Distributed Modeling and Economic Analysis of Erosion in GIS for Watershed Restoration

Jan Boll[1], Daniel van Buren[2], Chris Campbell[1], Erin Brooks[1],
Shulin Chen[3], Claudio Stöckle[3], Don McCool[4], Dennis Feichtinger[5].

[1] Biological and Agricultural Engineering, University of Idaho, Moscow, Idaho
[2] Wageningen Agricultural University, Wageningen, The Netherlands
[3] Biological Systems Engineering Department, Washington State University, Pullman, Washington
[4] USDA-ARS, Pullman, Washington
[5] USDA-NRCS, Boise, Idaho

Contact: Jan Boll, Department of Biological and Agricultural Engineering, University of Idaho, Moscow, ID 83844-0904

Keywords: integrated systems approach, hydrology, spatial variability, water quality, crop yield

ABSTRACT

An integrated systems approach under development for watershed restoration in the Northwest Wheat and Range Region in the Pacific Northwest was described and applied to an example watershed in northern Idaho. Two constraints placed on model development are that input data is based on publicly available data sources, and that the models do not require calibration. Application of the current modeling approach to Lake Creek watershed shows that using these constraints provided very reasonable predictions on the hydrology and soil erosion. A very simple crop growth modeling approach based on actual evapotranspiration, provided by the hydrology model, and water use efficiency yielded reasonable, spatially distributed estimates of blue grass and wheat yields. Yield reductions after 75 years of soil erosion using the adjusted topsoil depths were somewhat low resulting in small yearly price reductions. The use of GIS and its spatial analytic capabilities in the example application shows the potential of the integrated systems approach to address the challenges associated with watershed restoration.

INTRODUCTION

Pollution of streams, lakes and other surface waters has become a more pressing issue for society than ever before. The number of water bodies placed on the Clean Water Act 303(d) list for impairment of beneficial uses is staggering and still growing (USEPA, 1992). In the Pacific Northwest (i.e., Idaho, Oregon and Washington) around one thousand water bodies per state have been identified as impaired or limited for a variety of beneficial uses. As a result, the need for restoration activities in numerous watersheds is evident.

Watershed restoration efforts in the Pacific Northwest have been accelerated by mandates in the Clean Water Act and subsequent law suits brought onto the states by environmental groups. In order to execute this mandate, Total Maximum Daily Loads (TMDLs) and water quality management plans have to be developed for all water bodies on the 303(d) list in a relatively short time span (e.g., eight years for Idaho). For most of the watersheds, beneficial uses are limited by excessive sediment contribution from nonpoint sources.

Excessive sediment production is a major problem in the Northwest Wheat and Range Region (NWRR) located in northern Idaho, eastern Washington, and north-eastern Oregon, the geographic region targeted in this paper. While being one of the most productive dryland wheat-producing regions of the United States (Austin, 1981), the NWRR has been targeted as critical for controlling erosion and nonpoint source pollution by the Natural Resources Conservation Service (NRCS) (Duda, 1985).

Most of the cropland soils in the NWRR have suffered some productivity loss from erosion since they were first cultivated (Papendick et al., 1985). Some land classes may not have lost little productivity so far, but slow erosion has the potential to degrade even these over future years. Wheat yields in the last decades have increased from technological progress masking the adverse effects of erosion. However, it is a matter of time before yields will decline if erosion is not controlled.

Interestingly, the technology available for effectively controlling erosion and improving water quality exceeds by a wide margin its use by the farming community. The key to achieve restoration and subsequent sustainable ecosystems, therefore, is effective resource management which can best be achieved through an integrated systems approach. In this approach the technical engineering aspects are incorporated as well as the human behavioral and economic considerations of those living in and interacting with the environment. While the need for such an approach has been recognized for some time, examples rarely are found.

Natural resource management entails careful manipulation of complex systems (Mallawaarachchi et al., 1996). If a solid framework or model exists to describe these complex systems, watershed management plans to achieve TMDLs can be designed with properly assigned load reductions for all landowners in a watershed. In turn, an environmentally sound and economically viable system can follow the restoration process by assigning proper water quality standards to each landowner. In this framework or model, however, many physical, socio-economic, and ecological attributes, have to be considered both spatially and temporally. A very powerful way to achieve such a consideration is to integrate the spatial analytical capabilities of Geographic Information Systems (GIS) with process models using available data from individual watersheds. This paper outlines a GIS-based integrated systems approach currently under development and presents the first step in linking water, erosion, and crop growth modeling to an economic analysis to determine the cost of yield reduction due to onsite erosion in a watershed in northern Idaho.

THE GIS-BASED INTEGRATED SYSTEMS APPROACH

An important aspect of our systems approach is that we develop GIS-based modeling tools, which ultimately can be used as a decision support tool by resource managers at the county level. Likely, these managers do not have the full knowledge of the research team involved in the development of these modeling tools. This places two constraints on model development. First, the process models must minimize the number of parameters required to run them (Beven, 1989). Second, the input data for the process models must be readily and publicly available. A further constraint on the development of GIS-based process models using GIS is the need to validate the model using both the accumulated output from the entire watershed (e.g., streamflow, off-site losses), and the output on individual portions within the watershed, may it be a grid cell or field (e.g., runoff depth, on-site losses) (Grayson et al., 1993). The EPIC (Erosion-Productivity-Impact-Calculator) (Williams and Renard, 1985) model covers many of the processes in a watershed system, but since it considers small areas (ca. 1 ha), and requires many parameters, it can hardly be used as a planning tool at the watershed scale.

Mallawaarachchi et al. (1996) in New South Wales, Australia, reported on the development of the State-wide Resource Information and Accounting System (SRIAS). SRIAS is designed to address broad-scale resource, environmental and economic policy questions. The main aim of SRIAS is to develop spatially and temporally consistent data sets for easy linkage to policy and process models. Although the integrated systems approach in SRIAS has many of the characteristics of the approach we outline, the main difference is in the geographic scale. Instead of a state or regional scale, we place a strong emphasis on the watershed scale. At this scale, the resolution is higher and the need for more detailed process models becomes evident. We outline here the framework of our modeling environment, which is under development with cooperation of scientists from the University of Idaho, Washington State University, the Coeur d'Alene Indian Tribe, and the USDA-NRCS.

Figure 1 shows schematically how a resource manager would use the integrated systems approach at the watershed scale. A sequence of steps is initiated, if the system is not acceptable as determined by the resource manager following policy guidelines set forth by regulatory agencies. The assumption is that a database exists including digital maps in a GIS. First, a GIS-based physical science model is run to determine the hydrology, water quality parameters and crop growth for the present situation and for restoration scenarios. Results from the physical science model then are returned to the database and serve as the basis for a socio-economic evaluation. Using constraints placed on output of the models, an optimization scheme determines a plan of action which leads to an implementation plan. During and after the implementation phase, economic and ecological data are gathered to determine if the system is improving as planned. This sequence is repeated until the system returns to an acceptable level.

Components of the system are:

1. The physical process model consists of hydrology, erosion and crop growth simulation. In the future, nutrient and pathogen transport also will be included. Examples of variables transferred to other components of the system are the contribution of water quantity to the stream, onsite and offsite erosion, and crop biomass production as a function of evapotranspiration, water use efficiency, and topsoil depth. Different land use scenarios can be evaluated using the physical process model including Best Management Practices (BMPs) such as crop rotation, tillage, and structural practices.
2. The socio-economics model includes calculations which consider the cost of soil erosion either using distributed output from the physical science model or the cost damage function by Walker (1982). The sociological component takes data from farm interviews where land owners and operators are asked about their perception of erosion in the watershed and which practices they are likely to adopt given environmental and economic choices.
3. An optimization scheme to select the best combination of restoration strategies is based on either mathematical or linear programming.
4. Economic and ecological indicator assessment is based on data collected in the watershed of choice.

A brief overview of the hydrology, erosion, crop growth, and economic models is presented below. Since the development of the integrated systems approach is ongoing, we identify what currently is part of the systems approach and what we will incorporate at a later date.

Hydrology model

The hydrology model is the Soil Moisture Routing (SMR) model described by Frankenberger et al. (1999). The model is written as a sequence of commands within the GIS GRASS. The version reported by Frankenberger et al. (1999) has been adapted to fit the conditions of the NWRR (Boll et al., 1998).

The soil types that best fit this model consist of a relatively thin, permeable soil layer over a much less permeable fragipan, bedrock, or other restricting layer. This profile is typical of upland soils in the glaciated regions of the United States where a fragipan, bedrock or clay layer limits root growth and/or water movement. The model is most effective in areas of steep topography, where slopes are the main cause of lateral flow, and where rainfall intensities are below the soil's infiltration capacity.

Water Balance

SMR is based on a water balance at each time step (e.g., daily) for each grid cell of the area of interest. Cell size is optional but is typically of dimension of 30 m x 30 m. Soil moisture storage for each cell is predicted, and any moisture above saturation results in surface runoff. Input to each cell are precipitation and lateral flow from uphill cells, while output consists of lateral flow to downhill cells, percolation into the subsurface, evapotranspiration, and surface runoff. The soil layer can be divided into five layers identified in the Soil Survey.

Calculation of the water balance is facilitated by the GIS, which keeps track of input parameters such as elevation, soils data, slope, land use, and flow direction as well as the moisture stored in each cell at each time step using simple GIS commands. The model components are illustrated in Figure 2. They will be described briefly in the following sections.

Precipitation consists of all moisture input to the cell, including rainfall and snowmelt. Saturated hydraulic conductivities of soils where the model applies are generally higher than rainfall intensities, so all rainfall is assumed to infiltrate. Precipitation that occurs when the mean daily temperature is below 0°C is assumed to be snow, and remains in the snowpack until the mean daily temperature is above 0°C. Air temperature is distributed spatially over the watershed using a lapse rate. A simple temperature index method is used to calculate snowmelt.

Evapotranspiration (ET) is calculated for each cell using the ratio of actual to potential ET (PET) based on soil moisture content multiplied by the daily PET and a vegetation coefficient which varies throughout the year for each vegetation class (Doorenbos and Pruitt, 1984). PET is calculated using the Makkink equation (De Bruin, 1987). The (ET/PET) ratio is calculated using the relationship developed by Thornthwaite and Mather (1955) for ET at the potential rate when the matric potential is less than 1/3 bar.

No ET takes place when moisture content is below wilting point, and a linear relationship is assumed between wilting point and 1/3 bar moisture contents. Soil evaporation is based on PET of the top 2 cm of soil if the water content is above permanent wilting point following Stöckle et al. (1994).

Shallow subsurface lateral flow, or interflow, is a key component of the water balance. The quantity of lateral flow out of each cell is calculated from Darcy's Law, approximating the hydraulic gradient by the land slope at each cell. The hydraulic conductivity depends on soil moisture content and flow direction. If the average moisture content through the soil profile in a cell is less than field capacity, then vertical hydraulic conductivity is calculated based on moisture content of the profile using an exponential relationship (Bresler et al., 1978; Steenhuis and Van der Molen, 1986). The horizontal hydraulic conductivity is greater than the vertical hydraulic conductivity depending on soil depth (Boll et al., 1998).

Because of the restricting layer at shallow depth, significant vertical water movement stops when the soil becomes unsaturated at the deepest part of the profile. Lateral flow is divided among all cells that are downhill from a particular cell. A multiple flow path algorithm is used to allocate to each neighbor a portion of the total flow depending on (a) the elevation difference between it and surrounding cells, and (b) the distance between the cells.

If a saturated layer is present above the restricting layer or fragipan, water can percolate downward. An "effective conductivity", K_{sub}, of the restrictive layer is specified which limits the rate at which water can leak out of the root zone.

The main cause of surface runoff is soil moisture exceeding the limited moisture storage in the soil profile referred to as saturation excess overland flow. Moisture storage capacity is exceeded when input from precipitation and lateral flow from upslope cells exceed output from ET, lateral flow to downslope cells and percolation by more than the available moisture storage in the soil profile.

Erosion model

The Revised Universal Soil Loss Equation (RUSLE) is used as a first estimate of erosion (E). RUSLE uses the same empirical principles as the USLE (Wischmeier and Smith, 1978), but includes numerous improvements, such as monthly factors, improved equations for calculation of the slope-length factor, and incorporation of convexity/concavity of irregular slopes (Renard et al., 1991).

The equation has the well-known form of E = RKLSCP where R is a rainfall intensity factor, K a soil erodibility factor, LS the topographic (slope-length) factor, C the cover factor and P the prevention practice factor. The R factor is selected as 5.9 times the annual precipitation in inches based on data specific for the Pacific Northwest (Renard et al., 1993). K factors are derived from the Soil Survey. The LS-factor is calculated for each grid cell using the upslope contributing area using GRASS5.0 according to Mitasova et al. (1996). A detailed vegetation/land use map provides for the C factor using published tables. The P factor depends on the type of practices evaluated. Results from the entire watershed are accumulated to estimate offsite damages using the delivery ratio as a function of the area of the watershed (Haan et al., 1994).

Although the RUSLE combined with a delivery ratio provides some distributed erosion estimates within the watershed, it was originally developed for small hillslopes with uniform slope and does not provide temporal resolution. Hence, a physically-based approach is needed for watershed applications especially if site-specific practices are to be evaluated and spatially and temporally distributed results are desired. A GIS-based unit stream power based erosion/deposition model is being developed and tested for that purpose. This model will be based on work by Hairsine and Rose (1992a,b) and field research in the NWRR to determine model parameters. In order to incorporate the stream power theory, the model will evaluate storm events and include a kinematic approximation to overland flow (Wang et al., 2000).

Crop growth model

Water use efficiency, which is equivalent to the ratio of above ground dry matter production and ET (Stoskopf, 1981), varies from crop to crop and is climate related. In our initial effort, therefore, crop growth is based on a linear relationship simply consisting of product of actual ET and the water use efficiency. In order to apply this linear relationship, we assume that crop growth in the NWRR will be limited primarily by the available water in the soil, that the fields are adequately fertilized, and that pests and weeds are controlled to minimize their effect on the final yield. The effect of reduced topsoil due to erosion on the water storage capacity is implicitly accounted for in the model. Root mass is distributed with depth following a pyramid shape (Stöckle et al., 1994).

In the near future the crop growth model will be transformed to a simplified version of CropSyst (Stöckle et al., 1994), which will use a vapor deficit dependent water use efficiency and include radiation as another limiting growth factor. Similarly, the effects of erosion on crop yield such as changes in topsoil hydraulic properties and productivity will be incorporated (Daniels et al., 1989).

Economic model

The current economic model for the NWRR solely evaluates the cost of onsite erosion. An empirical evaluation of the cost of onsite erosion was provided by Walker (1982) and applied to the NWRR previously by Wang (1991). Walker (1982) developed a damage function assuming that the effect of cumulative soil loss on productivity for a particular soil type can be expressed with a yield function relating crop yield to topsoil depth. As such, the cost of onsite erosion is proportional to the reduction in crop yields, which decline partly because essential nutrients and organic matter are lost, and because eroded soil suffers from moisture deficiency (Burnet et al., 1985).

Conventionally, a reduction in annual crop yield also can be valued using capitalization theory. This theory is most easily explained as any reduction in future income that can be replaced by the interest of a certain sum, which is the value of the lost future income. This sum is calculated as the reduction in annual income divided by the interest rate. It is noted that this method will only be valid as long as society can afford to lose production potential from cropland. If this is no longer the case, the actual cost of erosion will be the investment needed to restore the soil to its former productivity.

Future work on the economics model includes a more in-depth calculation of onsite erosion for different BMPs and calculation of offsite erosion effects. In addition to calculating the cost of yield reductions due to onsite erosion, different crop rotations and tillage practices can be evaluated. Each tillage practice or crop choice would have different production costs, and add a rate of technical progress to the existing yield function (Walker, 1982). A yield penalty due to different fertility, disease and weed control problems also would be included. Offsite costs may include costs to remove sediment from ditches, roads or water storage reservoirs, and the deterioration of aquatic ecosystems, which can express itself in smaller stocks of fish like trout and salmon, and, therefore, a loss to quality of life. To express the latter deterioration in monetary units is a difficult task and will be subjective.

DETERMINATION OF THE COST OF EROSION: AN APPLICATION

As a preliminary application of the integrated systems approach, we determine the cost of yield reduction due to onsite erosion for a watershed in northern Idaho representative of the NWRR. The purpose of this application is to show the linking of SMR, RUSLE, crop growth, and the economic calculations, and to illustrate the use of GIS for spatial and temporal input and output.

Description of the Study Area: Lake Creek Watershed

The study watershed is Lake Creek watershed (9,942 ha) located 45 km south of Coeur d'Alene, Idaho in the Coeur d'Alene Lake Basin in northern Idaho. The watershed spans two states, two counties, and includes cultural aspects in the form of the Coeur d'Alene Indian Tribe and absentee landowners. Lake Creek is a tributary to Coeur d'Alene Lake, entering the lake at Windy Bay (Figure 3). Elevations range from 1585 m at the headwaters to 650 m at Windy Bay (Figure 3).

Geomorphic features of the region include loess-covered basalt plains, hills with large steptoes, undulating plateaus, and some river breaklands. The region is dominated by typically loess soils with a dark A horizon high in organic matter. Major soils include the Santa, Setters, Kruse, Taney, Larkin, and Santa Variant soils. These soils are moderately deep to a restrictive layer of clay, fragipan, or bedrock, and exhibit a seasonal high water table. Typical crops in the area are bluegrass seed, winter wheat, spring barley, oats, lentils, and hay. Approximately 7,662 ha of Lake Creek watershed are located in Kootenai County, Idaho, and 2,280 ha in Spokane County, Washington. Forest covers the upper elevations of the watershed and the steeper breaks near the lake comprising of 60% of the area. Nearly 36% of the watershed is in cropland and 4% in pastureland and emergent wetland (Figure 3).

Coeur d'Alene Lake and associated tributaries have been identified as having nonpoint source pollution problems associated with agricultural and silvicultural activities. Lake Creek has significant water quality impact on Coeur d'Alene Lake, which is on the 1996 303(d) list for the beneficial uses of domestic water supply, cold water biota, salmonid spawning, and primary and secondary contact recreation. Lake Creek is on the 1996 303(d) list for the beneficial uses cold water biota and salmonid spawning. These uses are limited by excessive sediment, elevated temperatures and flow fluctuation extremes. Current restoration efforts, therefore, focus on erosion control and water quality related activities.

Two continuous event-based water quality monitoring stations have been in operation since 1996 (Figure 3). Both stations continuously record stream discharge, turbidity, air and water temperature, and total precipitation. Radiation and wind speed have been measured since 1998. Grab sampling has established a linear relationship between turbidity and Total Suspended Sediment (TSS) and total phosphorus. Since 1993, BMPs have been implemented by the State Agricultural Water Quality Plan through individual water quality contracts on a cost-share basis.

Model Input and Output, Parameter Selection, and Scenarios

SMR was run for the period of January, 1999 through March, 2000. Input to SMR for Lake Creek watershed was a digital elevation model (DEM, Figure 3), a digital soil map and associated Soils5 database, a digital land use map, and weather data (e.g., precipitation and air temperature). These are all publicly available data. All pertinent parameters are derived from these data including slope, soil horizons, saturated hydraulic conductivity, porosity, percent rock, depth to restrictive layer, and ET coefficients. The saturated hydraulic conductivity of the restrictive layer was set at 5 mm/day throughout the simulations. Based on data from a small research watershed in the NWRR (Boll et al., 1998), the ratio of horizontal to vertical saturated hydraulic conductivity was 10 in the top soil layer horizon and reduced exponentially to one for the lowest soil layer.

Output from the SMR model consisted of predicted stream flow, made up of surface runoff, subsurface lateral flow, and base flow using a recession coefficient of 0.09, cumulative monthly runoff maps, and daily values of actual ET for the crop growth model. No model calibration was performed.

Parameters for the RUSLE were determined using Haan et al. (1994) and Renard et al. (1991, 1993). The R-value was equal to 136. K, C and LS factors were distributed over the watershed according to soil, crop cover, and elevation data in GRASS5.0, respectively. The P factor was taken as one in all simulations since no practices were considered. Because erosion from the forested parts of Lake Creek watershed essentially originates from roads and from within the stream, erosion from the forested part of the watershed could not be simulated with RUSLE.

The erosion model provided an estimate of annual erosion amounts for crop land areas in the watershed. Erosion amounts then were converted to reduction in topsoil depth after adjustment by a delivery ratio (discussed later).

The water use efficiency used in the crop growth model was between 1.8 and 2.0 kg dry matter per 1000 kg of evaporated water following Shants and Piemeisel (1927), who found a similar water use efficiency in Colorado for most grass-species (including wheat and barley). The crop growth model output consisted of annual above ground biomass maps for agricultural crops.

Two land use scenarios were tested. Scenario 1 assumed current land use conditions in Lake Creek watershed which is dominated by blue grass seed production. Field burning of blue grass fields is debated heavily in Idaho. Therefore, Scenario 2 assumed that all blue grass fields are converted to winter wheat. This scenario also relates to other watersheds in the NWRR where wheat production is more common. Crop biomass, and, in turn, yield reduction was estimated using the crop growth model for each scenario based on today's topsoil depths and based on topsoil depths after 75 years of soil erosion without any erosion limiting efforts by landowners. Seventy five years was chosen to include approximately three generations of landowner/operator. Walker's (1982) yield function also was used to estimate yield reduction after 75 years. This function also used the topsoil depths of today and after 75 years.

Economic calculations depict the cost of yield reduction based on 75 years of field soil erosion (corrected by a delivery ratio) for both scenarios, using results from the crop growth model and the yield function by

Walker (1982). These calculations were the product of the percentage reduction in grain yield, derived from above ground biomass reduction, the price of blue grass (Kg/ha) and wheat (bu/ha), respectively, and a capitalization rate of 5%. All monetary amounts reported are in present dollar values.

RESULTS AND DISCUSSION

Results from the SMR model were evaluated visually using stream flow and runoff generation within the watershed. Predicted stream flow is in good agreement with observed stream flow at both monitoring stations, especially since no calibtration was performed. Figure 4 shows the comparison for the lower monitoring station for the period of January, 1999, through March, 2000. Predicted discharge is slightly lower than observed discharge during snow melt periods which may be due to inaccurate snow fall measurements since unshielded rain gauges are used at both stations. During the summer, the SMR model over-predicted stream flow somewhat.

Figure 5 depicts the variability both spatially and temporally in runoff generating areas typical of the variable source area hydrology observed in watersheds of the NWRR. Each map in Figure 5 represents the cumulative amount of runoff predicted in mm. In January (Figure 5a), the lower portion of the watershed and areas with converging topography or reduced soil depth became saturated and produced moderate amounts of runoff. In February (Figure 5b), the runoff amounts and the number of runoff contributing areas reached a maximum. The lower portion of the watershed dried out during March (Figure 5c), but snowmelt in the forested areas continued to produce runoff. In April (Figure 5d), runoff generation ceased in the lower portion of the watershed, and was reduced in the forested areas. These predictions are in agreement with observations in the watershed.

Areas generating erosion from crop land, predicted with the RUSLE, are shown in Figures 6a and Figure 6b for current land use conditions (Scenario 1) and for land use conditions where all blue grass fields were converted to winter wheat (Scenario 2). Erosion generating areas overlapped with runoff generating areas on approximately 82% of the crop land area. At first sight, this agreement is somewhat surprising considering that the RUSLE and SMR model are independent of each other. Results from both models, however, depend on upslope contributing area. As Figure 6a shows, blue grass production does not produce much erosion. The high erosion producing areas are wheat fields. Comparison of Figure 6a and Figure 6b shows that conversion to winter wheat would produce much more erosion than current conditions on a yearly basis. Obviously, accounting for crop rotations and residue reduces the erosion on winter wheat fields.

The total amount of erosion predicted from all crop land using the RUSLE for Scenario 1 was 96,830 metric tons/yr. Measured sediment between the upper and lower monitoring stations was 16,563 tons for 1999, equal to 17% of the predicted erosion. A delivery ratio of 17% would be reasonable for the watershed area covered by crop land (Haan et al., 1994). A small logging operation, however, took place just upstream of the lower monitoring station, which clearly affected the turbidity measurements during parts of 1999. To account for this effect and known stream bank erosion, the delivery ratio was set to 10% when cell-based erosion amounts were converted to topsoil reduction on erosion generating areas.

Above ground biomass production predicted by the crop growth model gave reasonable estimates for blue grass and winter wheat, but they were lower than yields generally obtained in the NWRR (data not shown). Possibly, the over prediction of streamflow in the summer by the SMR model was the result of low actual ET estimation, which caused lower above ground biomass production.

Despite the low biomass estimates by the crop growth model, the percent yield reduction after 75 years can be used to show the spatially distributed effect of erosion. Figure 7a shows the yield reduction for Scenario 1, while Figure 7b shows the yield reduction for Scenario 2. While the majority of the crop area experienced yield reductions from 0 to 1 percent, some areas experienced large yield reductions (Table 1). Such reductions may have occurred on areas with severe soil erosion and/or shallow topsoil depth. As expected, the greater amount of erosion for Scenario 2 caused greater yield reductions.

Results of the application of Walker's yield function to determine yield reduction after 75 years of erosion are shown in Figure 7c and Figure 7d for Scenario 1 and Scenario 2, respectively. Two observations are made. First, Walker's function predicted lower yield reductions than the crop growth model both having the same topsoil reduction based on the RUSLE. Second, the yield reduction for Scenario 2 was more severe than Scenario 1.

In dollar amounts, the yield reductions predicted for blue grass and winter wheat in Lake Creek watershed do not appear very substantial for most areas. Using a price of $1.87 per Kg of blue grass seed, a yield reduction of one percent is equivalent to a loss of $2.55 per ha per year. Similarly, using a price of $4.00 per bushel of wheat, a yield reduction of one percent is equivalent to a loss of $1.33 per ha per year. The difference in losses between blue grass seed and wheat reflects that blue grass seed is a higher value crop than wheat. Obviously, the economic calculations performed here do not represent all costs associated with soil erosion as mentioned earlier. Hence, in an absolute sense these numbers are not meaningful yet.

Overall, this application shows how the integrated systems approach can provide spatially distributed information regarding hydrology, erosion, crop growth and economics. Although model integration in this application is preliminary, the use of GIS and its spatial analytic capabilities shows great merit to address the challenges associated with watershed restoration. Further expansion of the systems approach will increase these capabilities and provide site-specific information at the scale of a farmer's field or larger if so desired.

CONCLUSIONS

An integrated systems approach under development for the Northwest Wheat and Range Region was described and applied to an example watershed. Once complete, a suite of models in the systems approach will be linked through a GIS database so that management plans for watershed restoration can be constructed based on input from the physical sciences, socio-economics and ecological disciplines, and optimization schemes. Given the desire to transfer the integrated system to county level resource managers, two constraints were placed on model development. First, input data is based on publicly available data sources, and, second, the models do not require calibration.

Application of the current modeling approach to Lake Creek watershed in northern Idaho shows that using these constraints provided very reasonable results. The hydrology model successfully simulated observed stream flow and distribution of runoff generating areas in the watershed. Erosion distribution in the watershed determined using the empirical RUSLE, which used an LS factor based on upslope contributing area, gave reasonable agreement with the distribution of runoff generating areas. In addition, total erosion amounts appeared in agreement with observed sediment measured in the stream.

A very simple crop growth modeling approach based on actual ET provided by the hydrology model, and water use efficiency yielded reasonable, although somewhat low, spatially distributed estimates of blue grass and wheat yields. Yield reductions after 75 years of soil erosion using the adjusted topsoil depths were somewhat low resulting in small yearly price reductions.

The example application shows the potential of the integrated systems approach in yielding very useful site-specific information. We believe that this tool eventually will assist resource managers to identify critical source areas within a watershed and properly assign load reductions for individual landowners.

REFERENCES

Austin, M.E. 1981. Land resource regions and major land resource areas of the United States. U.S. Dep. Agric., Agric. Handbook No. 296.

Beven, K.J. 1989. Changing ideas in hydrology: The case of physically-based models. J. Hydrol. 105:157-172.

Boll, J., E.S. Brooks, C.R. Campbell, C.O. Stockle, S.K. Young, J.E. Hammel and P.A. McDaniel. 1998. Progress toward development of a GIS based water quality management tool for small rural watersheds: modification and application of a distributed model. Presented at the 1998 ASAE Annual International Meeting in Orlando, Florida, July 12-16, Paper 982230, ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

Bresler, E., D. Russo and R.D. Miller. 1978. Rapid estimate of unsaturated hydraulic conductivity function. Soil Sci. Soc. Am. Proc. 42:170-172.

Burnett E., B.A. Stewart and A.L. Black. 1985. Regional effects of soil erosion on crop productivity-great plains. P. In Soil Erosion and Crop Productivity, eds. R.F. Follet and B.A. Stewart, Ch.17, 285-304. Madison: ASA-CSSA-SSSA.

Daniels, R.B., J.W. Gilliam, D.K. Cassel and L.A. Nelson. 1989. Soil erosion has limited effect on field scale crop productivity in the Southern Piedmont. Soil. Sci. Soc. Am. J. 53:917-920.

De Bruin, H.A.R. 1987. From Penman to Makkink. In: Versl en Meded. 39: p. 5-31, Comm. Hydr. Onderz. TNO, 's Gravenhage.

Doorenbos, J. and W.O. Pruitt. 1984. Crop water requirements. FAO Irrigation and Drainage Paper 24.

Duda, A.M. 1985. Environmental and economic damage caused by sediment from agricultural nonpoint sources. Water Res. Bull. 21:225-234.

Frankenberger, J.G., E.S. Brooks, M.T. Walter and T.S. Steenhuis. 1999. A GIS-based variable source area hydrology model. Hydrol. Processes 13:805-822.

Grayson, R.B., G. Blöschl, R.D. Barling and I.D. Moore. 1993. Process, scale and constraints to hydrological modeling in GIS. Proceedings of the Vienna Conference, IAHS Publ. No. 211:83-92.

Haan, C.T., B.J. Barfield and J.C. Hayes. 1994. Design Hydrology And Sedimentology For Small Catchments. Academic Press, San Diego.

Hairsine, P.B. and C.W. Rose. 1992a. Modeling water erosion due to overland flow using physical principles. 1. Sheet flow. Water Resour. Res. 28(1):237-243.

Hairsine, P.B. and C.W. Rose. 1992b. Modeling water erosion due to overland flow using physical principles. 2. Rill flow. Water Resour. Res. 28(1):245-250.

Mallawaarachchi, T., P.A. Walker, M.D. Young, R.E. Smith, H.S. Lynch and G. Dudgeon. 1996. GIS-based integration modelling systems for natural resource management. Agricultural Systems 50:169-189.

Mitasova, H., J. Hofierka, M. Zlocha and R.L. Iverson. 1996. Modeling topographic potential for erosion and deposition using GIS. Int. Journal of Geographic Information Science 10(5):629-641.

Papendick, R.I., D.L. Young, D.K. McCool and H.A. Krauss. 1985. Regional effects of soil erosion on crop productivity - The Palouse area of the Pacific Northwest. In Soil Erosion and Crop Productivity, eds. R.F. Follet and B.A. Stewart, Ch.18, 305-320. Madison: ASA-CSSA-SSSA.

Renard, G.K., D.K. McCool, K.R. Cooley, C.K. Mutchler and G.R. Foster. 1993. Rainfall-runoff erosivity factor (R). In Predicting Soil Erosion by Water - A Guide to Conservation Planning with the Revised Universal Soil Loss Equation RUSLE, ed. Renard, Foster, and Weesies, Ch. 2. Publication ARS. U.S. Department of Agriculture, Washington, D.C.

Renard, G.K., G.R. Foster, G.A. Weesies, and J.P. Poter. 1991. RUSLE - Revised universal soil loss equation. J. of Soil and Water Cons. 46:30-33.

Shantz, H. L. and L.N. Piemeisel. 1927. The water requirements of plants at Akron Colorado. Journal of Agricultural Research 34: 1093-1190.

Steenhuis, T.S. and W.H. Van der Molen. 1986. The Thornthwaite-Mather procedure as a simple engineering method to predict recharge. J. Hydrol. 84:221-229.

Stöckle C. O., S.A. Martin, and G.S. Campbell. 1994. CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yields. Agricultural Systems 46:335-339.

Stoskopf, N.C. 1981. Understanding Crop Production. Reston Publishing Company, Virginia.

C.W. Thornthwaite and J.R. Mather. 1955. The Water Balance. Laboratory of Climatology, Publ. No. 8, Centerton NJ.

United States Environmental Protection Agency. 1992. National Water Quality Inventory, 1992 Report to Congress. EPA 841-R-94-001, Office of Water, Washington DC, pp. 328.

Walker, D.J. 1982. A damage function to evaluate erosion control economics. Amer. J. Agr. Econ. 64:690-698.

Wang, G., S. Chen, J. Boll, C.O. Stöckle and D.K. McCool. 2000. Modeling overland flow based on Saint-Venant equations using a discretized hillslope approach. Submitted to Hydrol. Processes.

Wang, Y. 1991. An onsite and offsite economic analysis of erosion and nonpoint source pollution in Idaho's Tom Beall watershed. Unpublished MS Thesis, University of Idaho.

Williams J. R. and K.G. Renard. 1985. Assessment of soil erosion and crop productivity with process models (EPIC). In Soil Erosion and Crop Productivity, ed. R.F. Follet and B.A. Stewart, Ch.5, 67-103. Madison: ASA-CSSA-SSSA.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S. Dept. Agric., Agric. Handbook No. 537, Washington, D.C.

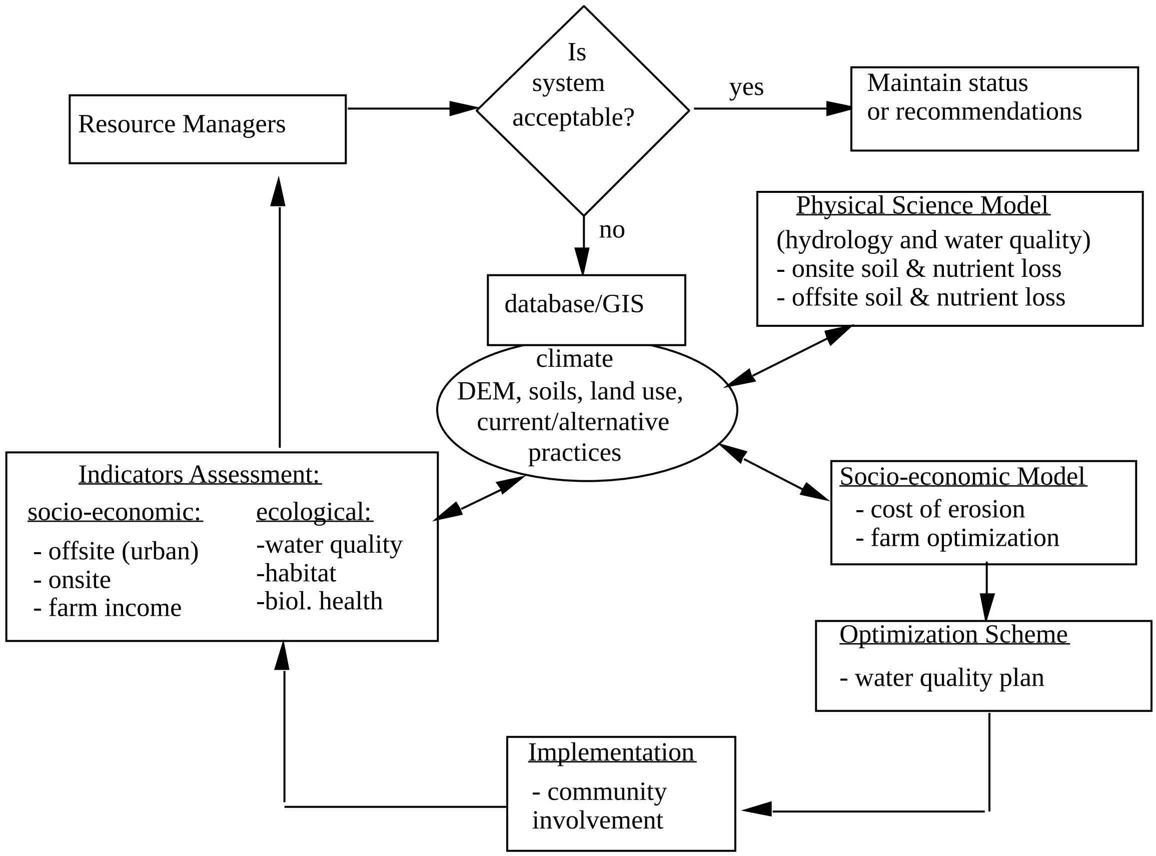

Figure 1. Schematic Representation of the GIS-based Integrated Systems Approach.

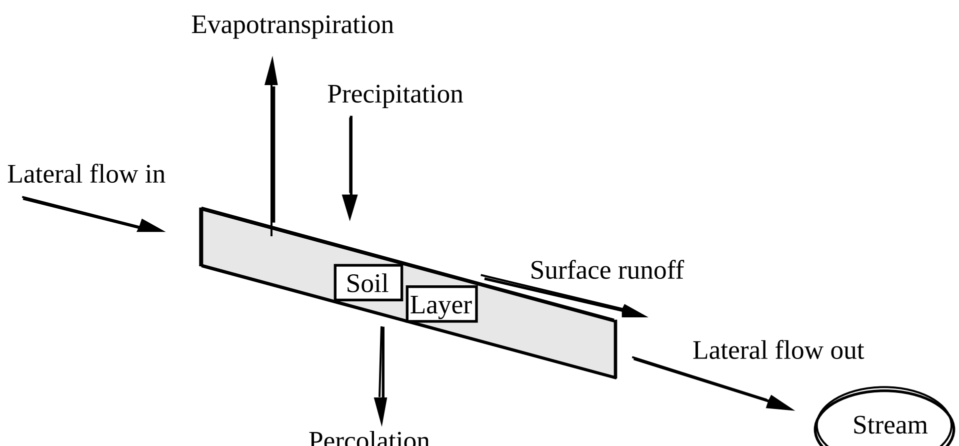

Figure 2. Conceptual Hydrologic Model.

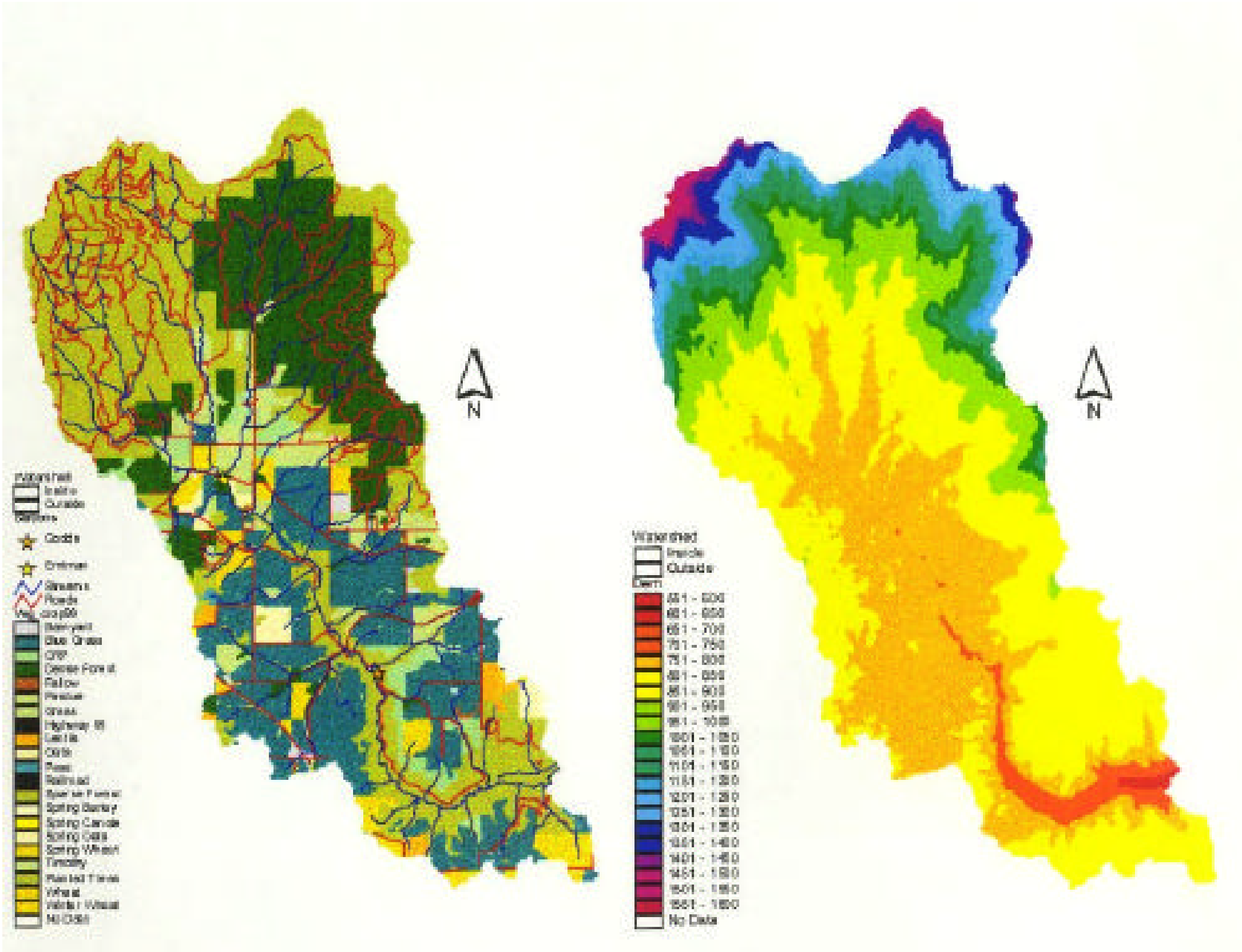

Figure 3. Land Use Map (left) and DEM (right) for Lake Creek Watershed

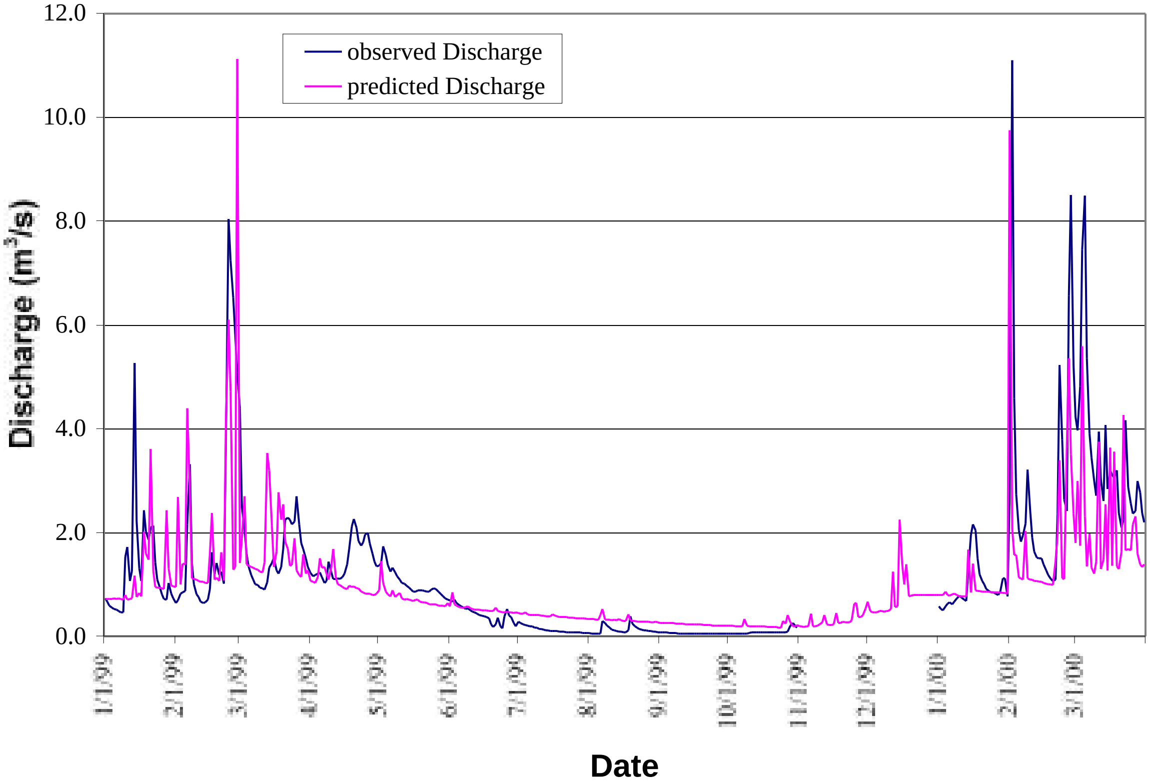

Figure 4. Observed and Predicted Stream Flow at Lower Monitoring Station in Lake Creek Watershed from January, 1999 to March, 2000.

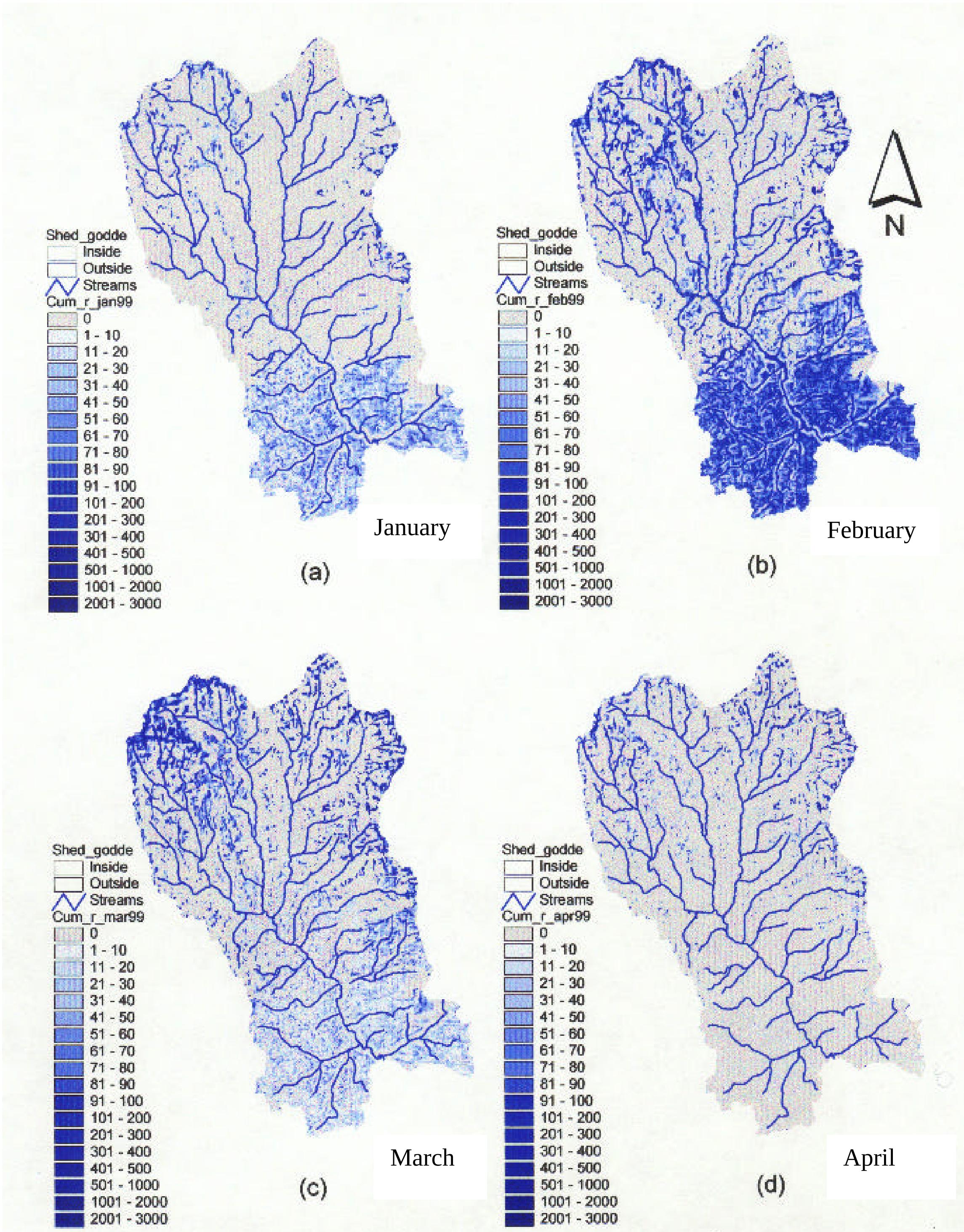

Figure 5. Cumulative Monthly Runoff (mm) for January (a) to April (d), 1999 in Lake Creek Watershed.

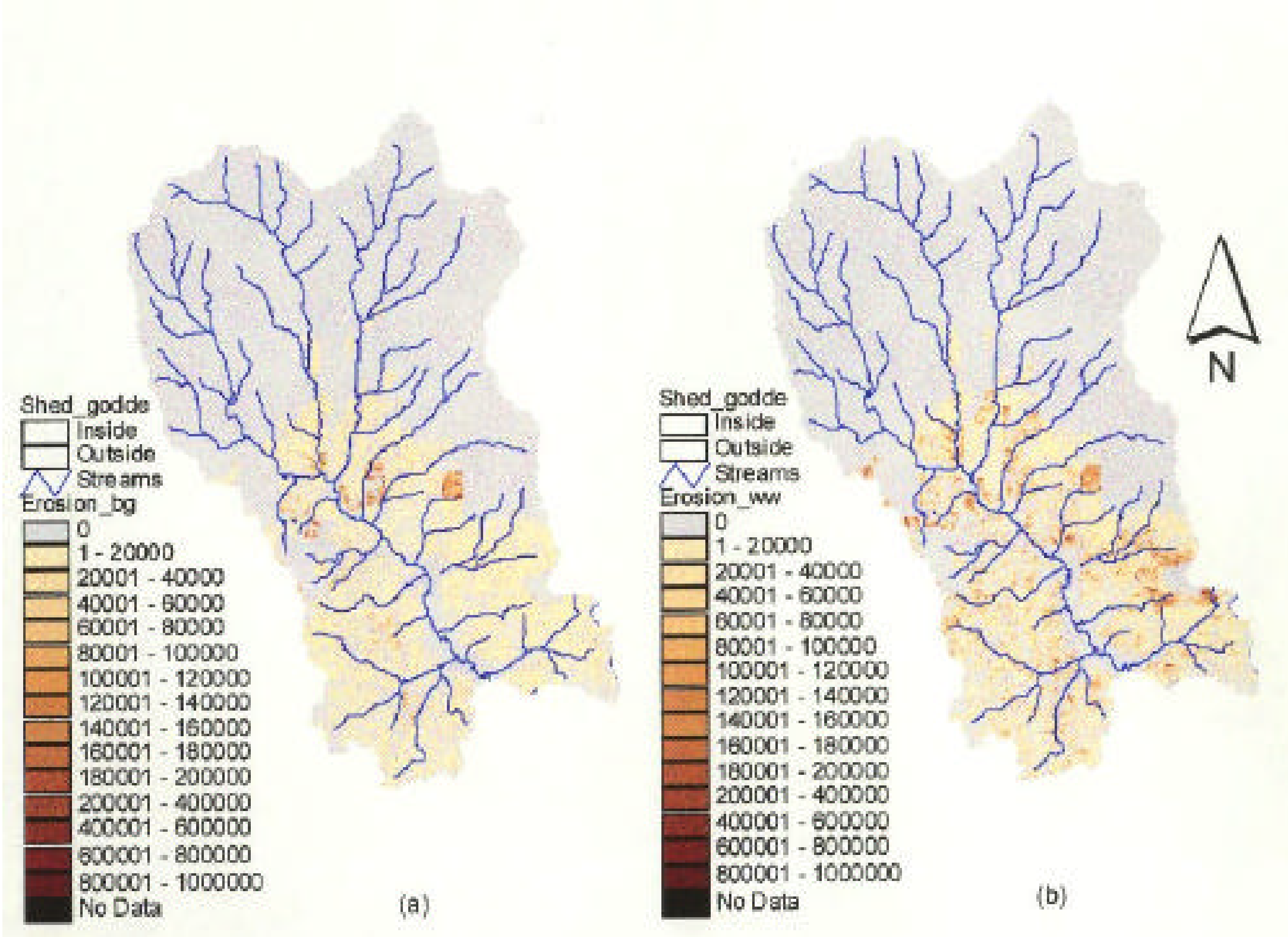

Figure 6. Erosion Prediction (Kg/ha) in Lake Creek Watershed for Scenario 1 (left) and Scenario 2 (right).

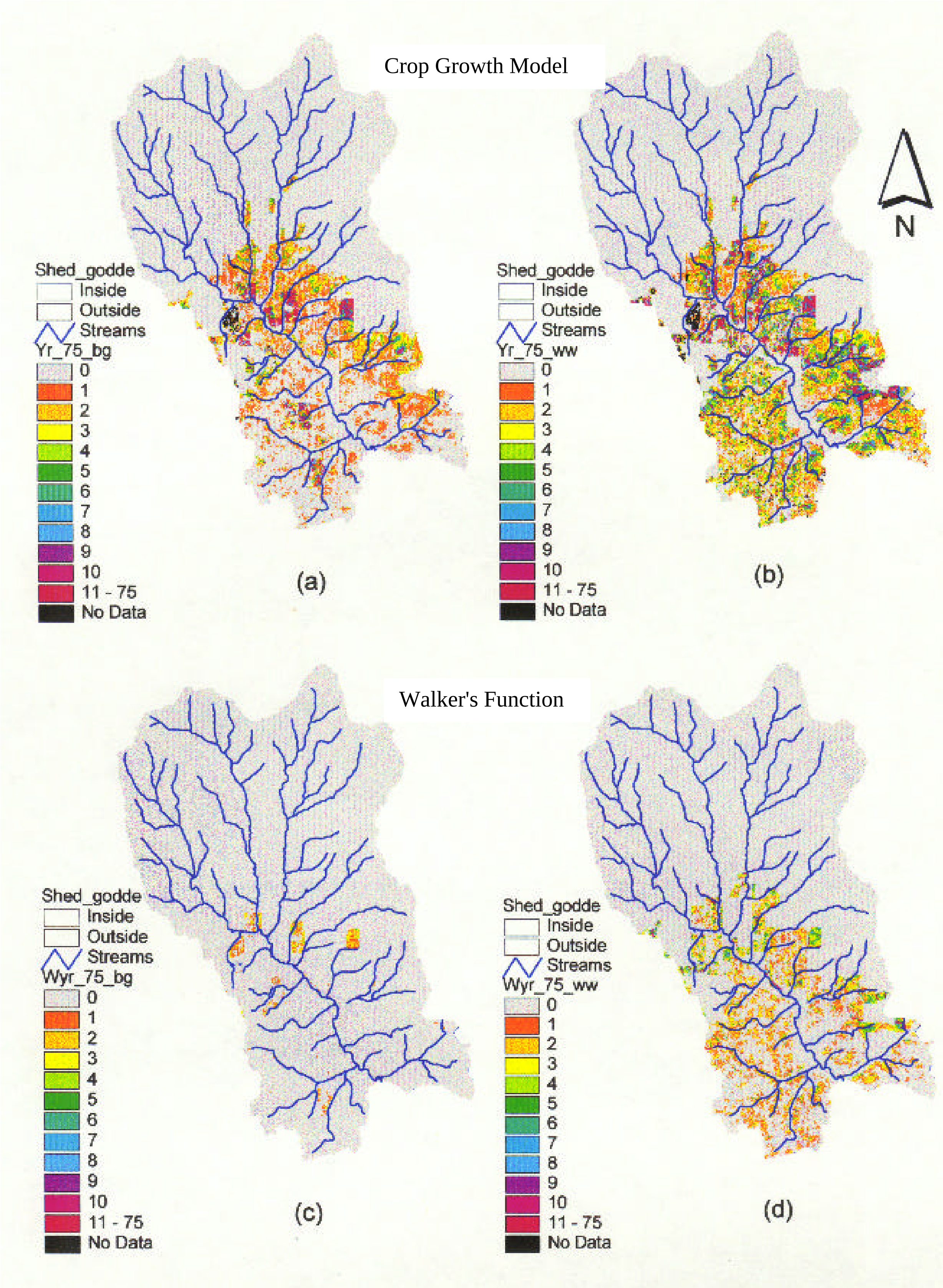

Figure 7. Yield Reduction after 75 Years of Onsite Erosion for Scenario 1 (left) and Scenario 2 (right).

Table 1. Area Percentages of Yield Reductions for Crop Land Shown in Figure 7 for Scenario 1 (bg) and Scenario 2 (ww) Using the Crop Growth Model (Yr_75) and the Walker's Function (Wyr).

%yield reduction	Yr_75_bg	Yr_75_ww	%yield reduction	Wyr_75_bg	Wyr_75_ww
0	59.4	31.0	0	97.2	71.6
1	19.6	15.1	1	1.2	9.4
2	8.8	13.9	2	1.1	9.0
3	2.9	9.1	3-75	.5	9.9
4	2.1	6.7			
5	1.3	5.0			
6	0.9	4.0			
7	0.7	2.7			
8	0.6	2.3			
9	0.5	1.7			
10	0.4	1.3			
11-75	2.4	5.7			