USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Modeling winter hydrology and erosion in the Northwest Wheat and Range Region (NWRR)

Focus Categories: HYDROL, SED, MOD

Keywords: Agriculture, management, winter hydrology, soil erosion, climate, NWRR, computer models

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Principal Investigator(s) Name(s) and Universities:

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Collaborators:

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Congressional District of University Where the Research Is to Be Conducted: 5th.

Statement of Critical Regional or State Water Problems

Soil erosion by water from cropland is a major agricultural and environmental problem in the Northwest Wheat and Range Region (NWRR). Soil erosion can lead to reduced agricultural productivity and increased costs for road side ditch cleaning and water conveyances and hydraulic structures maintenance. Previous research shows that most of the cropland soils in the NWRR have suffered varying productivity loss from erosion since they were first cultivated only 120 years ago. In addition, soil erosion has direct impact on stream water quality and fish habitat. The health and viability of fish stocks in the Pacific Northwest has long been a critical issue for politicians, regulatory and land management agencies, Indian tribes, and individuals. The recent listing of additional salmon species as threatened or endangered by the National Marine Fisheries Service further signifies the urgent need for fish habitat protection.

Controlling soil erosion to maintain agricultural productivity and conserve soil and water resources is a great challenge to farmers in the NWRR. In this region, combined winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and inadequate management practices can result in extremely high erosion rates. Although it is widely known that most soil erosion in the NWRR is related to rain on frozen or thawing soils, understanding of the soil freezing and thawing dynamics and the associated impacts on winter runoff and erosion is extremely limited. Essentially no existing models can be directly applied to this region for long-term, continuous simulation without adjustment. Lack of suitable models as prediction tools has largely hampered the process of determining and adopting agricultural Best Management Practices (BMPs) by farmers. For instance, the no-till farming has been recommended to farmers as a BMP for erosion control. Yet the effectiveness of this practice has not been clearly demonstrated to the farmers through the use of an appropriate model. An urgent task is thus to adequately establish the relationships between the soil freeze-thaw processes and water erosion, and to incorporate these relationships into erosion prediction models. This study focuses on elucidation of the highly dynamic water erosion processes during soil freeze and thaw though properly designed laboratory experiment, and modifying the physically-based, USDA's erosion prediction model, WEPP (Water Erosion Prediction Project) based on the experimental results. Through the uses of the improved WEPP, typical agricultural farming practices in the NWRR will be assessed and the BMPs determined. Information obtained from this study will be useful to a wide audience including scientists, farmers, extension staff, and regulatory personnel.

Statement of Results or Benefits.

Current models for predicting soil erosion by water are limited in their applicability to the NWRR. On one hand, empirical models lack event-based or off-site erosion prediction capability and may require time-consuming and costly model calibration before use, and on the other, process-based models cannot properly account for the NWRR's unique winter hydrology and erosion processes driven by frequent cycles of soil freezing and thawing. Expected results from the proposed study include: (1) an improved design of laboratory experiment for testing soil strength variables as affected by soil water tension under both frozen and thawed conditions; (2) a better understanding of the fundamental process of water erosion and an improved WEPP model applicable to the NWRR; and (3) selected agricultural BMPs for the NWRR and guidelines for making the selection. Results and findings obtained from this study will significantly contribute to the knowledge of winter hydrology and erosion in the NWRR as well as other geographic areas of similar climatic conditions. In addition, the BMPs determined from this study will serve as a prototype and provide useful information to interested scientists, county extension staff, consultants, farmers, and regulatory personnel.

Nature, Scope and Objectives of Research

Soil erosion by water from cropland is a serious and continuous agricultural and environmental problem in the Northwestern Wheat and Range Region (NWRR) (McCool, 1990; Papendick et al., 1995). Covering northern Idaho, eastern Washington, and northeastern Oregon, the NWRR is generally categorized into three climatic and agronomic zones based on the annual precipitation: low (23–33 cm), intermediate (33–43 cm), and high (43 cm and up). Average annual soil loss rates of 30 t/ha for the low- and high-rainfall zones and 50 t/ha for the intermediate zone, much higher than the tolerable rates of 5.0–12.0 t/ha recommended by the Natural Resources Conservation Service, have been documented (USDA, 1978). Soil erosion can reduce agricultural productivity and increase costs for road side ditch cleaning and water conveyances and hydraulic structures maintenance. Previous studies (Papendick et al., 1983; 1985) have shown that, most of the cropland soils in the NWRR have suffered varying productivity loss from erosion since they were first cultivated only 120 years ago, and that crop yield is closely related to topsoil depth (see Fig. 1). Soil erosion also adversely affects stream water quality and fish habitat by degrading and reducing spawning habitat (Alexander and Hansen, 1986; Chapman and McLeod, 1987). The health and viability of fish stocks in the Pacific Northwest has long been a critical issue for politicians, regulatory and land management agencies, Indian tribes, and individuals. The recent listing of additional salmon species as threatened or endangered by the National Marine Fisheries Service further signifies the urgent need for fish habitat protection.

The high soil erosion rate in the NWRR is a result of a combination of winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and management practices that often leave the soil pulverized and unprotected during the rainy season (Papendick et al., 1983). Various soil conservation practices emphasizing tillage management and crop rotation have been intensively tested on research experimental plots and have shown great potential as a general strategy in reducing soil loss on a regional scale (McCool et al., 1999). However, adoption of conservation farming practices by individual growers in the NWRR has been very slow. Data from the USDA Economics Research Service (1994) show that, in 1993, only 4% of Washington winter wheat acreage was on no-till, 22% on minimum-till, and the total conservation tillage was much less than the national average of 35% in that year. Currently, about 80% of the winter wheat across the entire NWRR is seeded after summer fallow, a major contributor to water erosion (Ramig et al., 1983). When fields are summer fallowed under conventional tillage, uncropped land is clean tilled to control weeds and store moisture for growth of the next year's crop, creating a condition most prone to water erosion.

Determining at an individual farm level the optimum cropping systems or the so-called Best Management Practices (BMPs) that maintain agricultural productivity while minimizing the adverse environmental impact is not a trivial task. It generally involves consideration of multi-faceted, dynamic and interactive economic, environmental, and in many cases, social and political, factors. In addition, it requires arduous efforts of comparing a variety of management scenarios. Many of the previous studies aiming at identifying effective soil conservation practices were based on some sort of erosion modeling. Nevertheless, it has been widely recognized that current erosion prediction technology, best represented by the empirical model, RUSLE (Revised Universal Soil Loss Equation) (Renard et al., 1997), and the physically-based model, WEPP (Water Erosion Prediction Project) (Laflen et al., 1991; Flanagan et al., 1995), in their present forms, are not suitable for use in such studies under conditions of the NWRR. The WEPP model lacks the capability to adequately account for the unique winter erosion processes in the NWRR, while RUSLE (though having been calibrated for this region) does not provide event-based or off-site erosion estimates. Most soil erosion in this area is related to rain on frozen or thawing soils (see Fig. 2) and is often exacerbated by warm, moist Pacific air masses that cause precipitation and rapid thaw (Yoo and Molnau, 1982; Zuzel et al., 1982). Yet the effect of freezing and thawing on soil detachment and transport remains one of the least understood aspects of the physical erosion process. During freezing, water moves from deeper soil layers and concentrates in the frozen zone. When a warming trend occurs and the soil begins to thaw, most of the time the surface is saturated. Should a rain occur under these conditions, there is essentially no place for the water to go but as runoff, carrying with it large amounts of soil. Due to its simplified representation of the highly transient and complex freezing-thawing processes, WEPP tends to misrepresent winter erosion processes in the NWRR.

Lack of understanding of the dynamic erosion processes during soil freeze and thaw processes has largely limited the applicability of the current erosion models to the NWRR, which has in turn hampered the establishment and rapid adoption of agricultural BMPs by farmers in this region. Hence, an urgent task is to adequately establish the relationships between the soil freeze-thaw processes and water erosion, and to incorporate these relationships into erosion prediction models.

The main purpose of this study is to elucidate the transient water erosion processes during soil freeze and thaw through properly designed laboratory experiment, and to modify the WEPP model based on the experimental results for use in determining long-term erosion and agricultural BMPs. The specific objectives are to:

(1) Experimentally identify and mathematically formulate the mechanisms by which freezing and thawing of soils influence runoff and soil erosion by water;

(2) Improve the winter hydrology and soil erosion routines in the WEPP model, by properly incorporating into it the relationships between soil freeze-thaw processes and runoff and erosion;

(3) Determine long-term crop production and soil erosion for selected, representative management practices in the NWRR using the improved WEPP model and identify BMPs by considering both crop yield and soil erosion.

Methods, Procedures, and Facilities

Methods and Procedures by Objective

> ***Objective 1*** Experimentally identify and mathematically formulate the mechanisms by which freezing and thawing of soils influence runoff and soil erosion by water.

A laboratory experiment on soil erodibility and critical shear stress will be designed following the basic procedures of Van Klaveren and McCool (1998). A Palouse silt loam soil (fine silty, mixed mesic Pachic Ultic Haploxeroll) typical of the NWRR drylands, a benchmark soil parameterized in the WEPP model, will be tested to obtain rill erodibility and critical shear stress values under non-frozen, frozen, and thawing conditions, and at different applied flow rates and soil water contents/tensions. Van Klaveren and McCool (1998) used a tilting flume to facilitate near-natural freeze of soil with controlled soil water conditions, and tested the soil strength variables under thawed conditions. In this study, we will conduct tests under all three conditions, thawing, frozen, and non-frozen. Substantial modifications will be made to the tilting flume to facilitate the tests. Specifically, the test bed of the tilting flume will be redesigned to enable more rapid preparation and testing by improving the means of consolidating the soil under tension. Ambient temperature will be controlled to speed the freezing and thawing processes using radiation plates. The experimental setup will allow freezing from the soil surface to a depth of 10–20 cm and partial or complete thawing from the soil surface. Interaction between freezing rate and the amount of water migrating to the freezing front will be determined. Through the experiment, quantitative relationships between soil erodibility and critical shear stress and soil water tension will be established. In addition, a 14-year experimental plot data set on runoff under different surface cover and slope conditions collected from the USDA-ARS Palouse Conservation Field Station (PCFS) near Pullman, WA (McCool et al., 1995), will be analyzed to validate the lab-determined relationship between runoff and erosion and soil freezing status.

> ***Objective 2*** Improve winter hydrology and soil erosion routines in the WEPP model, by properly incorporating into it the relationships between soil freeze-thaw processes and runoff and erosion.

Model description

The brief summary below, extracted primarily from Flanagan et al. (1995), describes the WEPP model's structure, major functions, and how those important watershed physical and biological processes are represented within the model.

WEPP is based on the fundamentals of infiltration theories, plant science, open channel and impoundment hydraulics, and erosion mechanics. It can be used for routing overland flow and sediment through hillslopes and watersheds on a daily, monthly, or annual basis. For watershed scale applications, WEPP uses a conceptual discretization strategy to dissemble a watershed into hillslopes, channels, and impoundments. A hillslope in WEPP consists of rill (between vegetation canopy) and interrill (beneath vegetation canopy). WEPP has an embedded random climate generator, CLIGEN, which can be used to generate daily data for long-term or single-storm simulations. WEPP's surface hydrology component provides its erosion component with information related to surface runoff. Important calculations involved in this component are infiltration, rainfall excess and its duration, depression storage, and peak runoff rate. The cumulative infiltration is computed using a modified Green–Ampt Mein–Larson model. Rainfall excess volume is computed in conjunction with the infiltration calculation and adjusted for soil saturation conditions and depression storage. Peak discharge is calculated based on the kinematic wave model. Evapotranspiration is a modified Ritchie's model. WEPP simulates both cropland and rangeland plant growth and the vegetation impact on hydrologic and erosion processes. The phenological development of crops is subject to daily heat unit accumulation and water and temperature stresses, while the initiation and growth of range plants are estimated with potential growth curves that can be either an unimodal or a bimodal distribution. The soil component accounts for soil properties. Many critical variables, such as rill and interrill erodibility, and critical shear stress can be either input directly when field data are available or estimated internally by WEPP. Overland flow characteristics are described by the Darcy–Weisbach equation. Hillslope erosion is modeled based on the governing equations for sediment continuity, detachment, deposition, shear stress in rills, and transport capacity.

Limitation of WEPP's rill erosion prediction technology

Sediment moving in a rill is contributed by rill detachment and interrill delivery (the latter is generally much less than the former). Shear stress, τ, the force developing in the direction of flow on the bed of a rill and a commonly used index of flow erosivity, is expressed as:

$$\tau_f = \gamma \ R \ \sin(\alpha) \left(\frac{f_s}{f_t}\right) \qquad (1)$$

where τ_f is flow shear stress, γ is fluid specific weight, R is hydraulic radius, α is mean slope angle, and, f_s and f_t are dimensionless soil and total rill friction factors, respectively.

Interrill sediment delivery is considered to be proportional to the product of rainfall intensity and interrill runoff rate. Rill detachment capacity is given by

$$D_c = K_r \ (\tau_f - \tau_c) \qquad (2)$$

where D_c is rill erosion detachment capacity rate, K_r is rill erodibility, and, τ_f and τ_c are flow and critical shear stresses, respectively. It can be seen from Eq. 2 that, when shear stress is greater than the critical value, WEPP predicts net soil erosion from a rill.

The reason why winter hydrology featuring soil freezing and thawing cycles is not adequately represented in the present-form WEPP model is given below. Van Klaveren and McCool (1998) showed that, both critical shear stress and rill erodibility, change with increasing soil water content. The winter hydrology routine in WEPP simulates snow accumulation and density, snowmelt, and soil freezing and thawing. The routine for estimating soil freezing and thawing follows heat flux balance and is a simplified version of the sophisticated SHAW model for simultaneous heat and water transfer in a freezing snow-residue-soil system (Flerchinger and Saxton, 1989). The effect of soil freezing and thawing is reflected by dividing the rill erodibility K_r by a factor of 2 based on previous field and laboratory studies (Formanek et al., 1984; Kok and McCool, 1990). It should be noticed that, when soil is experiencing thawing, the critical shear stress and rill erodibility generally decrease/increase to *varying* extent depending primarily on soil type, soil water content, and surface cover. In addition, the soil strength variables are transient in nature. Under rapid evaporation, a thaw-weakened soil may regain its pre-freeze strength within a few hours (Kok and McCool, 1990). Hence, simply adjusting rill erodibility by a factor may easily lead to either an underestimate or an overestimate. Further, the current version WEPP does not model upward flux when soil is freezing, thus underestimating the soil water content and overestimating the infiltration capacity of the surface layer during this process.

Modification of WEPP's winter hydrology and erosion routine

Based on the lab-obtained relationship between soil water tension and erodibility, relevant algorithms in WEPP will be modified. First, upward movement from deeper soil layers during a freezing process will be added to the model. Second, adjusting the rill erodibility will follow a more sophisticated relationship between transient soil water content (and maybe even other factors) and soil erodibility. The modified code will then be used for erosion prediction. The WEPP input will be primarily prepared from the long-term climatic and soil data collected at the PCFS. The current-version WEPP will be first run to obtain long-term soil erosion. The same inputs will then be used to run the improved WEPP model after incorporating into it the lab-obtained erodibility functions. Results from both runs will be compared, and the winter routines of WEPP may be further modified by adjusting for the interactive effects of surface cover and freeze-thaw of soils based on the analysis of the 14-year PCFS experimental plot data.

> ***Objective 3*** Determine long term crop production and soil erosion for selected, representative management practices in the NWRR using the improved WEPP model and identify BMPs by considering both crop yield and soil erosion.

A total of 12 combinations of cropping and tillage management treatments (Table 1) will be tested using the refined WEPP model for the climate and soil conditions of the NWRR. As the current dominant crops grown in each of the three climatic zones are different, both the current crop rotations in each zone and the no-till with continuous spring wheat (an annual cropping system demanding less water than winter wheat) will be examined. In general, continuous cropping will lead to the best winter soil protection among alternative rotations while winter wheat/summer fallow the worst; and, no-till will generate better erosion protection than conventional tillage. In this study, the BMPs will be determined considering both soil erosion and crop yield.

Table 1. Management practices to be tested using the improved WEPP model.

Cropping\Tillage	Conventional	No-till
Low Precipitation Zone		
Winter wheat/Summer fallow	MP_1[†]	MP_2
Continuous spring wheat	MP_3	MP_4
Intermediate Precipitation Zone		
Winter wheat/Spring barley/Summer fallow	MP_5	MP_6
Continuous spring wheat	MP_7	MP_8
High Precipitation Zone		
Winter wheat/Spring barley/Legume	MP_9	MP_{10}
Continuous spring wheat	MP_{11}	MP_{12}

[†] MP, management practice.

Work Plan

A Ph.D. student will work closely with Dr. Joan Wu and other participating scientists to complete this study. The tentative work schedule is planned as below.

03/00 - 04/00 - Set up the laboratory experiment and become familiar with the WEPP winter hydrology and erosion routines (with help from Drs. Joan Wu and Arthur Xu);

05/00 - 09/00 - Carry out laboratory experiment, document and analyze experimental data (with help from Drs. Donald McCool and Arthur Xu);

10/00 - 11/00 - Formulate mathematical relationship of erodibility versus soil water tension, refine WEPP winter routine codes (with help from Drs. Joan Wu and Arthur Xu);

12/00 - 01/01 - Validate the improved WEPP model against the PCFS experimental plot data; further refine the model if necessary;

02/01 - 03/01 - Test the selected agricultural management practices and determine BMPs; document project results and initiate the writing of the manuscript(s) for publication in scientific journal(s).

Recognizing that one-year project time is rather tight, given the comprehensiveness of the study and the intensity of the laboratory work, we will stress sound preliminary plan and flexible time arrangement for the Ph.D. student. The student may spend concentrated time during the project time to complete her doctoral research and postpone her course work. Additionally, time-slip students may be hired to help with the soil strength experiment using other funds (e.g., the PI's ARC project and initial compliment funds).

Further, free laboratory help may be available from those students who are interested in conducting unpaid undergraduate research.

Information Dissemination

The major goal of this project is to adapt the USDA WEPP model for use under the NWRR climatic conditions based on well designed laboratory test of soil strength variability, and to use the improved model to provide erosion predictions for assessment of farming practices. Therefore, efficient project results dissemination and technology transfer has been our major concern. We have planned the following approaches for information dissemination: (1) regular communication with relevant governmental agencies (Dr. Donald McCool will provide the project updates to the USDA NRCS; Dr. Joan Wu will frequently brief Dr. Claudio Stöckle, Director of the Washington State Water Research Center, about the major progress and results of the project, and the Center will in turn help to disseminate the information to various federal and state governmental agencies including the US EPA, USGS, and Washington State Department of Ecology), (2) publishing research findings in scientific journals (two manuscripts, one on the lab experimental design and results, and the other on WEPP adaption and application, are expected), and (3) presenting study results at professional meetings.

Future Work

The proposed study has several major limitations, including (1) experiment to be conducted on one type of soil and at a single laboratory scale only due to limited resources and time, (2) experiment not capable of examining and revealing the effect of surface residue on erosion, which has been increasingly recognized as an important factor controlling the number of freeze-thaw cycles and erosion, and (3) determination of agricultural BMPs dependent on crop yield and erosion amount only without performing rigorous economic analysis. Future research effort should be devoted towards clarifying these issues.

Related Research

Long-term experimental studies characterizing soil erosion as affected by management practice and topography under the climatic conditions of the NWRR have been reported (McCool, 1990; McCool et al., 1993). Van Klaveren and McCool (1998) carried out a laboratory experiment to determine erodibility parameters of soil frozen and thawed under controlled soil water tension. They concluded that rill detachment versus shear stress of flowing water is better described by a linear, instead of an exponential, relationship. Rill erodibilities from thawed soils are higher, and the critical shear stress values are lower, than those from non-frozen soils. Rill erodibility is strongly related with soil water tension, and can change rapidly as rills deepen or as soils thaw and drain, manifesting the transient nature. Formanek et al. (1984) conducted a laboratory study to examine freeze-thaw and consolidation effects on soil strength. They found that, after freezing and heaving, soil shear strength and erosion resistance tend to approach some minimum values during thawing. Changing soil water tension from about 4 kPa to 0 kPa may reduce the critical shear stress by five times. Kok and McCool (1990) performed a field test to quantify soil strength variability induced by soil freeze and thaw. Their test results show that, soil strength is inversely related to the water content of the top 10 mm of the soil profile. The soil water content of this layer during or immediately after rain or snow melt on unfrozen soil would not exceed 25% by weight, whereas it could reach 58% while the soil is frozen and 44% while the soil is thawing.

The validity of WEPP has been tested on experimental hillslopes and watersheds in different locations, primarily the East and Midwest of the United States (Wu et al., 1992; Flanagan et al., 1995). In the NWRR, the model was first tested against the runoff and erosion data obtained from the PCFS experimental plots by McCool and colleagues (1998). Their results indicate that, for the temporally frozen soils that often undergo several cycles of freezing and thawing during one winter season, WEPP consistently underestimated runoff and soil loss. A more complete analysis and modification of the winter hydrology and erosion routines in WEPP will be part of this proposed study.

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