of the weather generator ClimGen for several world locations. Published in Proceedings, Seventh International Congress for Computer Technology in Agriculture. Florence, Italy, 15-18 November, 1998.
5. Stockle, C.O. and G. Bellocchi. 1999. Calculating Penman-Monteith ET with limited data. ASAE Paper No. 992113, St. Joseph, MI., 1999.
6. Peralta, J.M., C.O. Stockle, and D. McCool. 2001. Evaluating a simple model for freezing and thawing in the Pacific Northwest. ASAE Paper No. 012139, St. Joseph, MI, 2001.
7. Peralta, J.M. and C.O. Stöckle. 2001. Surface runoff simulation using a numerical approach. Published in Proceedings, IV International Congress of Agricultural Engineering, May 9-11, 2001, Chillán, Chile.
8. Castellvi, F. and C.O. Stockle. Comparing the Performance of WGEN and ClimGen in the Generation of Temperature and Solar Radiation. Trans. of ASAE (In review).
9. Castellvi, F., C.O. Stockle, and M Ibanez. Comparing a locally-calibrated versus a generalized temperature generation process. Trans. of ASAE (In press).
10. Stockle, Claudio O., Jan Boll, Shulin Chen, and Donald K. MCool. 2001. A Problem-solving Tool for Mitigating the Impact on Water Quality of Management Practices in Small Rural Watersheds. State of Washington Water Research Center, Washington State University, Pullman Wash. Report WRC01-02, 15pp.

Problem and research objectives:

A productive approach for watershed water quality improvement is to act at relatively low levels of integration (i. e., small watersheds). At this scale, the number of landowners and water quality issues involved is limited. Analysis and implementation of corrective solutions are more manageable than when evaluating large basins as a whole. Evaluating water quality changes in smaller watersheds also means that changes in watersheds within a larger basin can be compared and analyzed. The objective of this project is to develop a computer-based tool for small watershed analyses applicable to the Pacific Northwest (PNW) where rain and snowmelt, often on frozen soil, dominate runoff and sediment production. However, the framework must be generic enough for applications elsewhere.

Methodology:

The following tasks were accomplished to address the objective of this study:

1. Develop a geographic information system for data management and display.
2. Finalize and test a weather generator to produce long-term series of daily weather data.
3. Develop a hydrologic model that includes the effects of snow accumulation/melting and frozen soil conditions as they occur in the Pacific Northwest.
4. Develop a cell-based surface and subsurface-hydrology simulator, including overland water and groundwater loading estimates.
5. Improve and test a simulator of productivity and water and nutrient balances for crop, range, and forestlands to be applied in each cell.
6. Develop a state-of-the-art user interface to handle the GIS-based watershed database and weather records, parameterize the simulators, specify changes in management practices over crop, range, or forested lands, and provide utilities for output customization, risk, and frequency analyses.
7. Apply the tool to a real watershed as a case study.

Principal findings and significance:

A protocol for interfacing simulation models with ARC/INFO GIS software was developed. The Spatial Analyst for ARCView, a commercially available and widely used software package was customized for geographical/spatial hydrologic analyses that are relevant to this project.

The technical development, testing, and programming of a user-friendly weather generator software package (ClimGen) was finalized, including features to improve temperature generation and to estimate solar radiation and vapor pressure deficit from temperature data, the latter allowing the application of the watershed model to areas with limited availability of weather records (see Castellvi and Stockle, 2001; Castellvi et al., 2001). Table 1 presents a comparison of actual and generated precipitation (P in mm), fraction of wet days (fwet), maximum (Tmax in degrees Celsius) and minimum (Tmin in degrees Celsius) temperature, solar radiation (St in MJ m^{-2} day^{-1}), vapor pressure deficit (VPD in kPa) and wind speed (U in m s^{-1}) for several world locations (Stockle et al., 1998).

Table 1. Statistics and indicators of agreement between generated and actual daily records for several world locations, summarized for monthly periods.

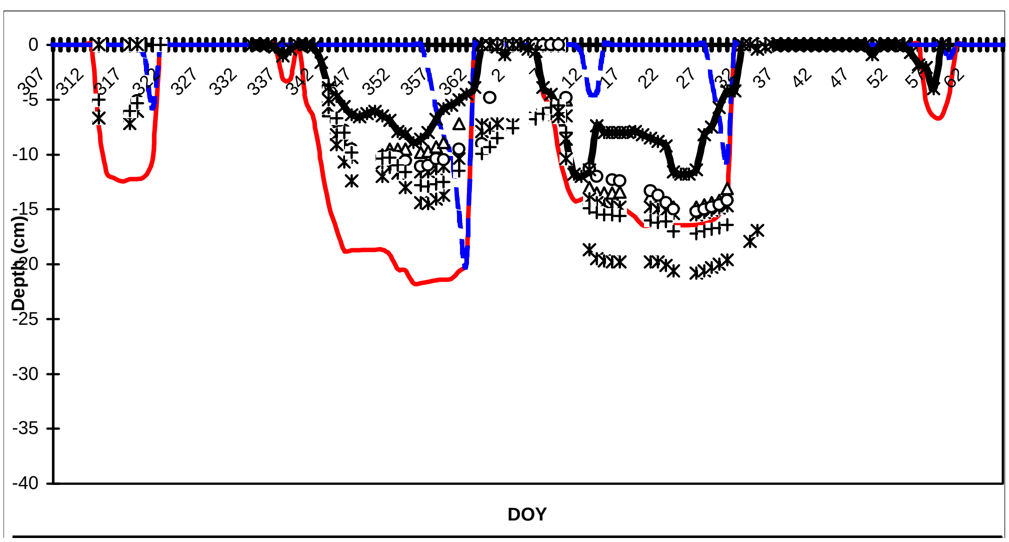
Location	Statistics		P	f_{wet}	T_{max}	T_{min}	S_t	VPD	U
Akron, Colorado	Actual	Mean	33.434	0.187	17.204	1.498	16.989	-	-
		Stdev	27.490	0.076	10.670	9.459	6.480	-	-
	Generated	Mean	33.230	0.189	17.253	1.576	16.592	-	-
		Stdev	25.916	0.074	10.573	9.327	6.328	-	-
		RMSE	4.382	0.014	0.376	0.310	0.457	-	-
		GSD	0.020	0.075	0.022	0.206	0.027	-	-
		d	0.999	0.989	0.999	0.999	0.998	-	-
Haarweeg, The Netherland	Actual	Mean	63.185	0.468	13.248	5.290	9.168	0.671	2.412
		Stdev	9.840	0.047	6.890	5.109	6.101	0.396	0.293
	Generated	Mean	65.855	0.480	13.256	5.128	9.279	0.704	2.420
		Stdev	10.599	0.068	6.747	5.178	6.031	0.404	0.285
		RMSE	0.194	0.026	0.273	0.334	0.198	0.049	0.033
		GSD	0.049	0.056	0.021	0.063	0.022	0.074	0.014
		d	0.998	0.939	0.999	0.999	0.999	0.995	0.996
Katherine, Australia	Actual	Mean	80.386	0.220	33.912	19.449	-	-	-
		Stdev	98.039	0.226	2.648	5.060	-	-	-
	Generated	Mean	80.733	0.221	33.988	19.425	-	-	-
		Stdev	98.075	0.223	2.509	5.029	-	-	-
		RMSE	4.833	0.016	0.196	0.161	-	-	-
		GSD	0.007	0.075	0.006	0.008	-	-	-
		d	0.999	0.998	0.998	0.999	-	-	-
Pisa, Italy	Actual	Mean	73.578	0.263	19.792	9.899	12.466	1.149	1.691
		Stdev	30.518	0.083	6.778	5.641	6.422	0.546	0.207
	Generated	Mean	74.110	0.265	19.804	9.938	12.520	1.181	1.709
		Stdev	32.573	0.093	6.904	5.766	6.463	0.739	0.267
		RMSE	6.479	0.017	0.253	0.252	0.484	0.207	0.082
		GSD	0.015	0.065	0.013	0.025	0.039	0.180	0.048
		d	0.999	0.989	0.999	0.999	0.998	0.969	0.964
Tel Hadya, Syria	Actual	Mean	-	-	24.635	10.359	17.309	2.540	2.817
		Stdev	-	-	10.161	7.625	7.566	1.717	1.158
	Generated	Mean	-	-	24.499	10.245	16.982	2.554	2.808
		Stdev	-	-	9.996	7.300	7.363	1.649	1.144
		RMSE	-	-	0.419	0.590	0.489	0.154	0.059
		GSD	-	-	0.017	0.057	0.028	0.061	0.021
		d	-	-	0.999	0.998	0.999	0.997	0.999

RMSE = Root Mean Square Error (RMSE), GSD = General Standard Deviation ($GSD = RMSE/\overline{O}$, where $\overline{O}$ is the mean of the actual data), d = Willmott index of agreement. The lowest limit of RMSE and GSD is 0, indicating perfect agreement between generated and actual values. The index of agreement ranges between 0 and 1, where a value of 1 indicates perfect agreement.

The Hydrology Component

In the Pacific Northwest (PNW), the risk of large runoff and erosion events is often complicated by the occurrence of three or four cycles of freezing and thawing during the winter. High runoff events are usually associated with fast thaw of the soil due to rising temperatures or warm precipitation over the watershed. In addition, due to migration of water to the frozen layers, when the soil thaws, it becomes saturated and very susceptible to erosion. As soil freezes, the infiltration is reduced, the stability of the aggregate is decreased, and consequently, runoff, erosion, and non-point pollution are expected to increase. To incorporate these effects in the watershed model, a soil freezing/thawing submodel based on the Stefan solution (SM) with heat storage was developed. This submodel was tested against field data and the SHAW model, a detailed energy balance-based, short time step model, for the same set of conditions.

Simulated values of duration of the freezing periods, number of freezing cycles per season, and frost depth were compared with measurements. Snow and soil frost data were measured at the Palouse Conservation Field Station (PCFS) near Pullman, WA from 1983 to 1991 (Donald McCool, personal communication, 1999). Climatic data, including daily air temperature, precipitation, radiation, and other variables were also available. The submodel performed well in predicting soil freezing under the conditions of the PNW. The number of soil frost cycles was simulated well while the average length of the cycles was somewhat overestimated. The SHAW model overestimation of the average length of the frost cycles was greater than that of SM. The variability in the length of the cycles was well simulated by both models. Similarly, simulation of the start date of freezing cycles was also adequate, with a lag of around 5 and 3 days for the SHAW and SM models, respectively. SM overestimated the frost depth, on average by 1.2 cm, with a range from 12.2-cm underestimation to 8.9-cm overestimation. The SHAW model underestimated frost depth by 6.0 cm on average, with a range from 19.0-cm underestimation to 6.1-cm overestimation. Adequate prediction of snow depth appeared critical in the simulation of frost depth. Examples of the performance of the models are shown in Figure 1. For more information, see Peralta (1999) and Peralta et al. (2001).



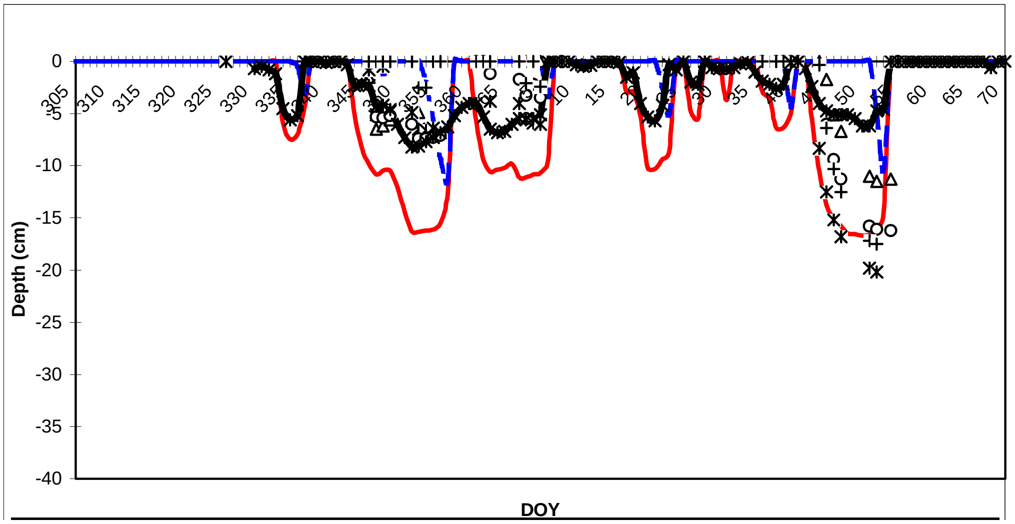


Figure 1. Comparison of simulated frost depth using the SM (thin line) and SHAW (thick line) with frost tube measurements (symbols). Data is for years 1986-87 (top) and 1989-90 (bottom), collected at the Palouse Conservation Farm near Pullman, WA.

Also in terms of hydrologic modeling, a one-dimensional finite difference numerical solution for water flow in the vadose zone was completed, including greater flexibility in boundary conditions, time step, and soil layering with the purpose of increasing the robustness of the numerical solution and/or computational speed. A sub-model to disaggregate daily rainfall into 30-minute intervals was developed.

A numerical model (NM) for runoff calculations was implemented and compared with the traditional Soil Conservation Service curve number approach (CN). Both methods were tested using data collected from 1978 to 1991 (McCool et al, personal communication, 1999), consisting of several runoff-erosion experimental plots located at the Palouse Conservation Field Station (PCFS) near Pullman, Washington. The soil in the site corresponds to a Palouse silt loam with a south-facing slope with 15.6 to 27.9% steepness. A few contrasting treatments were selected, including continuous bare fallow, tilled, winter wheat following summer fallow, tilled, and winter wheat following winter wheat, direct stubble, or no-till seeded. A few years of data, from a continuous mowed and baled bromegrass treatment were also included.

The NM model showed the best agreement with the observed data, although some overestimation of the runoff for conditions that include residue and grass was found during the winter and, more markedly, in spring (Figures 2 and 3). The CN model performed adequately for bare soil, but it overestimated runoff for the rest of land uses.

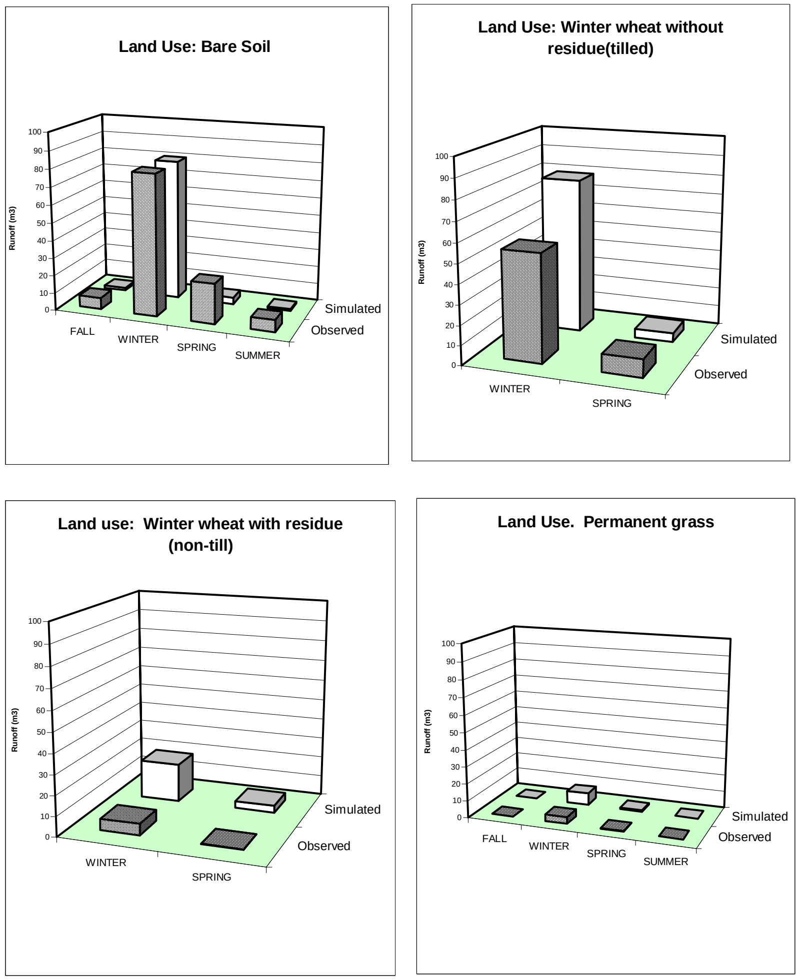


Figure 2. Total observed and simulated runoff, grouped by season and land use. Runoff determined by the numerical method (NM).

NM underestimated under bare soil conditions, which was attributed to soil surface sealing. The performance of the model improved when the hydraulic conductivity of the top layer was reduced by a 10-fold to indicate degradation of surface structural conditions (Fig. 4). The model seems sensitive to this parameter, which may show significant spatial and temporal variation. Temporal variations can be attributed to soil structure deterioration after winter runoff, producing crusting and soil sealing that leads to less infiltration capacity. For more details, see Peralta (1999).

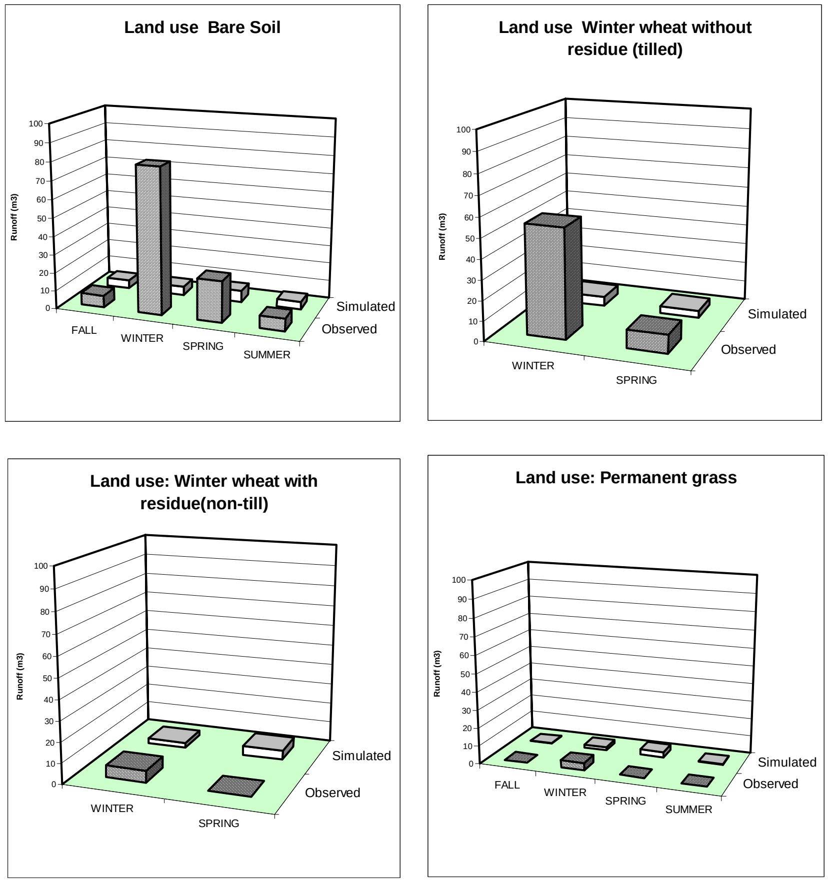


Figure 3. Total observed and simulated runoff, grouped by season and land use. Runoff determined by the original SCS CN method.

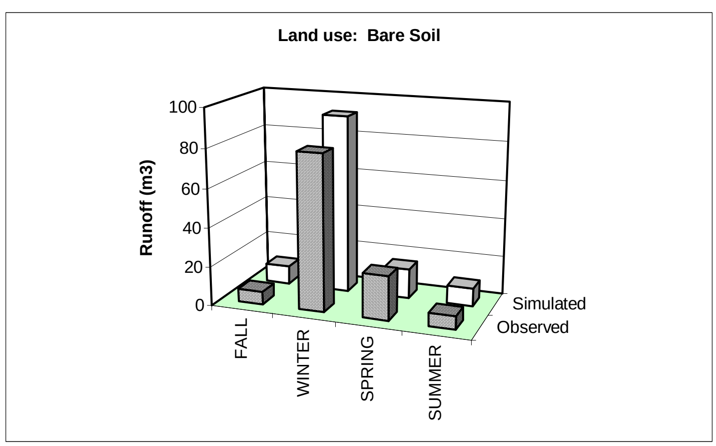


Figure 4. Total observed and numerically simulated runoff, for bare soil, grouped by season. Hydraulic conductivity of the first layer reduced by a factor of 10.

The lateral hydraulic conductivity is a sensitive parameter in the model when simulating for the typical landscape conditions of the PNW. To further understand the magnitude of lateral saturated hydraulic conductivity in the Palouse region, a 18 m x 30 m isolated hillslope plot, was installed at the Troy catchment (Fig. 5). Upslope lateral flow was diverted using a tile line installed on the hydraulically restrictive fragi-pan located approximately 0.75 m below the soil surface. The downslope lateral flow was collected in a tile line and measured using an automated tipping bucket installed in an insulated winter shelter. A surface runoff trough was installed and plumbed to a tipping bucket to quantify the magnitude and timing of surface runoff. The plot boundary was isolated using sheet metal plot borders. To ensure subsurface water did not bypass the tile lines, plastic sheeting was installed along the borders from the fragi-pan to the soil surface. Three automated piezometers measured perched water table fluctuations twice a day while five piezometers were measured during each site visit to identify the drawn down curve of the water table to the downslope tile line.

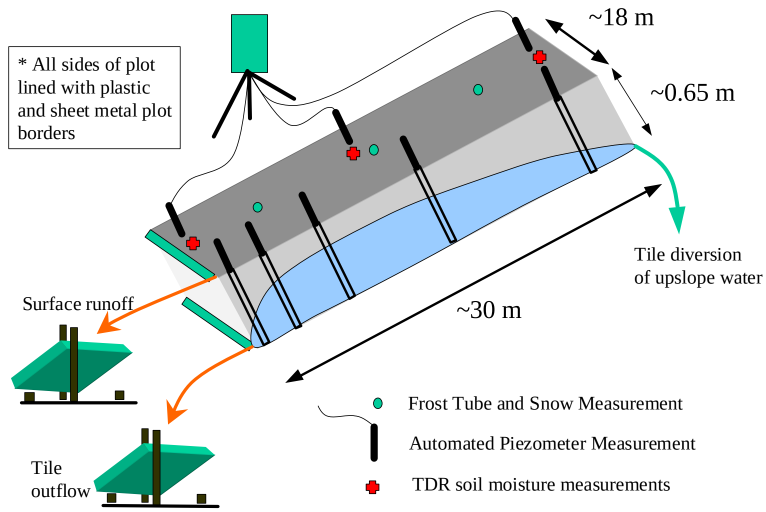


Figure 5. Hillslope plot layout and instrumentation.

The data collected from the plot was used for several purposes. First, a mass balance of the water in the plot gave an estimate of the amount of water that vertically percolates through the fragi-pan layer. Secondly, the rate at which the plot drains during the spring melt was used to calculate the effective lateral hydraulic conductivity of a 18 x 30 m block of soil in a landscape. The calculated lateral hydraulic conductivity was compared to watershed scale estimates using drought flow analysis and soil core scale (< 10 cm) hydraulic conductivity.

In this study (Brooks et al., 1999), 88% of the total precipitation left a 18 x 30 m hillslope plot having a fragipan at ~ 65 cm as subsurface lateral flow. The lateral K_{sat} decreased exponentially from 13.4 m/day and the soil surface to less than 0.5 m/day near the fragipan. These measurements of lateral K_{sat} were on average 7 times larger than vertical K_{sat} measured on 8 cm diameter soil cores and 7 times larger than the vertical K_{sat} indicated in the soil survey. A mass balance on the plot indicated that the vertical percolation rate through the fragipan layer is on the order of 0 to 0.01 cm/day. These findings indicated that the hydrology of the region is dominated by subsurface lateral flow that is the main driving force in the generation of variable source area saturation excess runoff. The measurement of the lateral K_{sat} and the percolation rate through a fragipan soil will reduce the calibration required in distributed hydrologic models developed for this region.

A bromide tracer study was conducted within the hillslope plot during melt conditions. Bromide was placed 7 m upslope of the tile line. The first bromide was detected at the tipping bucket after 9 hours, indicating a travel time of approximately 19 m/day. The peak bromide concentration occurred after 60 hrs. Both these findings confirm the large influence of subsurface lateral flow on the hydrology of the catchment.

In addition to the hillslope plot, monitoring continued at the Troy ID catchment including automated perched water table measurements throughout the 2 ha catchment, surface runoff measurements at the outlet, and a complete set of meteorological parameters. In order to test and validate the snow-melting algorithm in the model, snow water equivalent depth was measured at three locations representing different solar incident angles and snow drift patterns. Measurements were made weekly during snow accumulation and more intensively during melting conditions. Snow depth measurements were also made at each piezometer location (140 total) on two different days during snow melting conditions to validate how well the model can represent the spatial distribution of snow melting. Figure 6 shows predicted and observed snow water equivalent using a daily energy balance snowmelt model. The root mean square error between the measured and predicted points was 1.2 cm. The small error between predicted and observed values was produced with little calibration.

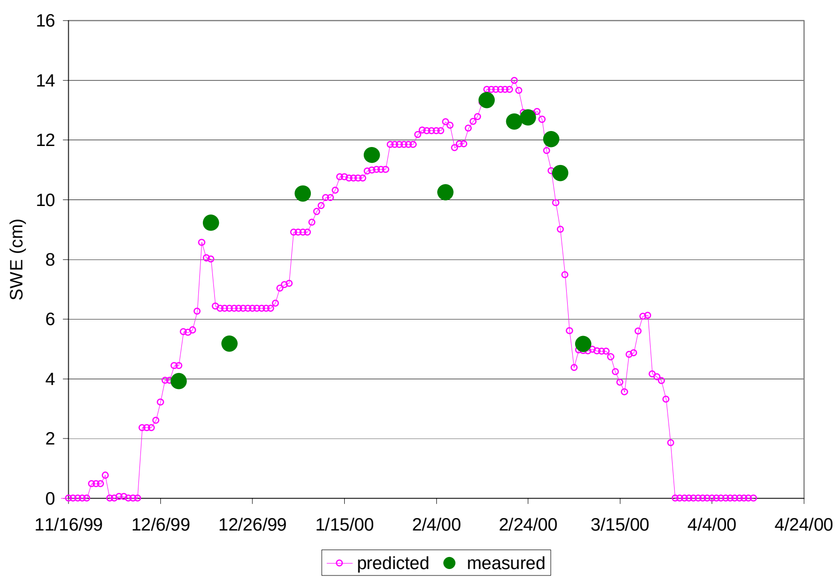


Figure 6. Measured and predicted snow water equivalent at the Troy ID catchment.

As discussed above, in the Palouse region the runoff and erosion is highly accelerated by a shallow frozen soil layer. When a soil freezes the soil pores fill with ice which significantly reduces infiltration and increases runoff. In order to quantify the reduction in infiltration due to a frozen soil layer infiltration experiments were conducted using a rainfall simulator. Runoff was measured from 1 m^2 plots installed before the soil froze in bare and tilled soil. Winter experiments could only be conducted on soil with a relatively thin (<10 cm) frozen soil layer due to the warm winter. The experiments showed that the infiltration on average was limited for a short period of time (~10 minutes) before macro-pores thawed and conducted the water through the frozen soil layer.

The Erosion Component

Calculations of sediment detachment, transport, and deposition based on the stream power approach were explored. In order to apply and test the erosion component it was necessary to conduct field experiments under typical thawing conditions of the Palouse region. Rill erosion experiments similar to the WEPP cropland soil field erodibility experiments were conducted in the summer on unfrozen tilled soil, in the winter of partially frozen soil, and in the spring on near saturated soil that had settled over the winter due to freeze/thaw cycles. Table 2 presents the average erodibility parameters for all events, and for the frozen, thawing, and unfrozen events separately (Brooks et al., 2001).

Table 2. Average K_{rc} (clear water rill erodibility), K_{rs} (sediment laden rill erodibility), and β (stream power erodibility parameter)

Description	Average	Standard Deviation	Number of Events
K_{rc} (K_{rs}), All events (s/m x 10^3)	1.14 (0.91)	1.66 (1.11)	73
K_{rc} (K_{rs}), Frozen events (s/m x 10^3)	0.19 (0.17)	0.56 (0.49)	12
K_{rc} (K_{rs}), Thawing events (s/m x 10^3)	1.82 (1.40)	2.32 (1.49)	14
K_{rc} (K_{rs}), Unfrozen events (s/m x 10^3)	1.18 (0.96)	1.53 (1.01)	47
β, All events	0.847	0.122	73
β, Frozen events	0.656	0.117	12
β, Thawing events	0.897	0.088	14
β, Unfrozen events	0.881	0.080	47

Frozen soil erodibility values were much lower than unfrozen or thawing erodibilities. Thawing soil erodibilities were not significantly different from unfrozen soil erodibilities. This could be attributed to thawing soil events which start frozen and have little soil erosion until the soil significantly thaws. The erodibility of a soil tends to decrease over winter indicating consolidation effects are present in Palouse soils. Manning's n and the depositability were the most sensitive parameters to calculate K_{rc} and β, respectively.

Despite this effort, a reliable implementation of the stream power approach for predicting soil erosion by water was not reached, and it has not been implemented in the current version of the watershed model. As an alternative solution, a dynamic implementation of RUSLE (Revised Universal Soil Loss Equation) was implemented within the crop growth simulator. Because RUSLE predicts soil loss and not watershed sediment yield, an approach was implemented to estimate sediment delivery ratio (eroded sediments that actually reach a continuous stream system) based on the following assumptions: a) the delivery ratio represents a steady state index of long-term delivery potential to a continuous stream, and b) the model variables are linearly combined, with uncertainties regarding the effects of variable interdependence. Figure 7 shows gross soil erosion from RUSLE for the Lawyer Creek Watershed, ID.

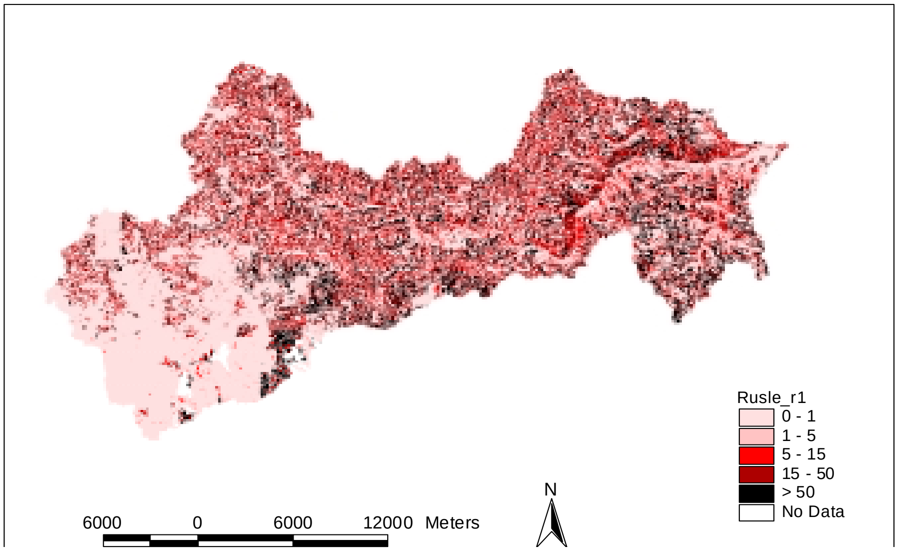


Figure 7. Gross Soil Erosion of Lawyers Creek Watershed (tons/ha/year)

To determine sediment delivery ratio (SDR), the mean travel time of all cells in the raster GIS representation of the watershed must be estimated, which is dependent on cell elevation and land use. An empirical B coefficient relates travel time and land use with SDR. For a typical land use of dryland agriculture at Lawyer Creek (similar to other dryland regions in the PNW), it was found that B could be estimated as a function of median travel time (Figure 8). Using these B values, the resulting sediment delivery ratios for the watershed are shown in Figure 9.

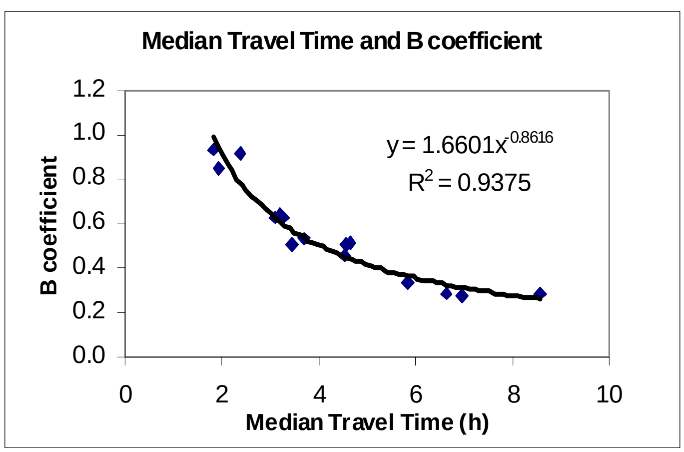


Figure 8. Relationship between B coefficient and median travel time

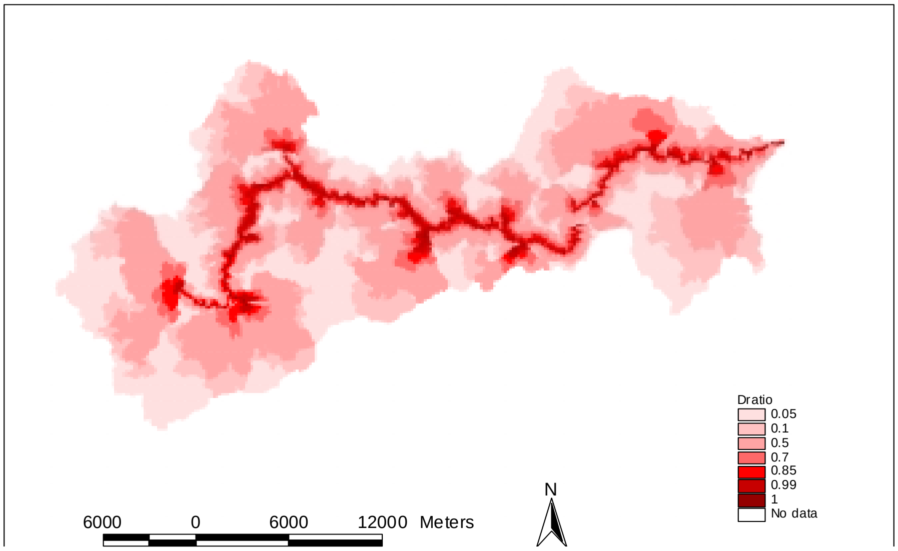


Figure 9. Sediment Delivery Ratio for Lawyers Creek Watershed

Watershed Model

The watershed model is currently operational (CropSyst Watershed), although more work will be required before reliable applications are possible. A first complete version of the user interface, data handling, simulation control, and output handling are available. Completely tested and evaluated weather generator (ClimGen) and cropping systems simulator (CropSyst) are built into the program. For more details and to download a preliminary version of CropSyst Watershed, visit bsyse.wsu.edu/cropsyst. Ongoing work will result in future improvements, which will be also made available in the web site.

In order to simulate surface transport of excess water (runoff), an analytical solution was developed for overland flow over a hillslope based on the Saint-Venants equations (Wang et al., 2001). This solution was designed specifically for the application in a GIS cell-based model. The analytical solution was tested using published data. This approach has not been found practical yet for implementation in CropSyst Watershed. A simplified kinematic wave approach is being studied for possible implementation to estimate overland flow.

A volume-based (cascade) approach is currently implemented in Cropsyst Watershed, similar to that used by the Soil Moisture Routing (SMR) model that was tested in conjunction with the hillslope experiment in the Troy catchment described above. Figure 10 shows a comparison of measured and predicted runoff (and snow water equivalent, SWE) at the outlet of the 2-ha catchment.

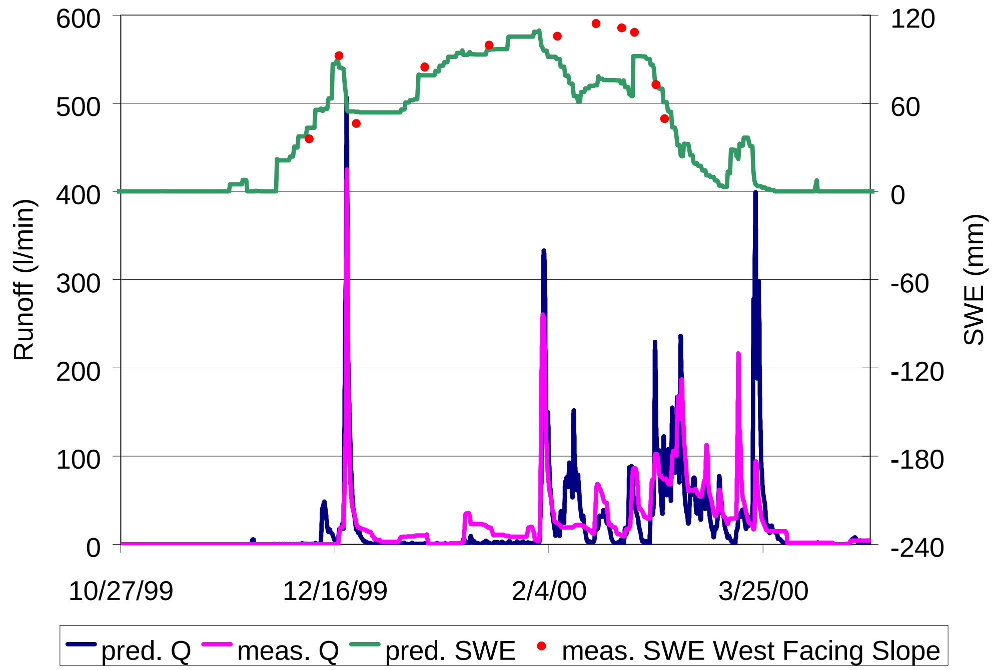


Figure 10. Measured and predicted runoff at the outlet of the 2-ha Troy ID catchment. Measured and predicted snow water equivalent for the period are shown on top.

The RUSLE-based erosion and sediment yield component of the watershed model described above are not functionally incorporated into the program interface at the time of this report. This and other new features of the software will be posted in the web site as they become available. Development of this tool will be a continued effort.

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Basic Information

Title:	Erosion of Cohesive Streambeds and Banks
Project Number:	WA-06
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Engineering
Focus Category:	Sediments, Hydrology, None
Descriptors:	Cohesive strength, bank erosion, secondary currents, soil erosion, stream sedimentation, watershed management.
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	THANOS PAPANICOLAOU

Publication

1. Papanicolaou, A. and Hilldale, R. Turbulence Characteristics in a Gradual Channel Transition. Journal of Engineering Mechanics (paper has been accepted).
2. Hilldale, R. and Papanicolaou, A. 2001. Re-suspension of Cohesive Materials is Streams Due to Turbulent Structure. Paper published at the Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25-29, 2001, I-176-I-183.
3. Hilldale, R. and Papanicolaou, A. Turbulence Characteristics in a Natural Channel Downstream of a Transition. Submitted for inclusion in the Proceedings of the World Water and Environmental Resources Conference, May 20-24, 2001, Orlando, FL
4. Papanicolaou, A. 2001 Erosion of Cohesive Streambeds and Banks. State of Washington Water Research Center, Washington State University, Pullman, Wash. Report WRC01-03. 24pp.

Problem and research objectives:

A disparity exists in the field of sediment transport between the knowledge of cohesive and non-cohesive sediment transport processes. Available literature on cohesive sediment transport lags behind that of sand and gravel transport processes, due largely to the complex and widely varied nature of particle bonds in cohesive soil. These complex particle bonds greatly complicate calculations of settling properties and a critical stress for erosion. Resuspension of cohesive soils has become a major concern in recent years due to the unique ability of cohesive soils to adhere to organic contaminants and heavy metals due to their large specific surface and reactive nature. Also of recent concern is the loss of spawning habitat for threatened or endangered fish species whose eggs become oxygen starved when laid in gravel beds contaminated with fine-grained soils.

To determine the resuspension criteria of cohesive soils, two factors must be accurately determined; 1.) The strength of the interparticle bonds that make up the soil and, 2.) The stresses imparted by the flowing water (considering turbulence and secondary currents) to break these particle bonds. These two factors combine to form the overarching goal of this field investigation, which was carried out in Union Flat Creek near Pullman, Washington.

Union Flat Creek has a bed consisting of coarse and medium gravel while its banks are a homogeneous combination of fine sand, silt and clay. The soil in the region is a result of aeolian soil deposits (loess) (Alt and Hyndman, 1996) that have been acted upon fluvially by the waters of Union Flat Creek. Since these soil deposits are not fluvially derived they do not exhibit the characteristic increase in particle size with depth as fluvially deposited soils do. As a result the bank soil in Union Flat Creek is homogeneous. This site was chosen so that an analysis of cohesive soil strength could be preformed, thus evaluating fluvial erosion of cohesive bank soils.

The specific location within Union Flat Creek chosen for this study is downstream of a channel transition, where flow is constricted to approximately one third of its width and then gradually expands, returning to the width that exists upstream of the transition. It is downstream of this expansion that three-dimensional velocity measurements were taken in seven vertical locations, resulting in 158 points of instantaneous velocity in a transverse-vertical plane. This location was chosen for the purpose of determining turbulence characteristics downstream of a gradual channel expansion. When flow enters an expansion it decelerates causing the Reynolds stresses to increase in magnitude (Song and Chiew, 2001). It was also determined that the flow is three-dimensional with secondary currents of Prandtl's second kind forming as a result of the gradual expansion. Little information is available on the subject of turbulence characteristics of expansions in natural channels, justifying the research performed in this study.

It is necessary to define the strength terms used throughout this paper, which is consistent with recent literature relating to the strength of cohesive soils. The *mechanical strength* of a soil is a macroscale quantity describing its undrained strength (or yield strength). This is the strength at which mass failure occurs such as the slip failure of a streambank (Millar and Quick, 1998). *Erosional strength* is a microscale quantity describing the strength provided by interparticle forces of attraction (Zreik et al., 1998). *Fluvial erosion* (or surface erosion) describes the entrainment of individual particles or aggregates due to the shearing action of the flow (Millar and Quick, 1998).

Many authors (e.g. Casagli and Rinaldi, 1999 and Darby et al., 2000) have investigated cohesive strength of river banks on a macroscale, evaluating mass failure of streambanks due to pore pressure changes or severe bed degradation. Mass failure is defined as the slumping or collapse of a riverbank when a critical height has been exceeded (Millar and Quick, 1998). However these failures are also the result of the timely removal of individual grains or aggregates by fluvial erosion. When fluvial erosion occurs at the bank toe, mass failure ensues due to the removal of the support mechanism. The resulting failure can be a slip failure or slumping of the bank resulting from cantilever failure. This study investigates both the erosional strength of cohesive soils and the turbulent stresses required to erode these soils fluvially.

The mechanical strength of bank soils is greatly increased by the presence of a system of roots (Millar and Quick, 1998). These authors qualitatively evaluate this effect but no quantitative value has been determined for the strength increase due to the presence of grass roots in a bank soil. This study will present a quantitative strength increase provided by the roots of Reed Canary Grass.

The objectives of this study are to develop an integrated approach to determine the erodibility of cohesive bank soil. This will be carried out by: 1.) Finding the critical strength for erosion of the cohesive bank soils, 2.) Determine the in-stream stresses applied by the flowing water acting to erode the cohesive bank sediment and 3.) Determining the turbulence characteristics downstream of a channel expansion.

2. Methodology:

Site Description

The location chosen for this study is a reach of Union Flat Creek that is approximately five miles south of Pullman, WA. This location was chosen because 1.) Its banks are composed of cohesive soil, 2.) The stream is small enough to allow velocity measurements to be taken with a reasonable amount of effort and 3.) Its close proximity to the WSU campus. Union Flat Creek flows through a small valley that is under wheat production during the summer months and lies dormant after harvest. Soils in the area are composed of Palouse loess, an aeolian derived soil deposit that covers the entire Palouse region and reaches depths of 61 meters in some places (Alt and Hyndman, 1998). In other areas the basalt layer, which also extends across the region, is exposed (Alt and Hyndman, 1998), as is the case in Union Flat Creek.

The site was surveyed with a Topcon Electronic Distance Measuring (EDM) device to establish channel widths, bank height and the water surface slope. The reach of Union

Flat Creek surveyed for this study is shown in figure 2-1 (this drawing is not to scale). The shaded areas indicate regions of weed growth that are exposed year-round except for run-off in the spring. The specific location of the cross section (denoted XS-1 in this figure) is in a braided portion of the reach, where the local slope is greater than the reaches immediately upstream and downstream. This cross section was intentionally chosen in order to study the role of morphology on turbulence. Two islands approximately 18 meters long create three separate channels. Of these three channels, the one with the greatest flow was chosen for taking velocity data. The elevation of these islands is coincident with the terrace. Figure 2-2 is a photograph of Union Flat Creek taken from the bridge shown in figure 2-1. The upper bank of the channel is hidden by weed growth on the terrace except in the upper left corner of the photo.

The compound nature of this channel is shown in figure 2-3. Flow is limited to the thalweg except during spring run-off. Reed Canary Grass (Phalaris arundinacia) completely dominates the vegetation growing within the channel. The average height of the upper bank is 1.8 meters and the average height of the lower bank is 0.6 meters. At some locations upstream of the braided portion of the reach, the banks are being undercut, resulting in the formation of a cantilever. This is also shown in figure 2-3. No such cantilever exists at the measuring location.

The bank material in Union Flat Creek is cohesive soil and the bed is composed of coarse gravel (figure 2-4). The coarse gravel portion of the streambed is 13 cm deep, underlain with a layer of fine gravel and sand 23 cm deep. Beneath that is a basalt layer that stretches across the region (Alt and Hyndman, 1996). The reported substrate depths are average values for the reach and were determined with a penetrometer. While the penetrometer does not provide accurate readings of strength for gravel, the readings can indicate a drastic change in substrate, as is the case here.

The largest gravel sizes ($> d_{84}$) are located randomly throughout the bed, located at a distance of six to eight times their d_{84} from their neighboring particles. This creates an isolated flow regime (Three roughness regimes exist, the isolated, wake and skimming Morris (1955), Schlichting (1968), White (1991), and Papanicolaou et al. (2001)). The isolated roughness is present when the flow field around individual roughness elements does not affect their neighboring particles (Morris, 1955).

For the analysis of turbulence as it relates to morphology it is necessary to have a scaled drawing for determination of specific conditions. Figure 2-5 is a scaled drawing of the channel 6.3-m upstream of the measurement location. This section shown here lies within the portion of the small channel formed by the island on the left side of the main channel. As can be seen the channel is constricted to a width of 44cm, approximately a reduction of 1/3. The channel gradually widens, returning to nearly the same width at the measurement location. Downstream of the measurement location (not shown) the channel remains straight until it meets the other two channels at the end of the islands.

3.2. ***Sediment Analysis***

3.2.1. Sediment Sampling Gravel samples from the bed were taken in order to gain information about the bed roughness and roughness regime (i.e. isolated, wake interference or skimming flow) of the channel. More than 60 lb. of gravel was taken from the top layer of the streambed to a depth approximately equal to the d_{84}. This was done far enough away from the measurement site that flow characteristics were not changed. These sediments were sieved in accordance with current ASTM standards. The soils at the site were sampled at three locations; the lower bank, upper bank and in the wheat field above the channel's left bank (see figure 2-3). These sediments were also sieved in accordance with ASTM standard and size distributions obtained for each. Because a significant portion of the soil from all three sites passed the number 200 sieve (75 μm) it was necessary to supplement the size distribution with a hydrometer analysis in order to obtain a complete distribution. The soil passing the number 200 sieve was retained and used for the hydrometer analysis.

3.2.2. Soil Properties Once a complete distribution of sediment sizes is obtained, the soil content can be determined using the sediment grade size chart published by Lane, (1947) and accepted by the Federal Interagency Subcommittee on Sedimentation as the standard grade size chart for sediment. Soil content will provide a breakdown of the types of soil (clay, silt, sand, etc.) that exist in a given sample.

Water content is a quantity expressed in percent that describes the amount of water held in the pores of the soil. Four samples each of soil from the upper and lower bank were taken from the site and brought to the lab in airtight containers to prevent evaporation. These samples were used to determine the natural water content.

The direct shear test is commonly used in soil mechanics to determine two properties of soil: 1) The angle of internal friction, ϕ (or the angle of repose) and 2) the cohesion, c. Briefly, a plot of at least three shear stress (y-axis) vs. applied normal stress (x-axis) values is plotted. This data will plot such that a straight line (least squares method) can be applied to the data. The friction angle is taken from the slope of this line and the y-intercept is commonly used in soil mechanics as the value for cohesion.

It is important to note that the value of cohesion determined in this manner is theoretically flawed (Schofield, 1998). Common practice is to continue the line (created by the applied normal stress vs. shear stress data) straight to the y-intercept to obtain the 'apparent cohesion.' Any shear stress that might be obtained at zero normal applied stress is not a result of soil cohesion but a result of interlocking of the soil particles, which is minimal because no normal stress is applied to force interlocking to occur. That is to say that the soil particles slide over one another rather than becoming interlocked due to the lack of an applied normal stress. Cohesion can only result from electro-chemical bonds formed between soil particles as a result of aging. For this reason only the angle of internal friction was obtained from this test. 'True cohesion', the strength at which interparticle bonds are broken is determined in this study via the flume tests.

However, because of the confusion surrounding the term ‘cohesion’ and the application in this study, this parameter is referred to as the erosional strength.

3.3. *Soil Strengths*

Two types of soil strength were evaluated in this study, mechanical and erosional. Mechanical strength was determined so that it could be compared to the erosional strength, which will support the hypothesis that erosional strength is the appropriate value to use as the critical shear stress for fluvial erosion. Mechanical strength was also determined so that the rooted, in-situ strength could be compared to an unrooted sample to determine the strength increase due to the presence of roots. Erosional strength will determine the stress required to break the interparticle bonds formed, determining the critical stress for erosion of individual particles or aggregates.

3.3.1. Mechanical Strength Three methods of determining mechanical strength were used in this study: 1.) Torvane tester, 2.) Unconfined compression test and 3.) Fall cone device. Most commonly used was the Torvane tester. This is a hand-held device that tests undrained shear strength (yield strength) of surficial soil. It is very simple to use and proved to be quite accurate in determining the in-situ mechanical strength of the soils in Union Flat Creek. In order to gain confidence in the Torvane, its results were compared to unconfined compression tests performed on identical soil samples. Average values using both methods indicated the same strength values.

To determine the increased soil strength provided by the roots of the Reed Canary Grass, it was necessary to reconstruct the soil sample with the roots removed. Once a proper rootless sample was obtained, its strength was determined with a fall cone test and the Torvane after the sample was properly aged and brought to the proper water content. Again both tests recorded very similar readings. The fall cone device is used to test weak soils.

3.3.2. Erosional Strength To determine the erosional strength of the soil a tilting, recirculating flume was used in conjunction with an undisturbed soil sample. This procedure closely matches the method of Dennett et al. (1998) with the exception of an undisturbed soil sample being used in this study. A diagram of the flume used in this study and its dimensions are shown in figure 2-7 (photo in figure 2-8). Beads having a diameter of 8.0 mm were packed in layers upstream and downstream of the sample box to create a uniform roughness in the flume flush with that of the soil sample. The bottom layers are glass beads while the top layer of beads is lead (figure 2-7). This prevented erosion of the glass beads during the tests. The soil sample was located 113.7 cm downstream of the entrance (> 30 times the greatest depth) which insured a developed boundary layer at the soil sample. Through a momentum integral analysis Dennett et al. (1998) determined that a distance of 20 depths was sufficient to develop the boundary layer.

The soil sample was taken from the streambank (very near the location where velocity measurements were taken) as a large block. The soil block was transported and stored in the stream fluid as to not cause any undue disturbance to the soil (e.g. changes in pH or electrolyte concentrations). The sample was then carved to fit the planform dimensions of a sample box (8 cm x 25 cm) built to fit into the flume. After the sample was placed in the box it was trimmed to the depth of the sample box (2.5 cm) with a thin, narrow serrated blade to make the top of the sample flush with the sample box. Cutting the sample with a serrated blade was necessary due to the presence of roots in the soil. When the sample was completely carved and ready for test, it was returned to its own stream water to sit quiescently for 24 hours. This allowed the particles on the surface of the soil sample to restructure themselves, which somewhat compensated for the disturbance to the soil during carving. Suspended sediment was monitored upstream and just downstream of the soil sample via 0.5 cm diameter glass tubes bent at 90 degrees and placed with the center of the opening 0.5 cm above the bed of the flume (figure 2-7). One tube was used upstream and four tubes were placed across the width of the soil sample just downstream of it. (The fact that the number of sampling tubes upstream and downstream was not the same is of no consequence, since the measurement used is per unit volume.) When the concentration downstream of the soil sample was the same as the concentration upstream of the sample, it was considered that no erosion was taking place.

Just before testing began the sample box containing the soil sample was removed from the stream water and placed in the flume. The sample was run at low shear stresses to erode the loose material (caused by disturbances to the soil from carving) from the sample. The sample appeared to stabilize after just two or three minutes however the sample was prepared in this manner for 15 minutes as to insure the sample was completely stabilized. The flow was then increased to a predetermined shear stress, allowed to stabilize and then suspended samples were collected up and downstream for 30 seconds. This cycle was repeated for increasing applied shear stresses. The samples of suspended sediment were then filtered through a 47 mm diameter glass microfiber filter and dried in an oven at 105^0 C to obtain the dry weight of the sediment eroded and the concentration. The background concentration (upstream sample) was then subtracted from the downstream sample. If the downstream concentration exceeded that of the background concentration erosion was considered to have taken place. Uniformity of the flow was insured by the use of the tailgate before suspended sediment samples were taken in the flume.
The applied shear stress was calculated using the uniform flow equation ($\tau = \gamma HS$). This equation is accurate when flow is steady and uniform, as was the case during the tests. The uniform flow equation was shown by Dennett et al. (1998) to coincide with shear stresses calculated using the slope of the semi-logarithmic velocity profile (Clauser method) near the bed. Aspect ratios (width/depth) were always below four to insure that no significant secondary currents were formed during the tests. Song et al. (1994) determined that no significant secondary currents form at aspect ratios greater than 3.5.

The ideal test would use natural stream water as the eroding fluid however this is impractical when a large volume of water is needed. It was found that the tap water available had a pH level very close to that of the natural stream water (pH 7.9 for tap water and pH 8.2 of the stream water). The temperature of the eroding fluid was maintained at 17-18^0 C of the stream water at the time of the velocity sampling.

Bond strength of cohesive soils has many parameters, the most significant of which are discussed here. 1.) The pH of the pore fluid determines the orientation of the clay particles (e.g. edge to edge, edge to face or face to face), which is important because the van der Walls forces of attraction become more significant with an increased surface area (Ravisangar et al. 2001). It has been reported that face to face associations predominate above pH levels of 7.0 (Ravisangar et al. 2001), which is the case in this study. 2.) Salinity of the pore fluid increases the attractive forces of the particles (Arulanandan et al., 1975), increasing the resistance to erosion. 3.) High concentrations of natural organic matter decrease the critical shear stress of the soil (Dennett et al., 1998). 4.) Different clay types have different specific surfaces (Krone, R., personal communication), affecting the particles ability to bond. 5.) The amount of clay in a soil will affect its strength. Increased percentages of clay will increase the erosional strength while decreasing its mechanical strength. 6.) Temperature affects the viscosity of the fluid, increasing the shear stress with a decrease in temperature. Other temperature effects such as freeze-thaw can be neglected because the soil at the bank toe is always submerged, preventing such an occurrence. 7.) Bond strength is increased due to the extracellular polymeric substances excreted by benthic diatoms present in the soil (Daborn, 1993).

3.4. *Flow Conditions*

USGS gage number 13350500 near Colfax, WA reports flow rates for Union Flat Creek between 0.05 and 3.0 cubic meters per second (cms), exceeding 3.0 cms for short periods during run-off season (spring). This gage is located approximately 10 miles downstream of the studied reach of Union Flat Creek so the flows at the study site will be slightly lower.

Velocity measurements were taken on July 3rd, 2000. Flow conditions and general information about the cross section are shown in Table 3-1.

Q	**R_e**	**F_r**	**V_{bulk}**	**W_{avg}**	**D_{avg}**	**$Slope_{ws}$**	**W/D Ratio**
[m^3/s]	[---]	[---]	[m/s]	[m]	[m]	[---]	[---]
0.10	188,000	0.16	0.25	1.28	0.29	0.01	4.4

Table 3-1: Flow conditions and cross section information for Union Flat Creek.

3.4.1. Velocity Sampling Flow conditions in Union Flat Creek were determined by recording instantaneous velocity in seven profiles (figure 2-9). An acoustic Doppler velocimeter (ADV) manufactured by SonTek was employed, sampling at 25 Hz. The bottom three points at each location were sampled for two minutes, resulting in 3000 samples of instantaneous velocity. The remaining points were sampled for one minute, providing 1500 samples. Data points were taken one centimeter apart except for the bottom three points at each location, which were 0.5 centimeters apart. This was done so the near-bed region could be better defined. Stream conditions allowed the ADV to sample at approximately 0.5 centimeters from the bed. Due to mild surface disturbances and the sampling volume of the ADV being 5.5 centimeters below the probe tip, velocity data very near the surface could not be sampled. WinADV (version 1.843) in conjunction with a spreadsheet was used to evaluate all velocity information in this study.

Flow induced vibration of the ADV probe can cause elevated intensity readings (Dancey, 1990). Therefore it was necessary to construct a rigid platform on which to mount the ADV (figure 2-10) to prevent such vibration of the probe while sampling. This was accomplished by constructing the mount for the ADV from 2 inch and 1.75 inch square steel tubing, with the larger tubing allowed to slide smoothly over the smaller tubing (the 0.25" gap was taken up by the wall thickness of the tubing). This allowed for infinite transverse and vertical adjustment anywhere within the cross section. Adhesive tape graduated in millimeters was mounted to the horizontal and vertical small tubing so that horizontal and vertical movement of the ADV (mounted to the larger tubing) could be measured quickly and accurately. The larger tube was prevented from movement during sampling by thumbscrews that tightened to the inner tube. The ADV mount was fixed to scaffolding constructed from 2" x 8" planks attached to steel poles. Rigidity of the platform was provided by plywood fixed to the top of the scaffolding and supports forming an X pattern attached to the legs. The steel post legs rested on the banks of the stream so they would not interfere with the flow and bias the readings.

Throughout this report the following sign convention will be used. Streamwise, transverse and vertical directions are designated by x, y and z, respectively. Instantaneous velocity in the x, y and z directions is denoted by U, V and W, respectively. Time averaged velocity is $\overline{u}, \overline{v}$ and $\overline{w}$. Fluctuating velocities are represented by u', v' and w'. Turbulence intensities are the Root-Mean-Square (rms) value of the fluctuating velocity, designated by the subscript rms. The index i indicates x, y and z directions when used in conjunction with u (e.g. U_i is instantaneous velocity representing U, V and W).

Equation (3-1) shows the decomposition of instantaneous velocity, which is provided by the

$$U_i = \overline{u_i} + u' \quad (3\text{-}1)$$

ADV. An example of the time series ADV data can be seen in figure 2-11. These data sets contain 3000 points of instantaneous velocity, taken over a period of two minutes. The velocities are averaged to obtain $\overline{u_i}$. With U_i and $\overline{u_i}$ known, u_i' is determined for each sample by subtracting $\overline{u_i}$ from U_i'. Profiles of mean velocity ($\overline{u}, \overline{v}, \overline{w}$), Reynolds stress ($\overline{u'w'}, \overline{u'v'}$) and turbulence intensity ($u'_{rms}, v'_{rms}, w'_{rms}$) were used in determination of the turbulence conditions and stresses at the measurement location.

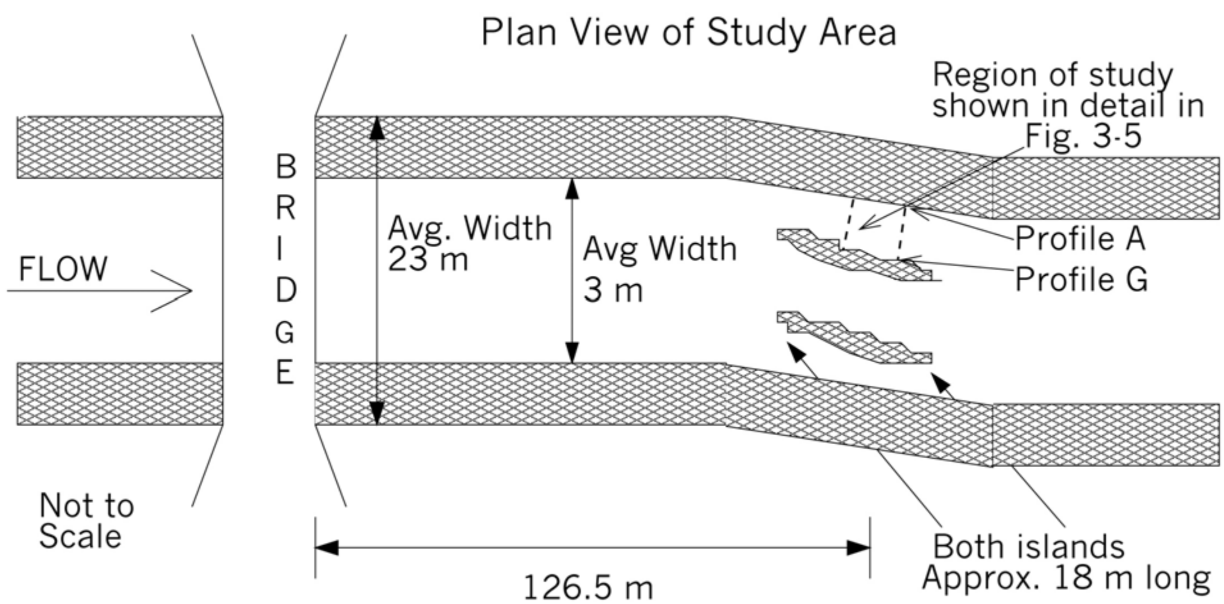

Figure 2-1: Diagram of studied reach of Union Flat Creek.

Figure 2-2: Photo of Union Flat Creek. Photo taken from bridge shown in figure 2-1. Note weed growth on the terrace portion of the channel. The upper bank is only visible in the upper left corner of the photo.

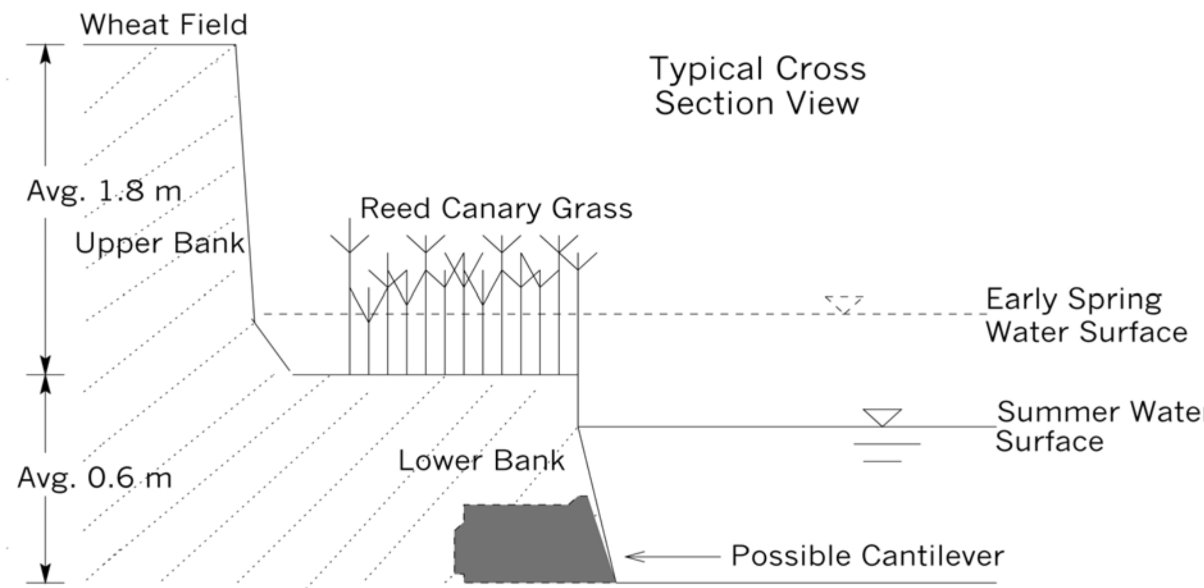

Figure 2-3: Detailed cross section of Union Flat Creek. The channel is symmetrical with average bank heights shown in the diagram. The cantilever shown does not exist at the measurement location however several locations upstream of the braided portion of the channel exhibit cantilevers, some as deep as 60 cm.

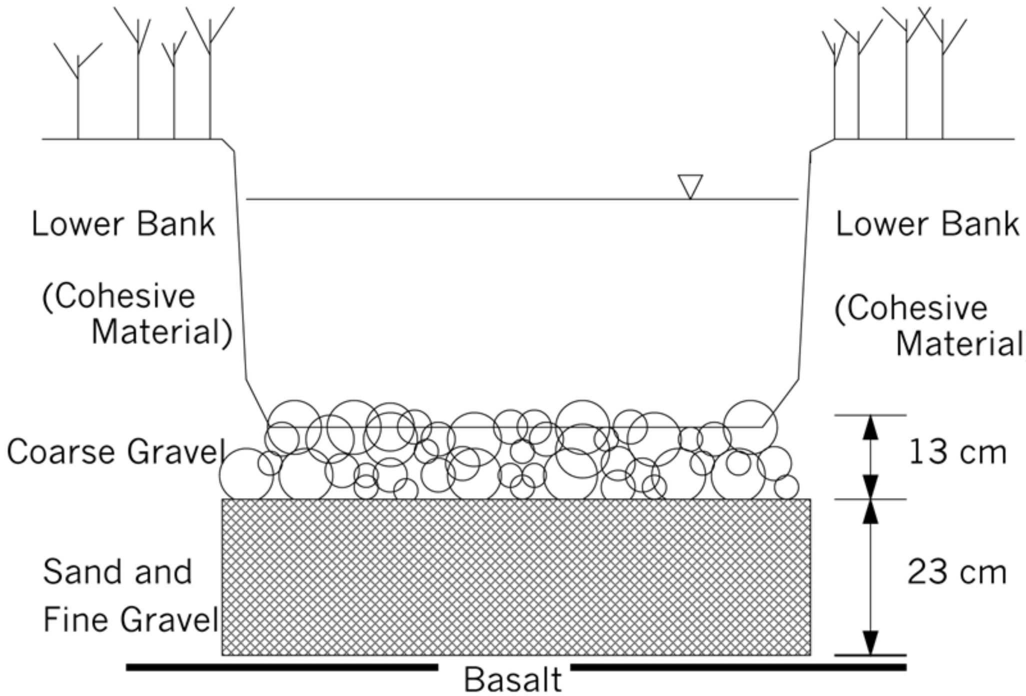

Figure 2-4: Simplified cross section showing the bed material of the lower bank and substrate. Depths shown are average for the reach studied and were determined with a penetrometer.

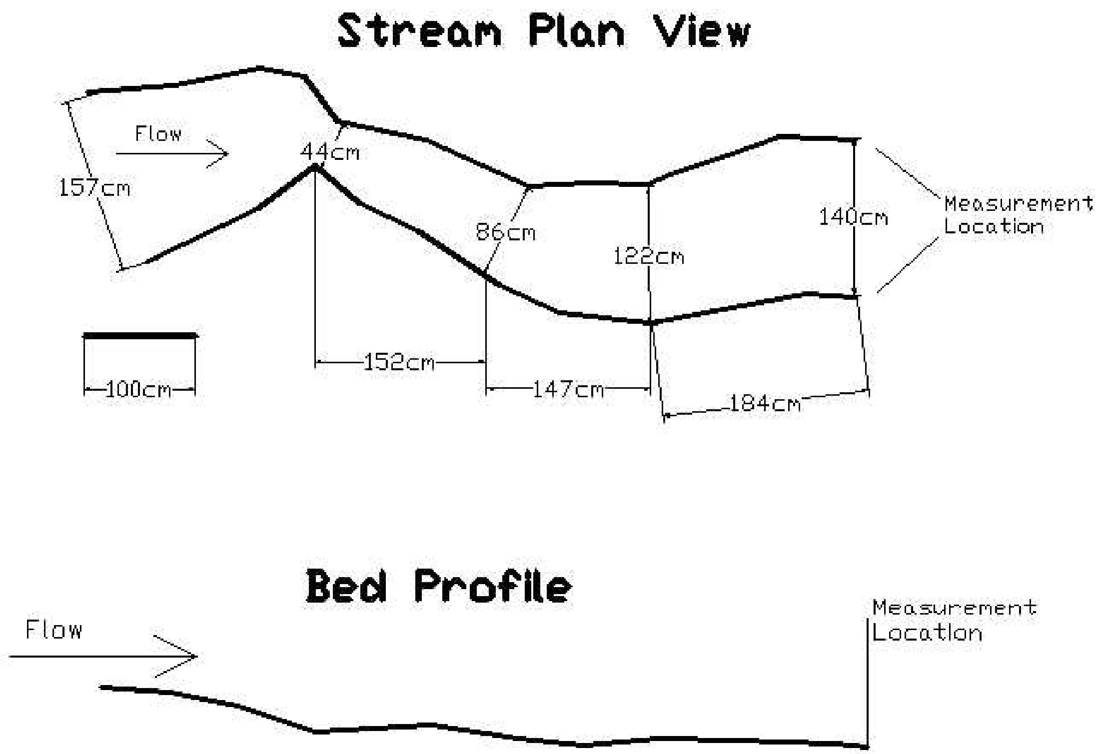

Figure 2-5: Detailed plan view and bed profile showing a distance approximately 8 m upstream of the measurement location. This section shown is entirely within the small channel formed by the left island shown in figure 2-1. Note the constriction shown has a width of 44 cm, approximately 1/3 of the upstream and downstream widths.

Size [mm]	Classification
4000-2000	Very large Boulders
2000-1000	Large Boulders
1000-500	Medium Boulders
500-250	Small Boulders
250-130	Large Cobbles
130-64	Small Cobbles
64-32	Very Coarse Gravel
32-16	Coarse Gravel
16-18	Medium Gravel
8-4	Fine Gravel
4-2	Very Fine Gravel
2-1	Very Coarse Sand
1-0.5	Coarse Sand
0.5-0.25	Medium Sand
0.25-0.125	Fine Sand
0.125-0.062	Very Fine Sand
0.062-0.031	Coarse Silt
0.031-0.016	Medium Silt
0.016-0.008	Very Fine Silt
0.008-0.004	
0.004-0.002	Coarse Clay
0.002-0.001	Medium Clay
0.001-0.0005	Fine Clay
0.0005-0.00024	Very Fine Clay

Figure 2-6: Sediment grade size chart used to determine the composition of bed and bank sediment within the channel (Lane, 1947).

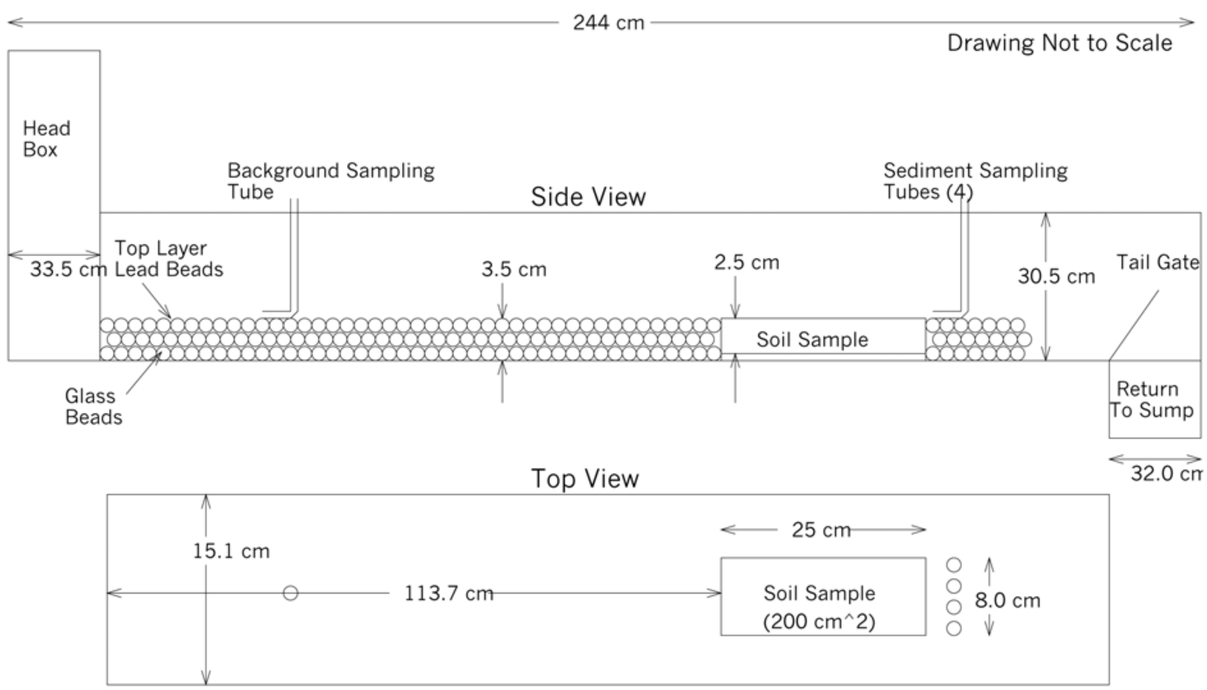

Figure 2-7: Sketch of the flume used to determine the erosional strength of the soil.

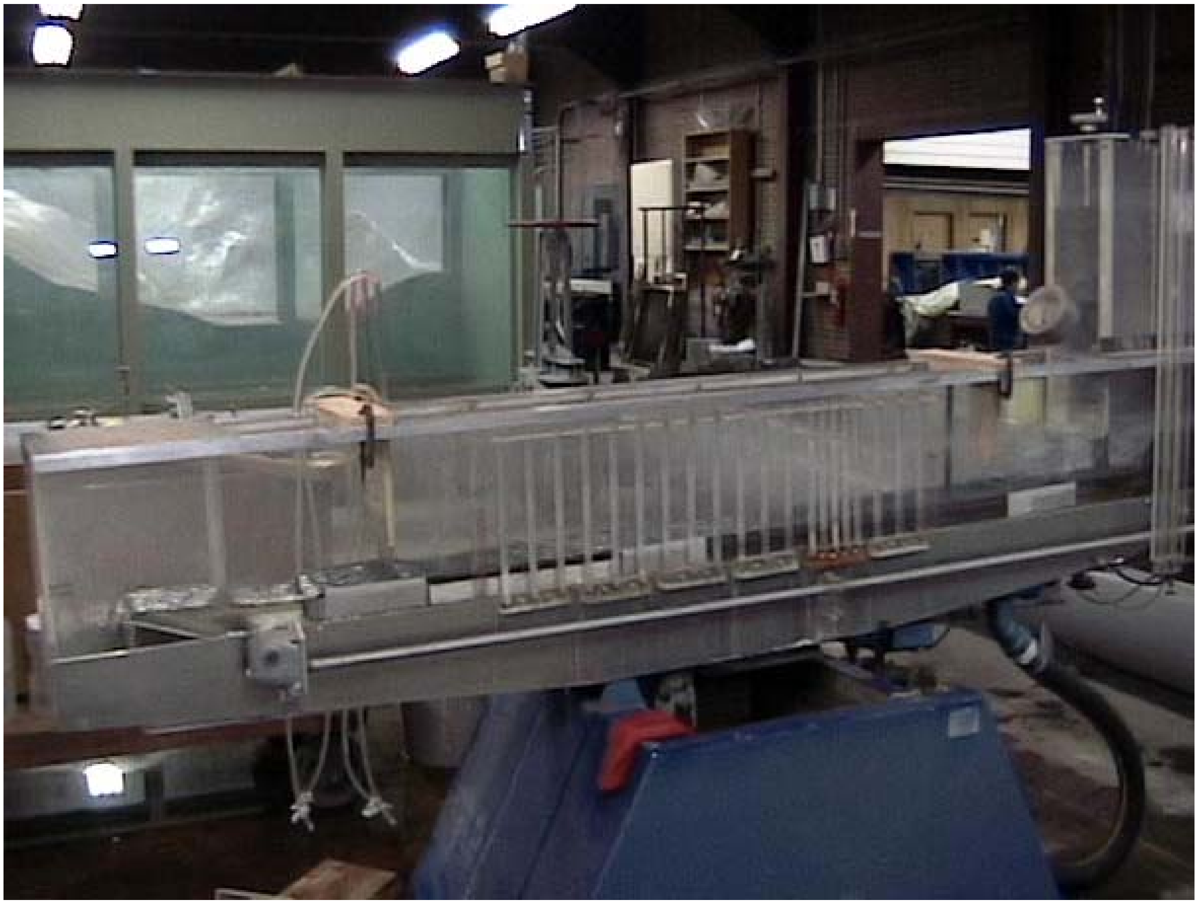

Figure 2-8: Photograph of flume used in this study.

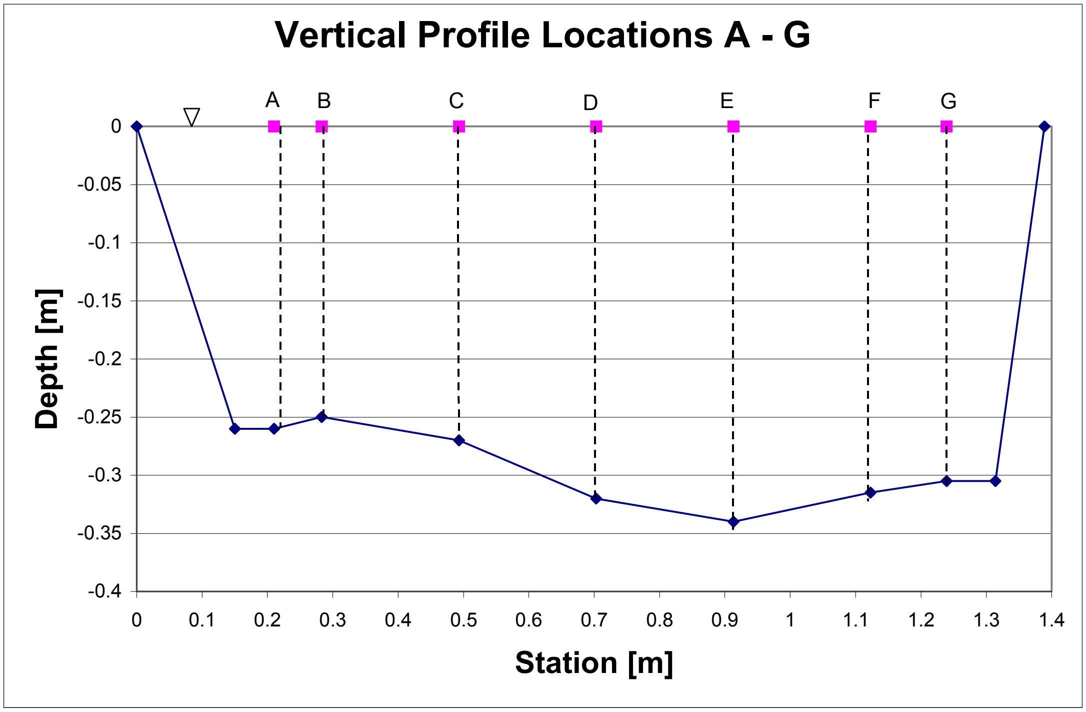

Figure 2-9: Diagram of the cross section showing locations of ADV data collection and width and depth of flow.

Figure 2-10: Photo of scaffolding used to mount the ADV. Legs of the scaffolding were placed on the banks as to not disturb the flow during measurement.

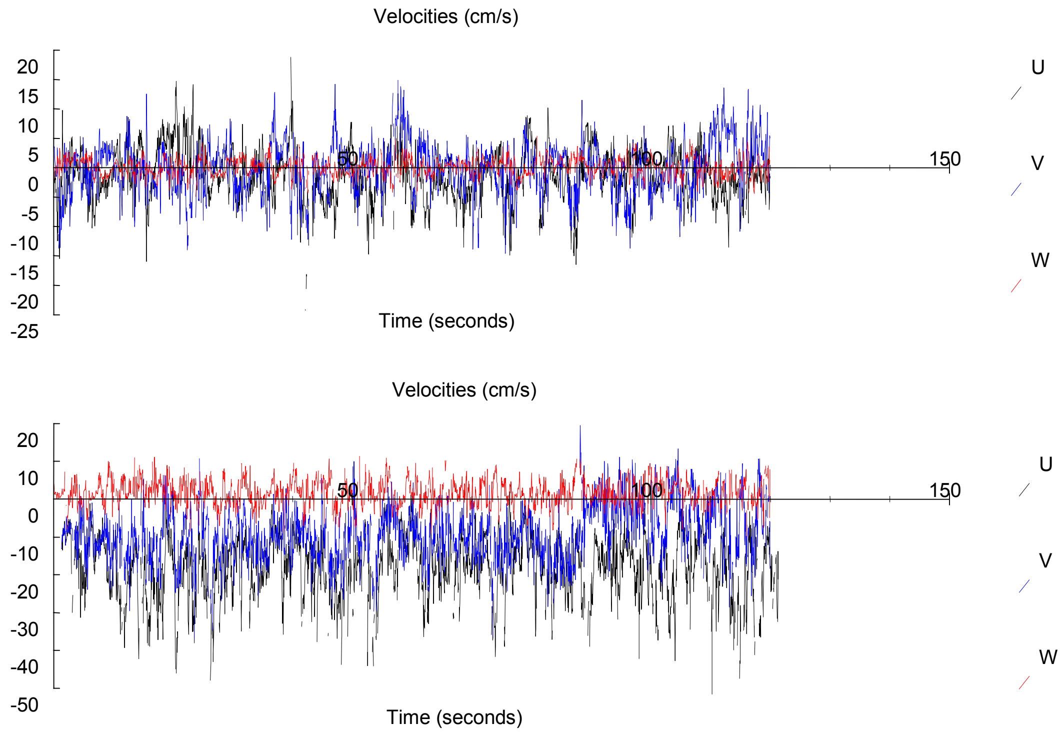

Figure 2-11: Example of time series data provided by the ADV. Black data is instantaneous streamwise velocity (U), blue data is instantaneous lateral velocity (V) and red data is instantaneous vertical velocity (Z). The top data set is the lowest measurement location in profile A and the bottom data is the bottom location in profile G. Note: the sign convention is reversed due to the orientation of the ADV during measurement. This was accounted for during calculations.

3. Results:

3.1. Mechanical Strength Fluvially deposited sediments normally exist in stratified layers according to their settling velocities, resulting in strengths that vary with depth. This typically applies to bed sediments. The fine-grained sediments in the banks of Union Flat Creek are homogeneous as a result of aeolian deposits that created the Palouse region. For this reason, strength characteristics as a function of depth do not vary. This was verified by testing the soil strength (mechanical) in-situ at various depths in several locations. The only change in strength resulted from varying root diameter and concentration. It was found that with larger root diameters, the undrained strength was greater. Near the surface of the bank (Figure 2-3) the root diameters do not exceed 4.0

the water. It was noted that the depth of the roots was coincident with the bank height and thus is likely a determinant of it.

In-situ strength of the soil was determined with a Torvane tester. This device allows quick and accurate measurements of in-situ soil strength at any location accessible by hand. In order to gain confidence in the results of the Torvane, soil strengths were verified with an unconfined compression test, which shows an average undrained strength of 20 kPa. All Torvane measurements of in-situ, undrained strength varied within the range of 15 and 25 kPa with an average value of 20 kPa. Strength as a function of depth was tested at various exposed bank locations and by digging a hole in the bank soil and testing at various depths. The higher strengths were coincident with greater root concentrations near the surface.

To determine the strength increase due to the presence of the roots it was necessary to reconstruct a soil sample in the lab with the roots removed, as there was no soil absent of roots in the lower bank of Union Flat Creek to test in-situ. The unrooted soil was tested with a fall cone device, commonly used to test the strength of weak soils. To again verify the results of the Torvane, it was also used to test the unrooted soil. Results of the fall cone test indicated an undrained strength of 2.0 kPa and the Torvane indicated an undrained strength of 1.9 kPa. These results indicate a strength increase of one order of magnitude provided by the roots present in the soil. It is important to note that some, if not all, of the algae in the soil was killed during the drying of the soil at 105^0 C, however organic matter such as carbon and nitrogen require much higher temperatures to destroy. It is therefore concluded that the strength decrease in the rebuilt, unrooted soil is due to the removal of the roots.

3.1.3. Erosional Strength Because it is improper to determine fluvial erosion of cohesive soils using its mechanical strength (Zreik et al., 1998), it is necessary to determine the soil's erosional strength. The results from the flume tests performed on the undisturbed soil are shown in figure 3-1. The results shown are from three separate soil samples taken from the banks of Union Flat Creek. The erosional strength (or critical stress, τ_c) was determined to be 5.6 Pa. Preliminary tests indicated that the critical stress was within the range of 4 – 8 Pa, narrowing the range of shear stresses needed to be applied to the sample. It is important to note that when the soil was subjected to stresses above critical, no erosion could be observed visually. This is not unexpected due to the extremely small sizes of the particles.

Rooted, in-situ Strength (mechanical)	Unrooted, remolded strength (mechanical)	Erosional strength
20 kPa	2 kPa	5.6 Pa

Table 3-1: Summary of soil strengths obtained in this study. The erosional strength is shown to be three orders of magnitude less than the unrooted mechanical strength.

Because the soil in this reach of Union Flat Creek is homogeneous the strength determined above is considered to be the strength at all bank locations within the reach considered.

The critical stress value obtained in this study falls within the range of critical stress values determined by other investigators. Dennett et al. (1998) report critical shear stress values up to 10 Pa for hard soil deposits.

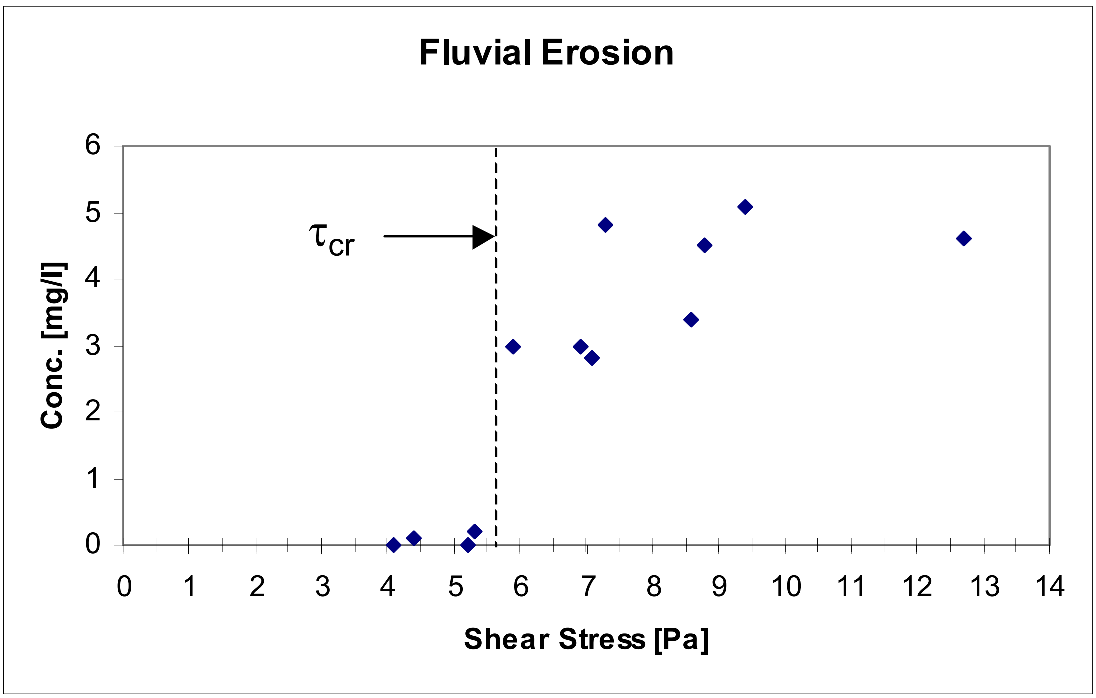

Figure 3-1: Results from the flume tests for critical erosion. A total of three soil samples were tested and the results were combined and are shown here.

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Information Transfer Activities:
The project findings were presented at two conferences, the Sixth Interagency sedimentation conference and the ASCE water resources conference.

Publications
Papanicolaou, A. and Hilldale, R. Turbulence Characteristics in a Gradual Channel Transition. Journal of Engineering Mechanics (paper has been accepted).

Hilldale, R. and Papanicolaou, A. 2001. Re-suspension of Cohesive Materials is Streams Due to Turbulent Structure. Paper published at the Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25-29, 2001, I-176-I-183.

Hilldale, R. and Papanicolaou, A. Turbulence Characteristics in a Natural Channel Downstream of a Transition. Submitted for inclusion in the Proceedings of the World Water and Environmental Resources Conference, May 20-24, 2001, Orlando, FL

Students Supported:

Jenny Filipy, undergraduate, Civil and Environmental Engineering
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Basic Information

Title:	Evaluating Water Policy Affecting Fish Habitat, Hydrology and Irrigated Agriculture in the Snake River Basin
Project Number:	C-04
Start Date:	9/1/1998
End Date:	2/28/2001
Research Category:	Biological Sciences
Focus Category:	Hydrology, Irrigation, Economics
Descriptors:	Hydrology, Irrigation, Economics
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	David Holland, Claudio Osvaldo Stockle, Joel Hamilton, Gary Johnson, Marshall English

Publication

1. Engle, Paula, and David Holland. 1999. "Water Leasing For River Flow Augmentation and Uncompensated Job Loss: A Case Study of South Central Idaho." Report A.E 99-3., Dept. Ag. Econ., Wash. St. U., Pullman.
2. Schuck, E., Genevieve Briand, Rob Davis, Paula Engle, Joel Hamilton, and David Holland. 2001. Evaluating Water Policy Affecting Fish Habitat, Hydrology, and Irrigated Agriculture in the Snake River Basin. State of Washington Water Reseach Center, Washington State University, Pullman, Wash. Report WRC01-01. 52 pp.

Problem and research objectives:

Changes in water management policies for the Snake River are required as a consequence of the Salmon River Sockeye and the Spring and Summer Chinook Salmon stocks being listed as endangered. The Snake River is heavily appropriated for irrigation and hydroelectric power production, resulting in problems relating to water quantity and quality in Idaho, Oregon and Washington. Further, surface water and groundwater are highly interdependent in the region. Consequently, changes in water policy to assist salmon recovery may dramatically affect the hydrology and the agricultural economy of the region.

The overall objective of this research is to evaluate alternative water policy choices for salmon recovery in the Snake River basin for effects on quantity and quality of stream flow, groundwater recharge and discharge, irrigated agricultural production, hydroelectric production, and the region's economy.

Methodology:

Research objectives were accomplished by integrating models of individual and regional crop production, ground and surface water hydrology, and regional economic impacts. Six models were used in the analysis: SPRINKS, a model of irrigation efficiency and uniformity; CropSyst, a crop production model; SRAM, a regional agricultural production model; a groundwater hydrology model; MODSIM, a surface water allocation model; and IMPLAN, a regional economic impact model. Crop/water production functions were developed using CropSyst. The groundwater hydrology model is being used to develop response functions to incorporate groundwater interactions into MODISM, which models surface water storage and allocation. SRAM and MODSIM will be iterated for each policy alternative. Results from SRAM will input to IMPLAN to estimate the regional economic impact of the alternatives.

Crop production functions were developed for zones in the upper Snake River basin represented by climatic conditions at Fort Hall and Twin Fall, Idaho. For surrounding areas, county level yields were obtained, which were used as references to adjust some of the crop parameters in CropSyst so as to improve yield simulation of the different crops involved. Complete weather records were obtained and modified for use in CropSyst. In addition, soil data for each area was identified and input files were prepared. Model calibration for alfalfa, corn, spring wheat, sugar beets, dry beans and potatoes under full irrigation were prepared. A reasonable agreement with observed yields was obtained. Simulations for 0 to 100 percent irrigation in increments of 10 percent were prepared. These yields can be used to accommodate any depth of field water application as predicted by SPRINKS for different irrigation uniformity and efficiency scenarios. An example of spring wheat production as a function of water is given in Figures 1 and 2.

SRAM has been developed to estimate the change in crop production at the regional level due to changes in water allocation. Data on water deliveries, crop acreage, irrigation efficiencies, crop water use and crop input and output prices were gathered for model development. SRAM was calibrated and tested using the policy scenario of government purchases of one million acre-feet of water to augment in-stream flow. Results from the SRAM model have been compared to the results obtained in the Million Acre Feet study that was separately conducted by the Bureau of Reclamation. In general the SRAM results were relatively consistent with results from the Million Acre Feet study lending some credibility to the SRAM exercise.

The SRAM model has been used to examine two alternative million acre-feet scenarios. In alternative one the impact on recreation was minimized at the expense of irrigated agriculture. In alternative two the impact on irrigated agriculture was minimized at the expense of recreation. In each scenario, the water transfer from each region was determined by using MODSIM and those transfers were fed into the SRAM model. The advantage of this approach is that MODSIM does take account of water rights and the hydrology of return flows. The disadvantage of the approach is that MODSIM is unable to account for the relative value of the water in each of the regions along the Snake River. So water is being taken out some regions were it is relatively valuable when other regions where water is less valuable are not transferring as much water.

Figure 1. Spring wheat yields as a function of water transpired by the Crop. Weather data correspond to years 1992-98 at Twin Fall, ID.

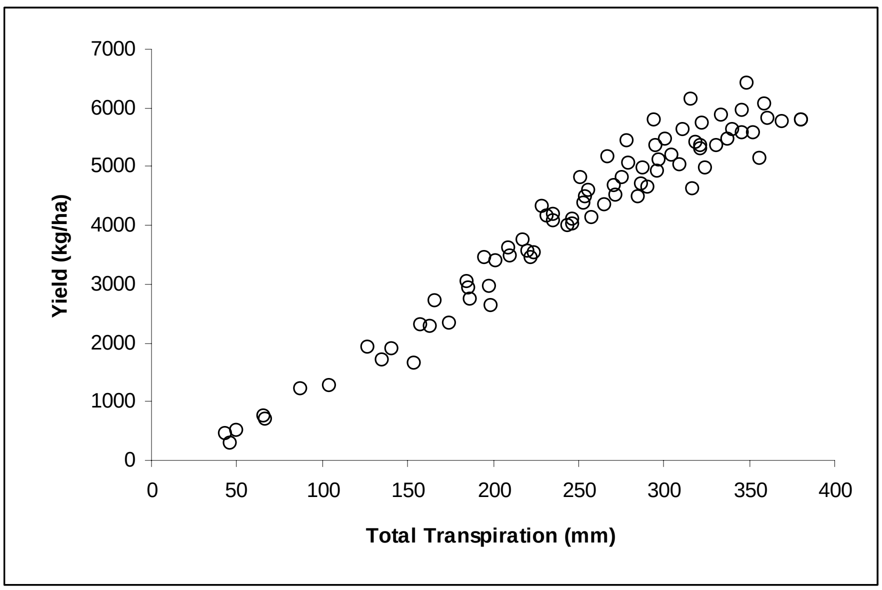
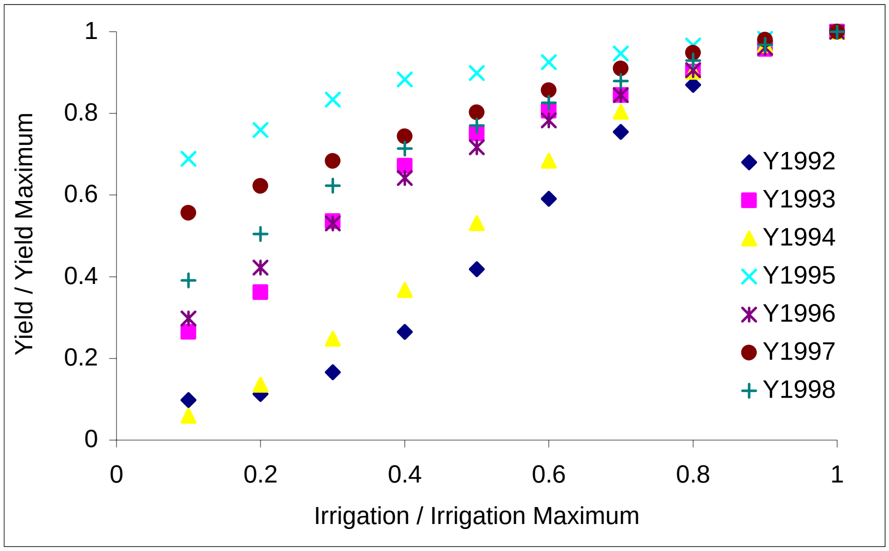


Figure 2. Normalized spring wheat yields as a function of different Levels of irrigation, expressed as fraction of full irrigation. Weather data correspond to years 1992-98 at Twin Fall, ID.



Work on MODSIM focused on two goals. First, enhance our ability of manipulating and interfacing with the MODSIM computer program. Second, develop an understanding of MODSIM as developed by the Bureau of Reclamation model of the upper Snake River basin, from Wyoming to Brownlee Dam on the Idaho-Oregon border. The most significant groundwater contributions to the river are in the eastern Snake River Plain, above King Hill. The changes to incorporate groundwater hydrology take the form of new attributes in the model, as opposed to changes in model code. Preliminary groundwater response functions have been used in the Snake River program of MODSIM with good success.

Principal findings and significance:

Over the past decade, four major salmon runs on the Snake River have received protection under the Endangered Species Act. In 1991, Sockeye salmon runs on the Snake River were classified as “endangered”. A year later, Spring and Summer Chinook salmon runs on the Snake River joined Sockeye runs with a “threatened” classification under the Endangered Species Act. Wild Steelhead runs followed with a “threatened” classification in 1997. Water management policies on the Snake River are changing as a direct result of these listings under the Endangered Species Act. Specifically, water transfers from the Upper Snake River basin to the Lower Snake River basin to augment stream flows for salmon are occurring. The first water transfers were formalized in 1995 when the United States Bureau of Reclamation (USBR) agreed to provide an additional 427 thousand acre-feet (kAF) of irrigation water for flow augmentation in the Snake River upstream from Lower Granite Lake. Since that time, the United States Army Corps of Engineers (COE) has requested an additional 1,000 kAF for instream flow augmentation.

This research focuses on the economic impacts of flow augmentation in the Snake River basin, with a specific emphasis on the economic impacts on irrigated agriculture in Idaho. The research addresses two distinct areas: the effects of alternative flow augmentation programs on production and acreage levels for irrigated agriculture in the Snake River basin, and the corresponding effects on the regional economy. The first area of the research relies on production simulation models using positive mathematical programming (PMP), while the second area of the research is evaluated through a regional input-output (I-O) model using the IMPLAN framework.

Value of Irrigated Agriculture in the Snake River Basin

The Snake River Basin (Basin) is heavily dependent upon agriculture. Across the Basin, several sectors of the regional economy are tied directly to agriculture. These sectors include: livestock, crop production, other agricultural production, forest and greenhouse production, agricultural services and agricultural processing. Together, these sectors account for between 9.66% to 22.1% of total employment and 9.69% to 30.12% of overall income (IMPLAN, 1994). Additionally, these industries affect service and retail employment through the Basin as workers in the agricultural sectors of the economy spend their incomes. Consequently, the role of agriculture in the Basin's regional economy extends well beyond those portions of the economy directly connected to irrigated agricultural production. The portion of the Basin's total sales, employment and income is summarized in Table 1:

Table1. Percentage of Regional Sales, Employment and Income Tied to Agriculture

Region:	Sales	Employment	Income
Eastern	15.27%	12.23%	13.13%
South Central	39.13%	22.1%	30.12%
South West	13.1%	9.66%	9.69%

Given the Basin's overall dependence on agriculture, changes in the supply of water for irrigation can have profound effects on the regional economy. Since water is a finite resource, current proposals for improving instream flows for salmon rely on transfers of water from agriculture to instream flows. This will be done either by drawing down irrigation reservoirs or reducing irrigation diversions. Determining the impacts on agricultural production of flow augmentation proposals and the resulting economic consequences are of paramount importance to the Basin. This research first determines the production effects of several proposed flow augmentation programs, and then determines the economic effects stemming from these changes in agricultural production. The cost and relative efficiency of each proposed policy are also discussed.

Effects of Alternative Flow Augmentation Programs

The USBR, the agency primarily responsible for managing irrigation water in the Snake River basin, is considering 2 major alternatives for flow augmentation. Both of these plans will increase flows by 1,000 kAF, and differ primarily in how that level of flow augmentation is reached. The first plan (designated 1427i by the USBR) achieves the target level of flow augmentation by reducing storage in USBR reservoirs. By drawing down reservoirs, irrigation water shortages are minimized. The second option being considered by the USBR is denoted 1427r. Under this plan, the USBR will augment instream flows without drawing down reservoirs. This is to be achieved through a combination of purchasing out-of-basin flow rights and reducing irrigation diversions. As a result, a significant portion of the water used for flow augmentation under the 1427r scenario comes from outside the Snake River Basin study area. This point cannot be overlooked when comparing alternative policy scenarios.

The economic consequences of these two plans are the major focus of this research. The economic impacts of the two proposed policies are evaluated using both the IMPLAN I-O framework mentioned previously and a crop production model showing how agricultural production and acreage would be expected to change with alternative levels of diversions.

Estimated Production Losses

Given the dependence on agriculture within the Basin, losses in agricultural production as a result of flow augmentation are a major concern across the various regions of the Snake River. To address these concerns, the research examines how alternative flow augmentation programs would affect acreage levels and cropping patterns across the affected regions of Idaho. The crop effects of the 1427i and 1427r flow augmentation plans offered by the USBR are evaluated and compared to two alternative management plans. The two alternative plans, designated “Priority Right” and “Least Cost”, differ from the two USBR plans in how irrigation water is allocated to flow augmentation. Under the 1427i and 1427r plans, the USBR assigns water sources for flow augmentation prior to economic analysis. The “Priority Right” and “Least Cost” options assign water for flow augmentation using different management criteria.

The “Priority Right” model assigns water for flow augmentation by assigning a priority right of 1,000 kAF to the Brownlee Reservoir in the lower Snake River basin. The USBR’s model of the Snake River basin’s physical and hydrologic system, MODSIM, then allocates water across the Snake River basin to meet this priority right driven demand. The “Least Cost” model is a laissez-faire economic model, which does not incorporate existing water rights structures. Under the “Least Cost” model option, irrigation water is allocated across the Snake River basin to whatever crops are most valuable. This meets the economic requirement that scarce resources be sent to their highest and best use. The “Least Cost” model is intended to provide a means of comparing market-generated outcomes to the outcomes produced by either of the 2 USBR management plans or the “Priority Rights” model.

The effects of these four alternative flow augmentation plans are evaluated using the method of Positive Mathematical Positive (PMP) first developed by Howitt (1995). The PMP framework uses current acreage allocation and cropping patterns in the Upper Snake River basin as a baseline for land and water use. The model then simulates how alternative flow augmentation programs change the agricultural economy of the Upper Snake River Basin from current practices. This agricultural production model is known as the Snake River Agricultural Model (SRAM).

Results from the SRAM simulations indicate that alternative solutions to the two USBR proposals might be found. Specifically, options exist which would lessen the economic impact of an additional 1,000 kAF for flow augmentation. The USBR's 1427r policy option requires a basin-wide reduction of nearly 319,000 acres. In comparison, the 1427i option leads to a 199,040 acre reduction, the "Priority Right" option takes 649,250 acres out of production, and the "Least Cost" option only reduces acreage by 644,320 acres. It should be noted that while the USBR policy scenarios lead to lower levels of acreage reductions, their impacts are mitigated through the use of out-of-basin flow rights and storage water. The latter two policy options restrict the effects of flow augmentation to the Snake River Basin, so their effects are relatively greater for that reason.

The simulations also indicate that the USBR's policy scenarios leads to relatively less water scarcity than the two other policy options. The regional scarcity value of irrigation water, measured by the average shadow values on water supply in SRAM, is only $26.82/af under the USBR 1427i plan and is $46.17/af under the USBR 1427r plan. The "priority right" option is the most expensive at $127.35/af. The "least cost" option is similar to the "priority right" scenario with an average scarcity value of $120.62/af. As noted previously, the difference between the two USBR policy scenarios and the "priority right" and "least cost" depend significantly upon how flow augmentation is obtained under each scenario. Since the two USBR scenarios rely on storage water and out-of-basin flow acreage, their effects will generally be lower than the scenarios that restrict the effects of flow augmentation to the Basin. These differences must be acknowledged when comparing the alternative scenarios. In particular, while the 1427i plan makes irrigation water the least scarce, its reliance upon reducing the water levels in storage reservoirs may make this plan unviable in the long-run. Additionally, since the 1427r plan relies on out-of-basin transfers and this analysis focuses solely upon the impacts of flow augmentation in the Basin, lower scarcity impacts in the Basin are coming at the expense of region's outside the study area. Even with these concerns, the average scarcity values provide a useful indication of water's marginal value to irrigators and is a good starting point for future negotiations regarding a "fair" price for water leasing.

Estimated Employment Losses

An IMPLAN based I-O model was used to estimate the regional economic impact associated with flow augmentation for the three economic regions of the Snake River Basin. The acreage results from SRAM for both of the USBR policy proposals, the "Priority Right" and the "Least Cost" option were fed into IMPLAN and used to generate expected reductions in sales, employment and income across the three economic regions of the Snake River Basin. Based on the acreage reductions implied by SRAM, the IMPLAN results suggest that the overall employment effects of flow augmentation will be confined to a relatively small segment of the regional economy.

The expected employment effects of the three policy options are summarized in Table 2. These indicate the percentage reduction in each region's baseline employment as a result of adopting each of the proposed policy options.

Table 2. Reductions in Regional Employment Under Alternative Flow Augmentation Plans

Policy:	1427i	1427r	Priority Right	Least Cost
Region:				
Eastern	0.54%	0.53%	0.74%	2.33%
South Central	0.44%	1.34%	3.13%	1.36%
South West	0.30%	0.53%	1.32%	0.54%

Based on the IMPLAN results and assuming average water supply conditions across the Snake River basin, the "Least Cost" and "Priority Right" options generally have greater employment impacts on both the Eastern and South Central Regions. However, the South West Region, which has the largest population of the three economic study areas, is less affected than the other two regions under the "Least Cost" option. Overall, the USBR's 1427i plan generally has the smallest employment effects. This is not surprising since this option preserves irrigation diversions by reducing reservoir storage. Collectively, the results indicate different policy options affect each region differently. The two USBR policy options appear to create the smallest employment effects across all regions, but their reliance upon storage water and out-of-basin flow rights does understate the effects of flow augmentation that would deliver 1,000 kAF to the Snake River Basin.

The IMPLAN results do not incorporate the effects of any compensatory payments to irrigators. Under existing water law, water rights are a real use right and individual irrigators are entitled to specific quantities of water. Consequently, the water transfers currently being proposed by the USBR would only be possible if the water were purchased by the USBR from irrigators willing to sell. As a result, the expected losses in employment presented here most likely represent a "worst-case" scenario. Revenues from selling irrigation water to the USBR could potentially offset the revenues lost when acreage is taken out of production and irrigators' income would not fall by as much as the IMPLAN results indicate. However, while water sales would compensate the holders of water rights for reductions in irrigation water supply, agricultural workers or individuals employed in agricultural processing would not be compensated. The effects of flow augmentation plans on these "uncompensated" workers are, therefore, a serious point of concern.

Conclusion

Augmenting flows in the Snake River Basin for salmon will have effects well beyond irrigated agriculture. Mathematical programming simulations of the region indicate that increasing instream flows may require sizable reductions in crop acreage and production. Lost production translates into reduced employment levels, but these are generally small as a percentage of current total employment levels, particularly for the two USBR policy options. The two other policy options explored in this study ("priority right" and "least cost") have relatively greater production and employment effects than the two USBR scenarios. However, since the non-USBR options confine all of the effects flow augmentation to the Snake River Basin and do not rely on storage or out-of-basin flow rights for water, they provide a useful counterpoint to the USBR scenarios.

Simulations also indicate that current USBR flow augmentation proposals, which rely heavily on either storage water or out-of-basin flow rights, may understate the costs of achieving instream flow goals. Specifically, SRAM results indicate that the USBR's 1427r plan leads to relatively lower average water scarcity values than does either a "priority right"or "least cost" economic allocation of water. However, the "least cost" policy option confines all flow augmentation costs to the Snake River Basin and does not recognize current water rights structures. It represents the cheapest way to achieve flow augmentation goals when all of these costs are confined to the Basin, so differences between the "least cost" and USBR scenarios provide a measure of how flow augmentation costs are mitigated by relying upon either storage or out-of-basin flow rights for water. The same is also true for the "priority right" scenario. Since the "priority right" scenario accounts for existing water rights, the difference in the average scarcity value between the "priority right" and USBR scenarios provides a measure of how either storage or out-of-basin flow rights mitigate the costs of flow augmentation given current water rights. As such, the two non-USBR scenarios provide useful indications of how flow augmentation costs increase when flow augmentation is confined to the Snake River Basin and does not rely on other water sources. The USBR may be understating the costs of flow augmentation by relying heavily upon water sources outside of the study area.

Information Transfer Program

Outreach and education are significant components of the mission and activities of the Center. The main objective is to provide opportunities for linking the academic work of research universities in the state with potential users and water stakeholders. Federal and state agencies, non-governmental organizations and citizens are in need of interpreted science that can be applied to problem solving. The Center makes substantial efforts to facilitate this process.

Basic Information

Title:	Information Transfer
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Electronic Publishing, Information Transfer, Statewide Outreach
Lead Institute:	State of Washington Water Research Center
Principal Investigators:	Claudio Osvaldo Stockle

Publication

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

1. Web page. This is an important vehicle to present information about the activities of the Center, news and events, research reports, and availability of water-related expertise. In today's world, this is a major element of interface with users. Therefore, a great deal of efforts is placed into continuously improving and updating the page.
2. Washington e-Water News. This is an informative electronic newsletter that reaches over 1,400 individuals and is published three times a year. It includes a variety of current and emerging research and extension issues presented in a format adequate for the general public. This newsletter has been extremely well received by our constituency.
3. Regional water quality coordination. This is a USDA-CSREES funded project that helps coordinate research and extension activities of the Water Research Institutes and Cooperative Extension Services in Alaska, Oregon, Idaho and Washington with EPA Region 10. This project has the potential for large extension and outreach impact.
4. A variety of other small activities are conducted such as a) service in response to telephone and e-mail requests from users, b) organization of small seminars and workshops, and c) attendance at extension and agency meetings.

USGS Summer Intern Program

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	5	10	0	0	15
Masters	2	4	0	0	6
Ph.D.	2	5	0	0	7
Post-Doc.	0	3	0	0	3
Total	9	22	0	0	31

Notable Awards and Achievements

None

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