Dynamic, distributed simulation of watershed erosion: The KINEROS2 and EUROSEM models

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ABSTRACT: Two models, KINEROS2 and EUROSEM, that simulate hydrologic event erosion on small catchments as a distributed, dynamic convective transport process are described briefly. Each employs a numerical solution of the mass balance equation, and uses time distributed rainfall rates as input. The equations for convective transport of sediment are quite similar to the kinematic equation for hydrologic response of a surface or channel. The features of the models are outlined, and the areas where research is needed are indicated. An example of simulation of rainfall plot test data is shown, demonstrating the practical value of dealing with particle size distribution, and an example is given of the value of these models in developing improved slope length factors in lumped models.

Today, most management and planning models for erosion or soil loss are lumped models, such as USLE (universal soil loss equation) or RUSLE (revised universal soil loss equation). Their approach is to look at the total expected soil loss from a typical event or from a long-term average as a function of the overall rainfall, topography, and management conditions. These factors are represented by single values of parameters. A higher level of complexity is represented by the WEPP and CREAMS models, which treat spatial variation by looking at steady state flow and sediment transport along a representative flow path. Time variation of conditions within a storm are neglected.

The purpose of this paper is to discuss two newer models that represent a still higher level of process detail by considering flow and sediment transport as they vary both in time and space during a storm event. The relative value of this type of model is suggested by some results presented below. It is recognized that there is an inherent limit of the spatial scale for which event models such as these are meaningful, since the travel time of sediment through a large catchment may span many events. KINEROS2 (Smith et al. 1995) is a second generation version of KINEROS (Woolhiser et al. 1990), an event-based runoff and erosion model, with changes discussed below. EUROSEM (Morgan et al. 1992) is a similar model to KINEROS, using different erosion and transport relationships, and including explicit rill/interrill hydraulics.

Dynamic, distributed flow (DDF) modeling of a watershed requires a record of the time distribution (and even better, the spatial distribution if known) of rainfall intensity, r(x,t). This data requirement is probably a major reason for general preference of users for more simple models. While representing a higher level of physical detail, it is not claimed that DDF models are always more accurate. There are still significant abstractions in comparing these model representations with reality on a given catchment (Smith et al. 1994). However, neither of these models are relegated strictly for research, although that is the primary application to date, and there is increasing interest and use by the consulting engineering community (e.g., Mettel et al. 1994)

Basic hydrologic modeling

DDF modeling fundamentally involves the solution of the dynamic water volume balance equations over the surface of a catchment and over the time of the runoff:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_i(x,t) \qquad (1)$$

in which A(x,t) is the cross-sectional flow area, Q(x,t) is the discharge, x is the distance, t is the time, and q_i is the local source or loss rate. In the *kinematic wave* method, Q is represented as a function of the local land slope and depth (or area A) using a normal flow equation. In the *diffusive wave* approximation, Q is a function of A and the water surface slope. Equation (1) may be applied equally to a surface, a rill, or a channel. A common misconception is that the kinematic wave routing can be applied only to flat planes. In fact, the only requirement is that there be a 'rating' relation between net Q and the storage variable, which is A in Equation (1). Solution of Equation (1) can also be obtained in terms of mean depth, h, given a relation h(A). Both EUROSEM and KINEROS2 employ the kinematic wave solution for surface water flow for a single design storm simulation. DDF modeling may also be used in continuous simulation models, as in *Opus* [Smith 1992].

Simulating runoff. Solving Equation (1) requires determining the infiltration rate f(x,t) to obtain $q_i(x,t) = r(x,t)-f(x,t)$. Both KINEROS2 and EUROSEM use an infiltration model based on unsaturated porous media physics, which models the onset of runoff and the reduction in infiltration capacity during the storm in a unified manner (Smith and Parlange 1978). In these models infiltration is simulated as a function of two soil parameters, initial saturation, and rainfall intensity. This algorithm can be configured to any soil type, including sandy soils, which best reflect the assumptions of the well-known Green-Ampt model. In addition, KINEROS2 contains a soil physics-based algorithm to predict the infiltration effect of a surface soil layer of different properties than the underlying layer. This may represent either a surface layer of higher infiltration capacity, such as a finer soil underlying the sand in a streambed, or a restrictive upper layer such as a crust (Smith 1990). Further, KINEROS2 includes a newly-developed algorithm to simulate the redistribution of soil water during storm intervals with either low or zero rainfall rates, thus simulating the recovery of infiltration capacity for periods of from several minutes to several hours (Corradini et al. 1994). This extends the model capability to include long and complex storms and storm sequences, while not actually making it a continuous simulation model. KINEROS2 also includes the capability to derive the local rainfall intensity pattern by inverse-distance interpolation from a network of rain gauges, based on their relative locations with respect to each portion of the catch-

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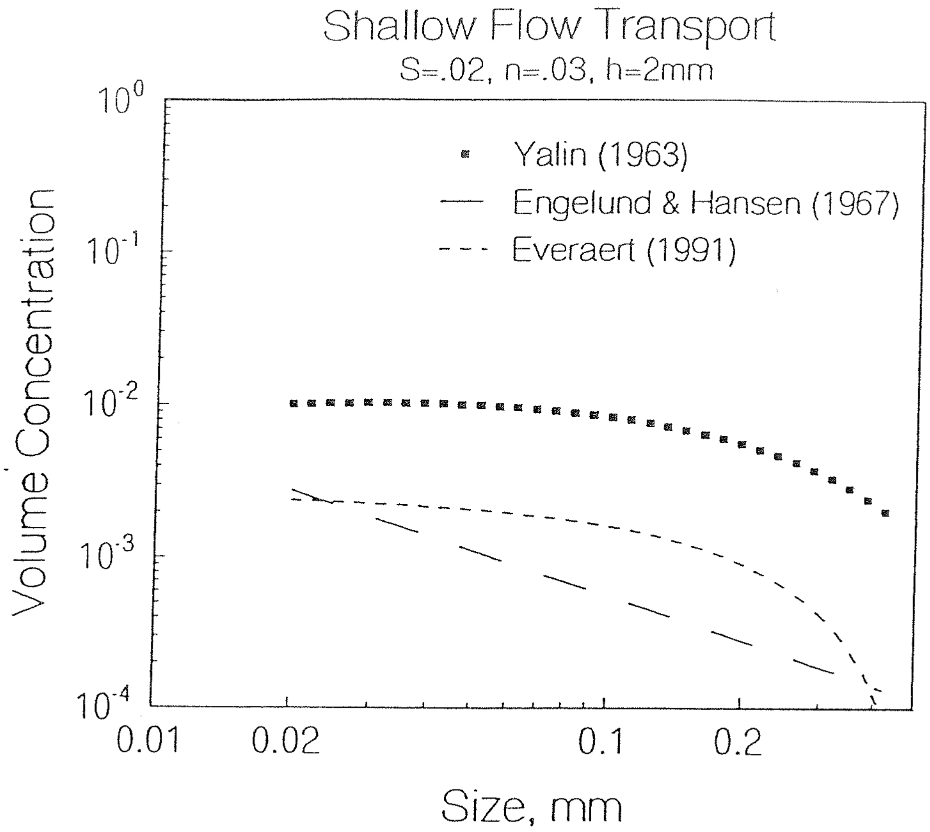

Figure 1. Sample comparison of the Yalin (1963) and Engelund and Hansen (1967) transport capacity equations with one developed from the shallow flow data of Everaert (1991)

Note: Several variables are involved, and here we have chosen to demonstrate the relative sensitivity to particle size.

ment represented by individual overland flow elements.

The Q(A) relation for runoff routing is taken from the Manning normal flow equation. Runoff and infiltration are linked with a simple model for microtopography. During recession of flow, rainfall is below infiltration capacity, and the soil can infiltrate primarily from the flowing surface water. A simple microtopography is assumed, such that below a certain maximum average water depth the width of flow decreases directly with depth, and thus the infiltrating area is reduced. Comparisons with experimental data have demonstrated this to be a useful model to help match observed recessions.

Simulating erosion processes

The DDF simulation of sediment transport treats the water moving on the surface as a vehicle for convective transport. The form of the dynamic sediment balance equation is quite similar to that of Equation (1), except that the balance involves sediment rather than water, and the source terms behave quite differently:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} = e_s + q_s C_s \qquad (2)$$

Here C(x,t) is local sediment concentration, e_s is the local erosion/deposition rate (including rain energy induced erosion) and q_s is local inflow of water containing concentration C_s, such as lateral inflows to a rill or channel. Just as in Equation (1) supply of input water, $q_i(x,t)$, is a balance between rainfall rate and infiltration rate, so in Equation (2) e_s is a balance between sediment erosion and deposition.

The term e_s is composed of two independent erosion processes:

$$e_s = e_r + e_n \qquad (3)$$

in which $e_r(r,h)$ is rainsplash erosion, dependent on rainrate r and water depth h, and e_h is net hydraulic erosion (+) caused by flowing water, or deposition (–) from the surface water. Hydraulic erosion e_h is treated as a dynamic difference between continuous processes of hydraulic soil particle detachment (which is a function of velocity, slope, and depth) and deposition. Given a solution to Equation (1), plus an initial and upstream boundary condition C(0,t), the numerical form of Equation (2) can be solved explicitly for the values of C(x,t), starting from upstream, for each step in time throughout the event.

Rill and interrill erosion. These two terms are commonly used in erosion modeling, but are often ill-defined or used in differing ways. One can distinguish the two concepts either by erosive mechanisms or by flow geometries, the latter being the more literal distinction. Often interrill erosion is associated with splash erosion rate e_r, and rill erosion associated with e_h. However, splash erosion can occur in rills and on the sides of rills whenever the water is shallow enough to distribute momentum of the raindrops directly to the soil. Conversely, some sediment can be picked up by flowing water on surfaces that have no defined rills. Most natural surfaces are sufficiently irregular to allow runoff waters to converge in paths of preferential flow, even though subtle. Thus, KINEROS2 does not explicitly separate 'rill' and 'interrill' processes except as in Equation (3), both process types can occur simultaneously in shallow flow and are not considered exclusive. EUROSEM, however, can additionally treat rill flows and rill/interrill microtopography in an explicit manner as indicated below.

The role of transport capacity. Transport capacity is the amount of sediment that a given flow can carry at steady conditions in equilibrium with a loose bed. There are a large number of equations to describe the transport capacity observed in flume studies. They describe transport capacity in terms of sediment discharge or sediment concentration, as a function of such variables as slope, velocity, depth, viscosity, and sediment particle size. EUROSEM and KINEROS2 use previously developed transport capacity relations describing a concentration, C_{mx}, in terms of local hydraulic variables and particle size and density. As indicated above, C_{mx} is assumed to represent a state of dynamic equilibrium between rate of erosion from a loose soil surface, e_q, and rate of deposition of soil particles in suspension, e_d. Deposition rate for any concentration C of particles with settling velocity v_s is Cv_s. Thus, at equilibrium, assuming a reversible process at the soil surface, for a given particle size,

$$e_q = e_d = C_{mx} v_s \qquad (4)$$

At any concentration, $e_h = e_q - e_d$, so the equation for net erosion e_h as a function of concentration C is

$$e_n = bv_s (C_{mx} - C) \qquad (5)$$

where b accounts for cohesive soil resistance to hydraulic erosion: b is one for

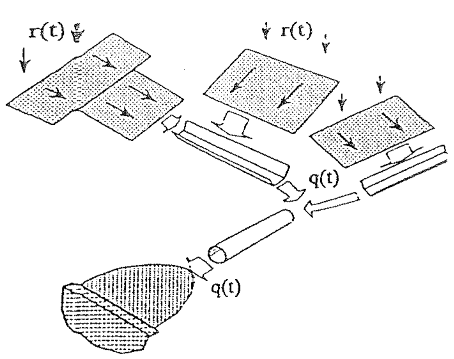

Figure 2. Schematic illustration of the major types of hydrologic elements in KINEROS2 and EUROSEM, and some of the ways that they may be arranged to simulate a complex watershed

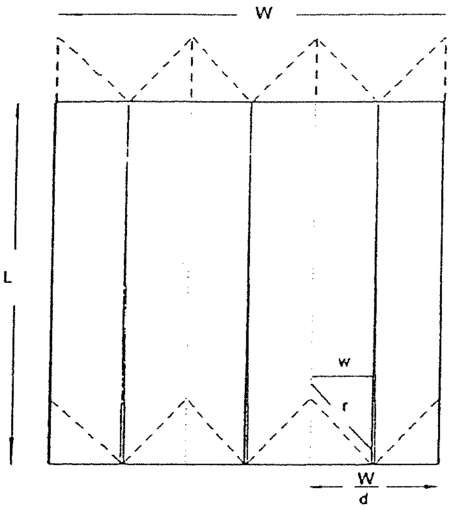

Figure 3. Diagram of the geometric approximation for rills used in EUROSEM
Note: The dotted lines indicate the literal flow geometry, with interill flow length r, for a surface of length L.

negative e_h (deposition), and is a factor less than one for positive e_h.

One limitation in watershed erosion modeling is that there is little experimental data for transport capacity of very shallow flows such as surface runoff. EUROSEM employs equations based on hundreds of shallow flow flume experiments (Govers 1990; Everaert 1991). Figure 1 illustrates how this and other available transport relations compare as a function of particle size. Another current challenge in erosion modeling is that the effect of soil cohesion [factor b in Equation (6)] is not well understood as a function of measurable soil properties.

Table 1. Relation of sediment yield to slope length for a 30 minute storm

Length, m	Unit runoff, mm	Total sediment, kg	Unit sediment yield, kg/ha	Approx. time of concentration, min.
10	1.24	0.5	50	8
20	1.06	1.2	60	12
40	0.77	2.0	50	18
60	0.56	2.2	37	23
100	0.34	2.2	22	31

Treating flows with distributed sediment particle sizes. Still another challenge is the lack of experimental guidance in how to apportion the hydraulic energy creating transport capacity among a variety of particle sizes encountered on a soil surface. One may ask the question, for example, if there were a steady flow with equilibrium $C = C_{mx}$ for a sand bed, and one began adding fine silt to the flow, what would be the result? There is now no known experimental answer to that question, whether the flow could carry the silt in addition to the sand, or if a balance would be struck, for example, with less sand being carried due to additional silt load. Current treatment of mixed particle size classes in KINEROS2 is based on treatment of a finite number of particle size classes, and employs the following assumptions, which are conceptually rather non-controversial:

1. Conservation of mass equation applies to each particle size class.
2. Particle class erosion rate is proportional to the relative availability in surface soil.
3. Hydraulic erosion is controlled by the erosion rate of the largest particle class in the surface soil (or else an "erosion pavement" would form).
4. Deposition rates of the particle classes are mutually independent.

KINEROS2 allows the particle distribution to be different on each watershed element, with particles drawn from the same overall particle size classes, which should encompass all sizes significant on the watershed. Thus, for example, channel bed material may be largely of a sand particle size, while a contributing surface may have sediment sizes drawn from silt, clay, aggregates, as well as some sand. When the contributed material enters the channel flow, the net sediment will be summed by size class, and carried or deposited according to the above rules, which processes will then determine the amount in each particle size class at the channel outlet and input to a downstream channel segment.

Describing the catchment topography

Both KINEROS2 and EUROSEM treat a natural catchment in terms of an

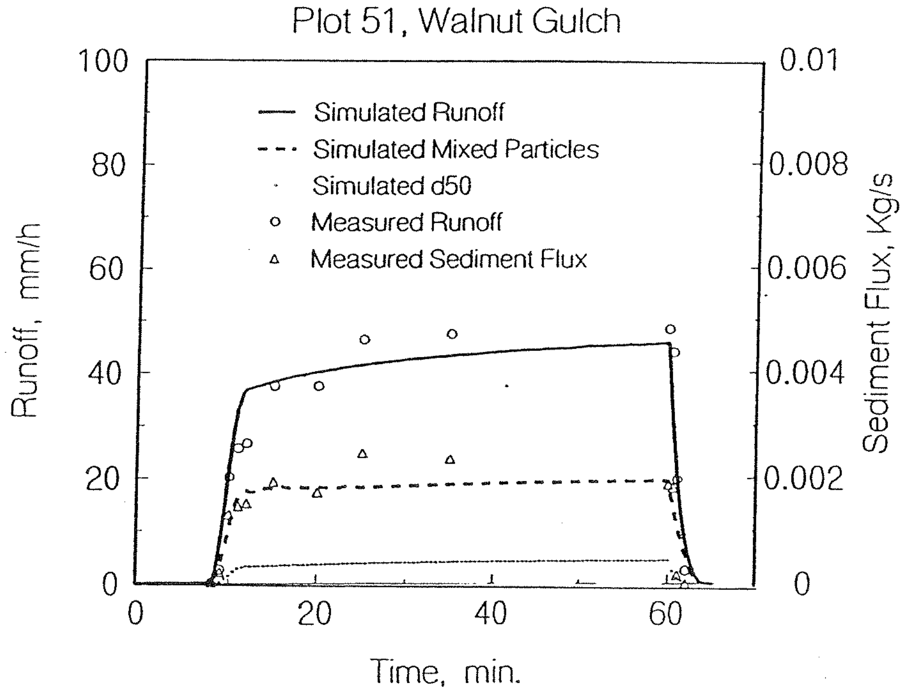

Figure 4. KINEROS2 simulation of a plot runoff experiment at Walnut Gulch, Arizona
Note: Preparation of the plot creates a loose surface layer, whose erosion can be modeled by KINEROS2 as shown here. The simulation using a single mean particle size is significantly biased, as shown (dotted line).

abstracted network of runoff surfaces, channel elements, and pond storages. Each is termed a watershed *element*. Figure 2 illustrates some of the arrangements that may be used to simulate the flow network on a catchment. A channel may be an open trapezoid or, in the KINEROS2 model, a closed conduit (with free surface flow). An open channel may receive flow along its length from an adjacent surface on one, both, or neither side. Surface elements are rectangular, but may be cascaded (linked in series) or may be arranged in parallel, so that combinations of surface elements may represent nonuniform slope profiles, convergent and divergent flow hillslopes, and variable slope lengths. KINEROS2 includes additional features to make it particularly suitable for application to urban catchments, including the closed conduit mentioned above, as well as an 'urban' element which combines impervious and pervious erodible areas within one element. EUROSEM is particularly adapted to the analysis of more highly eroded areas, by including explicitly both interrill and rill flows within a surface element. Figure 3 illustrates the geometric abstraction used in EUROSEM to represent a rilled element. The surface is subdivided so that a specified number of rills act as micro-channels to receive shallow sheet flow from the interrill areas. Cascading of planes can be used to simulate longitudinal changes in rill density. EUROSEM also includes parameterization of the effects of various kinds of plant cover and soil stoniness on erosion processes.

While there are questions regarding effect of microtopography, such as spatial distributions of roughness and other parameters, and complex flows in microchannels, the use of simple parameterization is considered useful given an appropriate subdivision of the catchment into relatively homogeneous areas (Goodrich 1991; Smith et al. 1995). In any case, it remains superior in many respects to "lumping" errors of lumped empirical models.

Applications and summary

This short paper is intended to briefly describe the DDF modeling approach rather than to describe, test, and validate any one model. The application and testing of KINEROS has been documented in the literature (e.g., Smith 1976; Zevenbergen and Petersen 1988; Smith et al. 1995) and will not be repeated here. KINEROS has been used far more often as a runoff model than an erosion model, partly because of limited time-distributed sediment data. The EUROSEM project is completing a validation exercise using several southern European experimental catchments, and the results are not yet compiled. In general, validation exercises have been encouraging; the results generally improve those of lumped erosion models, while the erosion predictions depend significantly on the quality of the runoff predictions, as is appropriate. Figure 4 illustrates application of the KINEROS2 model to plot runoff data from the Walnut Gulch Experimental Watershed. The use of a spectrum of particle sizes, even division into sand, silt, and clay fractions, significantly improves the simulation quality, as shown in this example.

Another important application of fully distributed models is in development and analysis of lumped or approximate management models. One example is the examination of the length factor in the USLE, which implicitly presumes steady flow over the length, as does the WEPP model in an explicit manner. In natural storms with a few periods of intense rainfall, steady flow is not usually achieved. The USLE assumes sediment yield increases as a 0.3 to 0.5 power of the length, depending on the slope (Wischmeier and Smith 1978). The actual effect for various lengths and storm durations can easily be simulated with a DDF model. As Table 1 illustrates, the sediment yield can as easily decrease significantly with length. The length relation actually depends on an interplay of the storm characteristics and the response time of the catchment. This table reports the results of a storm of 30 minutes, relatively steady intensities of 25mm/h for 12 minutes and 17mm/h for 18 minutes, on a slope of 4% with a final infiltration rate of 2.5mm/h. The peak runoff rate was 6mm/h, and runoff starts at about 10 minutes. For lengths shorter than the USLE standard plot (22.6m) the time of concentration, t_c, is on the order of the storm runoff period. The time of concentration for transported sediment is at least 50% longer than for runoff rate. Thus for shorter lengths, flow velocities and erosion processes vary with length and cause an increase in yield with length. For longer lengths, however, the rainfall excess from the upper part of the slope contributes less and less, so there is a reduction in unit yield with length. The critical length is very much a function of storm characteristics. This example points to an area of significant potential improvement in lumped erosion prediction models, to which DDF models can contribute.

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