Modeling runoff and erosion from construction sites in 2-D with RUSLE2

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Abstract
New techniques allow RUSLE2 to estimate average monthly runoff, the number of runoff events per year, and parameters describing the statistical distribution of runoff event depths for any combination of location, soil, and management. This allows the determination of runoff events of specific return periods and erosion computation during an accounting period for a representative sequence of runoff events that is based completely on existing RUSLE2 input information. Further, the RUSLE2 code has been modified to allow efficient grid-based sheet and rill erosion computations that can be driven by high-resolution elevation data. Local slope length is determined using the ratio of runoff entering a cell to that leaving the cell, thus reflecting upslope variation in soil and land use. Surface roughness, residue cover, and soil biomass properties are re-used for each combination of soil and management, creating computational efficiency. These developments overcome the limitations of having to describe a construction site as a series of one-dimensional representative profiles, allowing RUSLE2 erosion and sediment delivery computations to be applied in a GIS context to conduct "before" and "after" analyses of construction sites while making use of recent advances to the database and results reporting capabilities described by Yoder *et al.* (2007).

Introduction
RUSLE2 is the most recent in the family of USLE/RUSLE/RUSLE2 models proven to provide robust estimates of average annual sheet and rill erosion from a wide range of land use, soil, and climatic conditions. RUSLE2's capabilities have been expanded over earlier versions using methods of estimating time-varying runoff and the CREAMS process-based sediment transport routines so that it can estimate sediment transport/deposition/delivery on complex hillslopes. In addition, while RUSLE2 is generally driven with readily-available monthly climate information, calculations are done on a daily time-step, allowing the use measured or generated daily rainfall and erosivity values where those data are available.

RUSLE2 is a land use-independent model that has been widely used for conservation planning on construction sites by engineers, planners, reviewers, inspectors, and developers. Yoder *et al.* (2007) described enhancements made to the RUSLE2 interface and databases to facilitate this application. These enhancements include database descriptions of management practices such as mulches, blankets and vegetations, devices or structures such as permeable barriers (e.g., silt fences, straw bales, fiber rolls, compost socks, etc.) and sediment basins, and combination techniques such as vegetative filter strips. A major advance in results reporting was the definition of an "accounting period," the period of interest during which the construction planner is responsible for controlling sediment delivery from a site. Though the definition is flexible, in the example cited in Yoder *et al.* (2007), the accounting period begins with the first soil disturbing field operation and ends with the application of permanent erosion protection, defined as either application of a semi‐permanent non‐erodible surface (pavement, landscape fabric and cover, sod, etc.) or a specified period of growth of a perennial vegetation. The default for this period is 60 days of growth during which the average air temperature was above 1.7°C, thereby giving no growth credit for periods when vegetation is dormant. This approach gives the planner an incentive to keep the accounting period short, to reduce erosion and delivery during that period, to plan construction during non‐erosive periods, and to plant cover when it will grow, all of which are good conservation planning practices.

Two limitations with the current RUSLE2 for conservation planning of construction sites are that (1) the planner must define a representative one-dimensional hillslope profile, or series of profiles, to characterize the site both before and during construction, and (2) that erosion caused by concentrated flow in channels is not estimated. The purpose of this manuscript is to describe a new 2-D version of RUSLE2 that overcomes the first limitation and new RUSLE2 runoff-estimation techniques that allow direct linkage to a channel erosion model to overcome the second.

Grid-Based RUSLE2

GIS-based tools are being developed by Agren, Inc. (http://www.agren-inc.com/projects.php?proj=15) to allow high resolution LiDAR elevation data to be used with RUSLE2 to improve conservation planning on agricultural lands in Iowa. Since each RUSLE2 hillslope profile terminates at a location where overland flow intersects a concentrated flow channel, identification of the location of channels (including terrace channels and ephemeral gullies) within agricultural fields is a critical step in the process. Because detailed CAD drawings are usually available that describe the topography of construction sites very precisely, and the location of channels is often controlled by design, the new technology can be readily adapted to conservation planning on construction sites.

To improve computational efficiency and enable the automatic determination slope lengths in complex topographic settings, RUSLE2 was re-coded to allow re-use of common information in grid-based calculations (Figure 1A). The calculation of soil biomass, soil residue cover, soil roughness, and similar properties for every day of a simulation is one of the most time-consuming steps in RUSLE2 computations, so reusing this information for the limited number of soil and management combinations found in a typical site simulation greatly reduces the runtime of a grid-based simulation. Further, the determination of slope lengths as the ratio of runoff entering a cell to that leaving the cell has been integrated into the RUSLE2 engine (Figure 1C). This allows the automatic determination of an equivalent slope length, matching the results of the standard equations for uniform profiles yet permitting the correct representation of complex situations involving topographic flow convergence as well as seasonal and spatial variability in runoff generation related to soil and management combo effects.

A shell program was developed that sets up and executes RUSLE2 hillslope simulations using functions provided by the Application Programming Interface (API), distributed in the RUSLE2 .dll. The shell program defines input parameters and some RUSLE2 simulation options, executes the erosion simulation and retrieves computed erosion values, optionally links results to a channel erosion model, and displays results on the screen. The method is structured in three independent phases. Phase 1 encompasses most of the user interaction through a graphical interface and consists of identifying the simulation area, generating soil and management layers, retrieving a DEM in the required resolution, and then determining drainage networks and the locations of the concentrated flow channels that end RUSLE2 hillslope profiles. In Phase 2, the shell program sets up the RUSLE2 model for the 2D simulation area, executes the simulations, and exports simulation results for post-processing. Phase 3 converts simulation results into user-friendly formats such as maps, graphs, and summary tables according to user requirements. The computational module of Phase 2 accesses RUSLE2's computational engine through its DLL. It utilizes data layers prepared in Phase 1 (flow directions, slope steepness, soil map, management map, and channel network cells), and user-defined parameters such as RUSLE2 simulation options and requirements for data output. The module efficiently divides the simulation area into a number of profiles with varying numbers of raster cells, and manages the execution of the simulations through RUSLE2 API functions. RUSLE2 outputs of distributed soil erosion, sediment delivery to channels, and sediment deposition in channels and sediment basins are retrieved and saved. Optionally, channel erosion can be estimated by linkage of RUSLE2 results with a channel model as described in the next section.

Each cell crossed by a channel defines a drainage area outlet, corresponding to the end of an overland flow path. For each channel-containing cell in the network, the flow directions map is analyzed to determine which of the neighboring cells drain to that channel cell. The process is recursive and somewhat complex: if a cell drains into the cell being inspected, focus is shifted to that second cell. This process is repeated in checking uphill cells uphill until no inflow is detected for a cell. The no-inflow cell identifies the beginning of a flow path. The cell is marked and numbered. A reverse process is then started, following flowpaths downhill, defining the connectivity among the several cells that compose the area draining to the original channel cell. The process is repeated for each channel cell in the network. A RUSLE2 profile is thus created for each channel cell (Figure 1B). The channel cell itself is divided by the channel and potentially contributes to the slope length of the left and right bank overland flow paths. Each 2-D RUSLE2 profile therefore comprises an ordered collection of raster cells. RUSLE2 internally manages the transfer of runoff and sediment among the profile segments, but the sequence of computation follows the cell interconnectivity prescribed to RUSLE2 by the shell program for each profile. The RUSLE2 profiles can be computed independently, in any order, which permits optimization through parallel computations in multiprocessor or multicore computers.

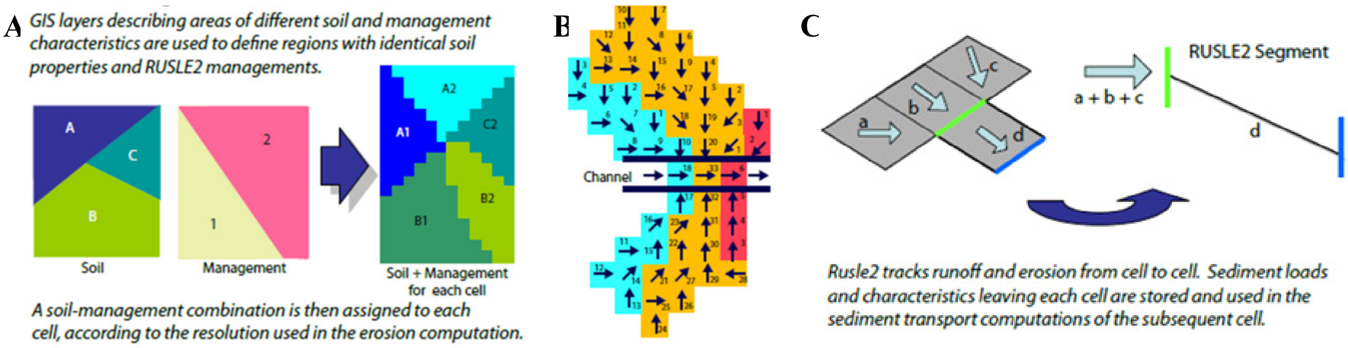

Figure 1. (A) Unique combinations of soil and management are termed "combos" and the resulting residue, roughness, and soil biomass properties for each day of the simulation are stored internally in RUSLE2 for efficient reuse. (B) Starting with each channel cell (black outline), a computer algorithm analyzes the flow directions map to determine the connectivity and computational sequence of the cells that compose a profile. The figure shows three profiles on each side of the channel, identified in different colors. (C) RUSLE2 determines effective slope length based on the ratio of runoff leaving a cell to that entering the cell, enabling the appropriate accounting for topographic, soil, and management effects on local erosion estimates.

Runoff Event Estimation

Dabney *et al.* (2010) proposed and evaluated a method for predicting a series of representative runoff events whose sizes, durations, and timing are estimated from information already in the RUSLE2 database. They developed regression relationships to approximate the mean monthly runoff, annual runoff event frequency, and a gamma distribution function scale parameter that characterized 30-year stochastic runoff predictions generated using the AnnAGNPS model (Bingner and Theurer 2001). These algorithms have now been coded into RUSLE2 so that the size of the runoff event with any return period can be estimated, allowing RUSLE2 to be used in risk assessment calculations. By assuming that the largest in a series of runoff events that cause annual average channel erosion had a 1-year return period ($Q_{1y,24h}$) and that the depths of the periodic runoff events were proportional to long term average daily runoff amounts, the dates and sizes of a representative runoff event sequence are now calculated within RUSLE2. The largest runoff event in the sequence defaults to $Q_{1y,24h}$, although a different maximum event can be selected; the sum of all runoff events approximates the annual runoff for any location, soil, and management combination; and the sum of sheet and rill erosion estimates from all events is very similar to the RUSLE2 estimates computed using normal procedures.

For application to construction sites, the portion of the annual series of events occurring during an accounting period can be used to efficiently drive grid-based computations of sheet and rill erosion and sediment delivery to channels. Further, the available event outputs of runoff depth, runoff rate, runoff concentration, and fractional contributions of sand, silt, clay, small aggregates, and large aggregates make it possible to link RUSLE2 outputs to a channel erosion model. Dabney *et al.* (2010) illustrated the procedure by linking RUSLE2 output to the channel erosion routines used in CREAMS (Foster *et al.* 1980), which are essentially the same as those used in the watershed version of WEPP (Ascough *et al.* 1997) and GeoWEPP (Renschler 2003) to estimate ephemeral gully erosion. The same approach could be applied to estimate erosion of potential channels in alternative construction site designs.

Summary

RUSLE2 offers a simple yet robust system for estimating sheet and rill erosion from hillslopes. Extensive databases exist for soils, climates, operations, vegetations, and residue descriptions that can be readily extended to other locations. New techniques have been developed to allow average monthly runoff estimation that can be adapted to most temperate regions of the world and could be extended to tropical regions with additional development. The RUSLE2 computational engine has been re-coded to allow efficient computation of sheet and rill erosion on a grid basis. Where high resolution elevation data are available, as is usually the case on construction sites, a variety of GIS tools can be used to create raster maps of flow direction, slope steepness, soil, management, and location of concentrated runoff channels. A shell program uses these raster maps to determine RUSLE2 profiles that end at each channel cell and calls the RUSLE2 calculation engine to determine distributed estimates of sheet and rill erosion. The results of these computations can optionally be linked to a concentrated flow erosion model if channel erosion is a resource concern at the site. Erosion and site sediment losses can be determined and reported for an accounting period

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that begins with the first site disturbance and extends until permanent cover is established. By allowing representation of complex two-dimensional topography and spatial variation in soil and land management properties, these developments allow RUSLE2 to be a state of the art tool conservation planning and stormwater management on construction sites.

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