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Soil erosion assessment tools from point to regional scales—the role of geomorphologists in land management research and implementation

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Abstract

Geomorphological research has played an important role in the development and implementation of soil erosion assessment tools. Because policy and management approaches include the use of soil erosion assessment tools, soil erosion research directly affects the public in terms of providing information on natural hazards and human impacts, and also as the basis for regulatory policy on land management. For example, soil loss calculations and geomorphological expertise are used to support soil conservation planning, both through agricultural legislation that defines maximum tolerable soil loss rates, and through federal and local legislation that requires soil erosion controls on many construction sites. To be useful for decision makers, soil erosion models must have simple data requirements, must consider spatial and temporal variability in hydrological and soil erosion processes, and must be applicable to a variety of regions with minimum calibration. The growing use of erosion models and Geographic Information Systems (GIS) in local to regional scale soil and water conservation raises concerns about how models are used. This has prompted interest in methods to assess how models function at management scales and with the types of data that are commonly available to users. A case study of a GIS-based soil erosion assessment tool using the process-based Water Erosion Prediction Project (WEPP) shows that using commonly available data rather than research grade data can have (predictably) a significant impact on model results. If model results are then used in management decisions, it is critical to assess whether the scale and direction of variation in results will affect management and policy decisions. Geomorphologists provide unique perspectives on soil erosion and can continue to affect policy through soil erosion research. This research should focus on fundamental processes, but equally important is continued development and evaluation of models that are matched to real world data availability, geomorphic settings, and information needs.

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Keywords: Soil erosion modeling; Soil conservation; Policy; Assessment; Implementation; Scale; GIS

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1. Introduction—the role of geomorphologists in soil and water conservation

Geomorphology involves quantitative and qualitative descriptions of landscapes and landforms, as well as investigations of the processes and process inter-

actions that create these forms in time and space. The dynamics of geology, climate, and vegetation result in movements of mass, driven by a combination of natural geomorphic processes. These movements of material underlie the development of landforms and landscapes. One component of this larger system is soil, the layer of weathered or partially weathered material at the Earth's surface. Weathering, the water balance, organic matter accumulation, erosion and sedimentation, and human actions all control soil development and degradation; thus, soils reflect both natural processes and human impacts. Defining soil erosion as the translocation of soil particles by processes related to climate, soil, topography, and vegetation, human activity magnifies, minimizes, or prevents the operation of these natural processes (Bork and Frielinghaus, 1997). In agricultural areas, for example, farming operations directly affect soil movement through activities such as tillage (Quine et al., 1999), root crop harvesting, and the trampling of soil and removal of vegetation by livestock (Poesen et al., 1996).

In the policy arena, the impacts of human activity on soil erosion have become a major concern both in terms of extreme events that cause major soil erosion and in terms of changes in the sensitivity and thresholds for higher frequency, lower magnitude events that also reduce agricultural productivity and increase water pollution. Early in the history of cultivation, erosion losses were small on a regional scale because total areas affected were small, and simple adaptations could be developed to overcome soil erosion impacts on the local scale (e.g., shifting agricultural location in nomadic fashion as soil erosion and nutrient depletion reduced productivity). However, as larger settlements were established, extensive, concentrated agricultural areas developed to supply food to the settlements (Goudie, 1990). This expansion and concentration of cultivated acreage led to extensive land use change and increased concern about soil erosion impacts. In response to increasing soil erosion hazards, especially from agricultural land, interest groups and policy-driving organizations worldwide fostered the development and use of techniques for soil and water conservation (Troeh et al., 1999). This development and application of soil and water conservation techniques involved specialists with a wide variety of backgrounds including areas that we might now define

as geomorphology, soil science, agronomy, and engineering.

Geomorphologists working in soil erosion have focused on understanding, predicting, and developing methods to control soil erosion processes (Boardman, 1996), and on understanding the magnitude, frequency, duration, areal extent, speed of onset, spatial dispersion, and temporal spacing of soil erosion for risk assessment purposes (Gares et al., 1994). To address soil erosion processes and risk, scientists and engineers from various fields have developed physical parameters, equations, and models with the intention of implementing assessment tools for educational, planning, and legislative purposes. Target audiences for such assessment tools include those involved in agriculture, forestry, mining, mill tailing, construction, watershed, and regional planning (Toy and Osterkamp, 1995). The aim of this paper is to provide an overview of application-oriented soil erosion research, to review the development and implementation of soil and water conservation assessment tools in the U.S., and to present a case study of the evaluation of a tool used to provide information that drives management and policy decisions.

2. Soil erosion research and policy

2.1. Public interest in on-site and off-site impact

Public interest in soil erosion in a particular area depends in large part on the extent to which erosion and its impacts are clearly visible and important over short time scales. In contrast, long-term sheet and inter-rill erosion are difficult to observe, appear trivial in scale to most casual observers, and are conceptually hard to relate to major impacts either on-site or off-site. For instance, soil erosion can easily be observed in the appearance of deep rills and ephemeral gullies on fields (Fig. 1), sediment-loaded surface runoff (Fig. 2), or gully and stream bank erosion in channels. Extreme events that lead to on-site, short-term yield reduction; major filling or sediment removal operations; or loss of harvest directly affect farm income on a time scale that is relevant to most farmers. Mid- to long-term effects of high frequency, low impact events on soil fertility, organic matter, and nutrients on-site have to be

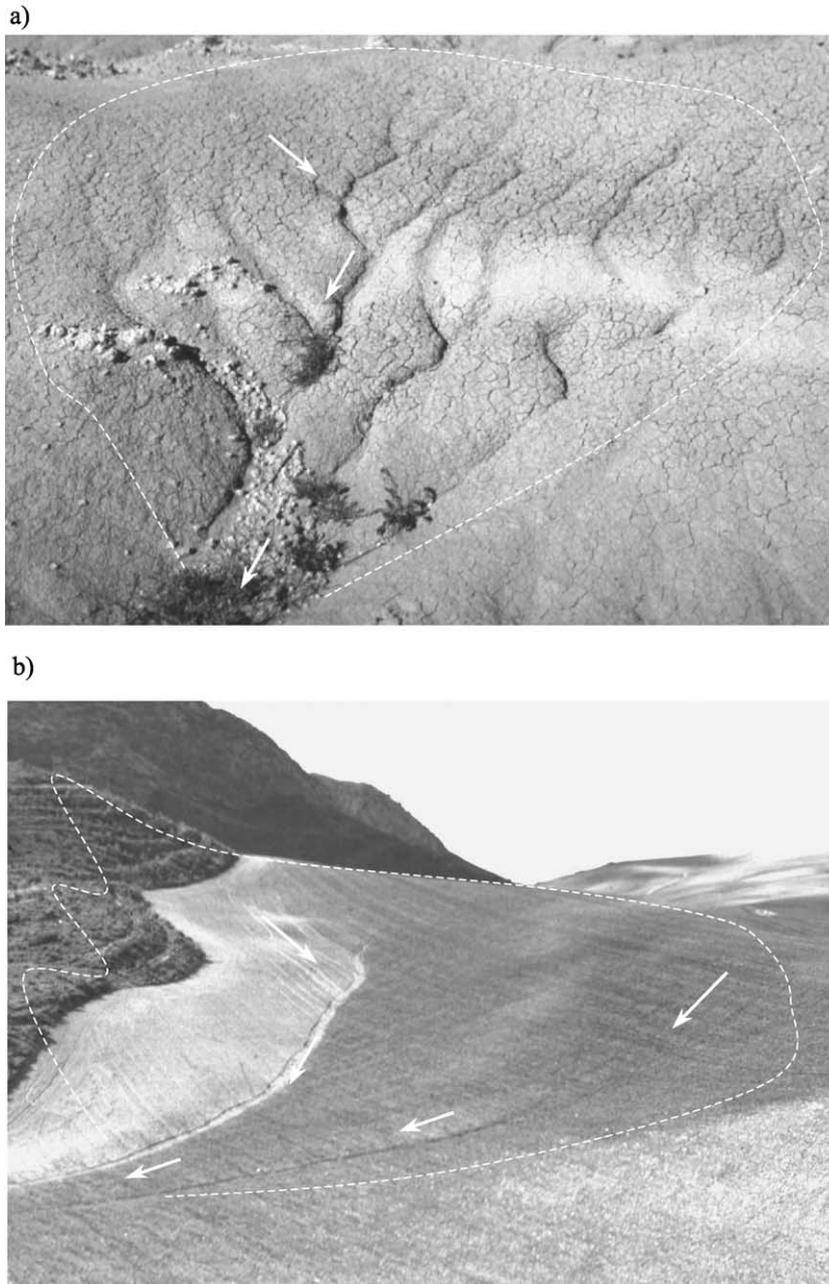


Fig. 1. Soil erosion features at different scales: (a) microscale of $< 1 \text{ m}^2$ (Badlands National Park, SD) and (b) hillslope/field scale with a few hectares (Guadalteba, Andalusia, Spain). Note that watershed boundary and flow direction of rills and ephemeral gullies are indicated.

equalized by additional fertilizer applications; but this cost is harder to tie directly to soil erosion alone, is less immediate, and so is easier to ignore (Lal, 1998). Similarly, on construction sites, sheet

and rill erosion appear trivial in scale to most casual observers, and are conceptually hard to relate to major impacts either on-site or off-site. However, when major storms produce gullying, road under-



Fig. 2. Confluence of the main and east branches of Nimishillen Creek, OH. Sights such as this provide easy to perceive indications of potential sediment pollution problems.

cutting, blocked storm drains, and extensive sedimentation on roadways adjacent to a site, the economic and environmental impacts of soil erosion receive heightened attention (Harbor, 1999).

In contrast to on-site impacts, which typically directly affect the people who control the source of the erosion, off-site impacts affect neighboring areas where the affected people have little or no influence

on the erosion source. The import of sediments and nutrients causes changes in soil surface structure and nutrient budgets, and sediment loading and eutrophication of surface water bodies affect aquatic life and water quality. As with on-site impacts, high frequency, low magnitude events traditionally produce little perceived impact on off-site conditions (although the longer-term, cumulative impacts may be large), and it is lower frequency, high magnitude events that spur public interest in impact assessment, regulation, and management. However, off-site impacts of erosion are potentially greater than the on-site productivity effects in aggregate (Foster and Dabney, 1995); thus, society may have a larger incentive for reducing soil erosion in the long run than individual farmers (Uri and Lewis, 1998) or construction site owners (Harbor, 1999).

2.2. Soil and water conservation in the United States

In the late 19th century, erosion-related environmental problems in the United States (U.S.) agriculture became increasingly apparent to farmers, researchers, and policy makers. In response to this, the U.S. Department of Agriculture (USDA) began a program of publishing “circulars” (technical notes)

that contained suggested measures for conserving soil and reclaiming “exhausted” land (Glanz, 1995). The start of modern soil conservation publications can arguably be dated to 1928 when Bennett and Chapline (1928) went significantly beyond technical notes and combined a description of field observations and technical knowledge of soil erosion by water in a USDA report (Table 1). Despite the findings of USDA soil scientists in the 1920s and the creation of the USDA Soil Erosion Service in 1933, the impetus for major changes in U.S. policy did not come until a major catastrophic event caught the attention of the public and policy makers.

In 1934, the Dust Bowl reached its worst extent when extensive wind erosion removed fertile soil from Kansas, Oklahoma, and Colorado, reducing agricultural productivity and creating clouds of dust that extended throughout the U.S. east coast, filtering into houses and offices. Federal response to the Dust Bowl included creation of the Soil Conservation Service (SCS), which was authorized by law to provide education and technical assistance to farmers, with a primary goal of ensuring that soil erosion would be controlled to prevent significant impacts on agricultural productivity and profitability. At the local level, the SCS cooperates with locally led and funded Soil

Table 1
Milestones and most recent developments in modern US soil and water conservation policy and implementation of model prediction technology

Year	Event/Research/Farm Bill/Implementation	Changes
1928	<i>Soil Erosion: A National Menace</i>	Start of USDA modern soil conservation movement
1933	<i>Soil Erosion Service</i>	Intensified USDA research for on-site benefit
1934	Dust Bowl	Public and political pressure on solving erosion problems
1935	Soil Conservation Act	Soil Conservation Service (SCS) assists on voluntary basis
1940s	<i>Regional soil loss equations</i>	First empirical soil erosion models on regional level
1958	<i>Universal Soil Loss Equation (USLE)</i>	Empirical soil erosion model for plots on national level
1960	Soil Bank Program	Encourage farmers to reduce erosion on affected land
1965	<i>Agricultural Handbook No. 282</i>	SCS implements USLE as prediction tool
1978	<i>Agricultural Handbook No. 537</i>	SCS updates implemented USLE
1985	Food Security Act/SCS implements law	Highly Erodible Land; Conservation Reserve Program; Accounting off-site impacts
1989	<i>Water Erosion Prediction Project (WEPP)</i>	First process-based model for complex hillslopes
1993	<i>Revised USLE (RUSLE)</i> Mississippi floods	SCS implements RUSLE by 1995 to replace USLE Maximum runoff, erosion, and sedimentation rates
1995	<i>Water Erosion Prediction Project</i>	First process-based model for small watershed
1996	Agriculture Improvement and Reform Act	Greater flexibility for farmers to develop and implement conservation plans
1997	<i>Agricultural Handbook No. 703</i> <i>Modular Soil Erosion System (MOSES)</i>	NRCS (former SCS) implements RUSLE Combines RUSLE, WEPP, and wind erosion models; NRCS plans implementation

and Water Conservation Districts (SWCDs). In the 1980s, the SCS' traditional focus on on-site benefits and increasing net farm income evolved into a new policy that included reductions in off-site impacts of erosion on a regional and watershed scale (Uri and Lewis, 1998) such as downstream sedimentation, navigability, flooding, water quality, and ecosystem health. Educational efforts have been augmented with new regulatory requirements for activities such as agriculture, construction, mining, and logging. Some of these regulations are tied specifically to soil erosion modeling, which is used to assess whether management plans meet regulatory requirements.

The 1985 Food Security Act required that farmers develop and implement soil conservation plans if they wished to remain eligible for most government farm programs. Further, the Conservation Reserve Program (CRP) was introduced to provide farmers with financial incentives to convert environmentally sensitive land to approved conservation uses with permanent vegetation cover for a period of 10–15 years. However, despite such extensive soil and water conservation efforts, the events surrounding the 1993 flooding of the Mississippi caused severe erosion. In the State of Iowa alone, an estimated 1.6 million ha of tillable land suffered erosion loss, of which almost 1 million ha lost more than an estimated of 45 t ha⁻¹ of topsoil (Bhowmik, 1996). The record setting runoff volumes, soil losses, sediment yields, property damage, and agricultural production losses of the 1993 floods underscored the continued need to understand, predict, and manage runoff and soil erosion processes. In 1995, the SCS was the Natural Resources Conservation Service (NRCS) to reflect this wider scope of service within an established, multi-disciplinary network of offices ranging from national, regional, and state to county level.

2.3. Research on soil erosion assessment tools

In addition to public awareness and planning programs in 1933, the USDA began a program to create 10 soil erosion experiment stations and 40 soil erosion control projects across the country. The experimental stations measured runoff and soil erosion rates from uniform plots and small watersheds with a range of soils and management techniques. Each soil erosion control project included an entire watershed in which

erosion control methods could be applied, evaluated, and demonstrated. The data collected at these stations provided a foundation for the development of new soil erosion models, such as Zingg's (1940) empirical equation, to predict the effect of slope steepness and length on field-scale soil loss. Zingg's approach was subsequently expanded to include factors representing the effects of rainfall erosivity, soil erodibility, crop management, and support practices leading to regional soil loss equations for Missouri (Smith and Whitt, 1948), the corn belt (Musgrave, 1947), and the north-eastern states (Lloyd and Eley, 1952). The USDA Agricultural Research Service (ARS), established in 1953, built on this earlier work by initiating a research project to determine a nationwide ("universal") approach to predicting soil erosion. The resulting Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1958) is an empirical equation for average annual soil loss, based on factors representing one or more processes involved in the erosion process:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the predicted long-term average annual soil loss by water in t ha⁻¹ year⁻¹, R represents the impact of climate through a measure of rainfall erosivity in MJ mm ha⁻¹ h⁻¹ year⁻¹, K represents soil characteristics and is soil erodibility under standard unit plot conditions in t ha h ha⁻¹ MJ⁻¹ mm⁻¹, LS represents topography in terms of slope length and steepness, C and P represent erosion reduction by management of land use cover and erosion control practices, respectively. Despite (or perhaps because of) the simple regression approach, the USLE has proved to be a practical and accessible model that has been used (and misused; Wischmeier, 1976) at various scales worldwide.

Research by geomorphologists and others contributed to eventual dissatisfaction with use of the USLE on spatial and temporal scales and in climate and soil conditions very different from those used to develop the equation. Such concerns over the general limitations of the USLE, combined with the difficulty of including new crop and management techniques introduced after the model was developed, led to renewed USDA efforts to produce alternative models. In the 1980s, ARS researchers argued that a new generation of erosion prediction technology was needed based on

a modern understanding of erosion processes, but that such models should maintain USLE style applicability and usability for support of conservation planning (Laflen et al., 1991). ARS pursued, therefore, two model styles: a revised version of the empirical-based USLE—the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991, 1997)—and an alternative process-based hillslope and watershed model of the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995).

WEPP drew heavily on theory, field research, and modeling produced by a wide range of academics and practitioners, including geomorphologists (Nearing et al., 1989). The WEPP model simulates climate, infiltration, water balance, plant growth and residue decomposition, tillage and consolidation, surface runoff, erosion, sediment transport, and deposition, as well as winter processes. WEPP is a continuous simulation, distributed parameter, erosion prediction computer program that can be applied up to small watershed scales over a range of time scales, including individual storm events, monthly totals, yearly totals, or an average annual value based on data for several decades. Unlike the USLE and RUSLE, the WEPP model includes simulation of sediment movement in small channels (Ascough et al., 1997).

In addition to the WEPP approach, hybrid model concepts have been developed for intermediate continuous assessment tools with algorithms based on some process descriptions, but retaining a substantially empirical base. Typically, such models focus on a particular aspect of on- and off-site predictions of soil and water conservation such as nonpoint source pollution of nutrients (AGNPS: Young et al., 1989), chemicals in runoff and groundwater (CREAMS/GLEAMS: Kniesel, 1980; Leonard et al., 1987), and economic and productivity aspects (EPIC: U.S. Dept. of Agriculture, 1990).

Similar model development trends have occurred in other parts of the world, leading to the European process-based process models EUROSEM (Morgan et al., 1992) and MEDALUS (Kirkby et al., 1998), and the Australian stochastic process-based GUEST (Misra and Rose, 1990). A comparison of the model performance using identical data sets among this latest model generation showed that model output differs and that particular models are best suited to specific time spans (Favis-Mortlock, 1998). The comparison study

also showed that data quality is an important control on model output and suggested that models that do not require calibration have some significant advantages. Generally, these comparisons showed that runoff could be predicted better than soil erosion with a common tendency to overestimate large events, suggesting that most models may share some common deficiency in process representation. Although model style and validity are important, in particular, in the academic community, the ways in which model results are implemented are of equal practical significance.

2.4. Determining tolerable soil loss

The regulatory program in the U.S. includes direct use of soil erosion models to determine compliance with requirements that erosion be kept below some allowable level. The modeling effort is critical in this, but equally important in a policy context is the examination of how allowable levels are defined. Defining a maximum rate of soil erosion that may occur while still permitting sustainable, high level crop productivity (Wischmeier and Smith, 1978; Schertz, 1983) has been a challenge for a long time (Johnson, 1987) and underlies the concept of a tolerable soil loss rate (T) that, when combined with the annual replacement rate for a certain soil type, produces sustainable land use.

In practice, T values are based on the properties of specific root-limiting subsurface soil layers, on current climate regions, and on economic feasibility grouped by land resource regions. Values of T typically range in integer steps from 1 up to 5 T acre⁻¹ year⁻¹ (11.2 t ha⁻¹ year⁻¹) (Natural Resources Conservation Service, 1999c). The NRCS uses these T values to assist landowners in designing site-specific conservation plans that, based on model calculations, produce $A \leq T$ (model estimated soil loss is less than the tolerable soil loss). The 1985 Food Security Act is strictly tied to the empirical USLE approach to maintain fair and easy application of the regulatory program, and farmers who cannot demonstrate that they are achieving less than or equal to tolerable soil loss may not be eligible for a variety of federal financial support programs. The tolerable soil loss program is focused, in particular, on farming activities in Highly Erodible Land (HEL; Soil Conservation Service, 1994).

Weaknesses of the T approach include the fact that T values are not explicitly based on consideration of

soil development and erosion processes, and do not account for the difference between the quality of soil lost at the surface and the quality of the soil being created at the bottom of the profile. Bork and Frielinghaus (1997) argued that T should be derived by including the consideration of soil development as a function of the local water balance, especially infiltration and interflow dynamics, matter transport within and through the soil profile, as well as current vegetation, crop rotation, and land use management. When additional concerns, such as loss of organic matter and nutrients from the top of the soil profile, are considered, it is clear that established T values may not provide a basis for long-term sustainability of agricultural production and soil quality.

Given concerns that current T values do not reflect long-term sustainable soil loss rates (Johnson, 1987), Botschek et al. (1997) suggested that the current approach based on a linear relationship between soil erosion and soil profile development should be replaced by a method considering the nonlinearities of rock weathering and soil development processes. Similarly, Lal (1998) described expanding the tolerable soil loss concept to include (i) rate of new soil formation, (ii) rate of soil erosion, (iii) on- and off-site agronomic effects, (iv) on- and off-site economic effects, and (v) environmental impact of water and air quality on ecosystems and the greenhouse effect. Van Noordwijk et al. (1998) suggested a change in thinking away from purely soil conservation to “soil erosion management” that takes advantage of the movements of material that result from soil erosion. In addition to minimizing on- and off-site effects of soil erosion, soil erosion management promotes methods designed to utilize runoff nutrient loads or spatially distributed soil fertility more effectively, making use of the nutrients and sediments that runoff and run on a field in a positive way. A major challenge, however, in attempts to redefine tolerable soil loss is to balance the need to have a scientifically acceptable and comprehensive approach that can be applied simply by using the type of data that are readily available to most potential users.

2.5. Model implementation

Widespread current and future use of soil erosion calculations to demonstrate compliance with regula-

tory requirements imposes important constraints on soil erosion models. Applicable models must be geared to the skill level and data availability characteristics of users, must be able to evaluate the need and future impact of new or adjusted management techniques, and must be sensitive to regional and local environmental conditions. Before the NRCS was formally empowered to provide funds based on successful soil conservation plans in 1985, the agency had already implemented the USLE as a planning tool, making use of instructions provided directly by the model developer (Wischmeier and Smith, 1965, 1978). This proactive adoption of a model suggests that the model was well suited to the needs and skill levels of the user group. In general, adoption of a particular erosion prediction technology by an agency or organization depends on several factors in the context of the intended application (Renard et al., 1994). These factors include a user-friendly approach, scientific and technical adequacy, as well as availability of expertise, input data, computers, other resources needed to use the new technology, and policy considerations.

Success in implementation and adoption is based on the adequacy of the model to meet user needs and by the costs involved in an implementation process for either a governmental agency or a commercial vendor. USDA ARS and NRCS are working toward combining second-generation versions of RUSLE and the process-based Wind Erosion Prediction System (WEPS) (Hagen, 1991) together with WEPP watershed capabilities under the umbrella of a single Graphical User Interface (GUI) for implementation in the NRCS field offices (Meyer et al., 1997). With increasingly widespread availability of powerful personal computers and increasing regulatory pressure, a larger group of non-NRCS users is potentially able to apply these models. Therefore, RUSLE and WEPP have available stand-alone interfaces (Yoder and Lown, 1995; Flanagan et al., 1998) designed for an audience of farmers, soil conservationists, and construction, mining, and military training site managers. Geomorphologists working on such models that are geared toward policy decisions should recognize that the best scientific models might lose out to simpler models more directly geared to the needs, abilities, and data availability of users.

3. Dynamics in soil erosion processes

3.1. The role of scale

Scale is a critical issue in soil erosion modeling and policy support because it influences model development and selection, as well as data availability and quality (Renschler, 2000). The resource conservation community and policy makers in the U.S. have identified four scale categories of interest (Zinn, 1997): (1) field/farm, (2) local/community, (3) state/regional/watershed/ecosystem, and (4) national/continental. Planners and managers gather information at a particular scale of interest and typically generalize or simplify data and models based on dominant properties and processes, and on the spatial and temporal variability of these properties and processes at the scale of interest. The process of simplifying complex geographical phenomena into distinct aerial units is often referred to as regionalization (Bernert et al., 1997). Because landscapes are spatially heterogeneous areas, the structure, function, and temporal change of landscapes are scale-dependent themselves (Turner, 1989) and, therefore, each regionalization method has to be developed and validated to fulfill the requirements for a specific purpose at a specific scale.

3.2. Temporal and spatial variability

The temporal variability of weather, especially rainfall, is extremely important for soil erosion risk assessment (Renschler et al., 1999). Soil erosion totals can, in some cases, be dominated by a few extreme events, thus monitoring, as well as simulation studies need to be long enough to capture these erosive events; Baffaut et al. (1996) recommended a minimum of 50 to 100 years. However, low magnitude, high frequency events can also be significant for long-term erosion rates. Frequency distributions constructed from time series of measured erosion events are usually highly skewed, which has a large impact on the simple arithmetic mean for the sample (Baffaut et al., 1998; Boardman and Favis-Mortlock, 1999). This is problematic because mean values are often used in soil conservation planning, whereas, for some applications, a more statistically suitable measure of central tendency is the median value. However, a

long-term mean together with the number and distribution of events is a good compromise central tendency measure because the mean is entrenched in current soil and water conservation practice (Favis-Mortlock et al., 1996).

One of the major challenges associated with scale issues in the management context is how to deal with the fact that landscape position and temporal climate variability can result in spatially and temporally variable aggregate stability (Boix-Fayos et al., 1998). Plot studies have shown that hillslope position plays a major role in surface hydraulic gradients, erosion rates can increase by as much as 60 times under seepage conditions representative of lower slope elements compared to drainage conditions that generally occur on upper slope units (Gabbard et al., 1998). Runoff from small watersheds with identically mapped surface conditions can be completely different if underground watershed divides and impervious layers cause different ground water and interflow responses between watersheds (Bonta, 1998). Mean soil loss rates from field size areas can be much lower than estimated from plot studies (Poesen et al., 1996) and long-term averages of sediment yield measurements within large river basins can vary by orders of two magnitudes, depending on the size of the watershed (Osterkamp and Toy, 1997).

According to the National Resources Inventory (NRI) (Natural Resources Conservation Service, 1999a), average erosion rates on U.S. cropland has fallen 35%, from $17.9 \text{ t ha}^{-1} \text{ year}^{-1}$ in 1982 to $11.7 \text{ t ha}^{-1} \text{ year}^{-1}$ in 1997. The sediment balance of the 360-km^2 large Coon Creek Basin in Wisconsin, one of the first watersheds to demonstrate the long-term effects of conservation techniques, shows that the total measured rate of alluvial sediment accretion for the period 1975–1993, $2.2 \text{ t ha}^{-1} \text{ year}^{-1}$, was only about 6% of the rate that occurred in the 1930s (Trimble and Lund, 1982; Trimble, 1999). However, changes within the watershed were highly variable (Trimble, 1999) and reflect complex interaction of slope erosion and storage and remobilization of alluvial material. Methods used to extrapolate observations of plot studies or even small watersheds to determine average annual soil erosion rates for large regions within the U.S., Europe, or on a global scale have proved controversial (Pimentel et al., 1995; Boardman, 1998a,b; Trimble, 1999).

Even the relatively large amount of unexplained variability observed in replications of plots under “identical” natural conditions and management treatments shows that a series of plots is needed to confidently estimate mean runoff and soil loss for comparison purposes (Wendt et al., 1986). Dominant erosion processes at various scales (including spatial variability and interactions of relevant physical, chemical, and biological phenomena) are summarized in Figs. 3 and 4. Scientists are well aware of these types of scale problems and expect robust models to explicitly deal with variability, as well as with the issue of how data on erosional processes at one scale can be extrapolated to processes operating at other scales (Poesen et al., 1996). However, sophisticated models that treat variability well often require types and scales of data that are unavailable to many users and policy makers.

3.3. Prediction tools considering scales and variability

Given the critical importance of recognizing and evaluating the implications of temporal and spatial variability in soil erosion parameter data, surprisingly little emphasis has been placed on this in tool development and evaluation. In modeling, shorter time scales are typically associated with smaller spatial scales because finer time resolution requires more detailed modeling of hydrological and sediment transport processes, which usually means consideration of variability at more detailed spatial scales (Kirkby, 1998). At different scales, different groups of processes are dominant, so the effective focus of the model also changes with scale. Most modern watershed models focus on the prediction of water fluxes for particular space and time scales (Fig. 4). Often

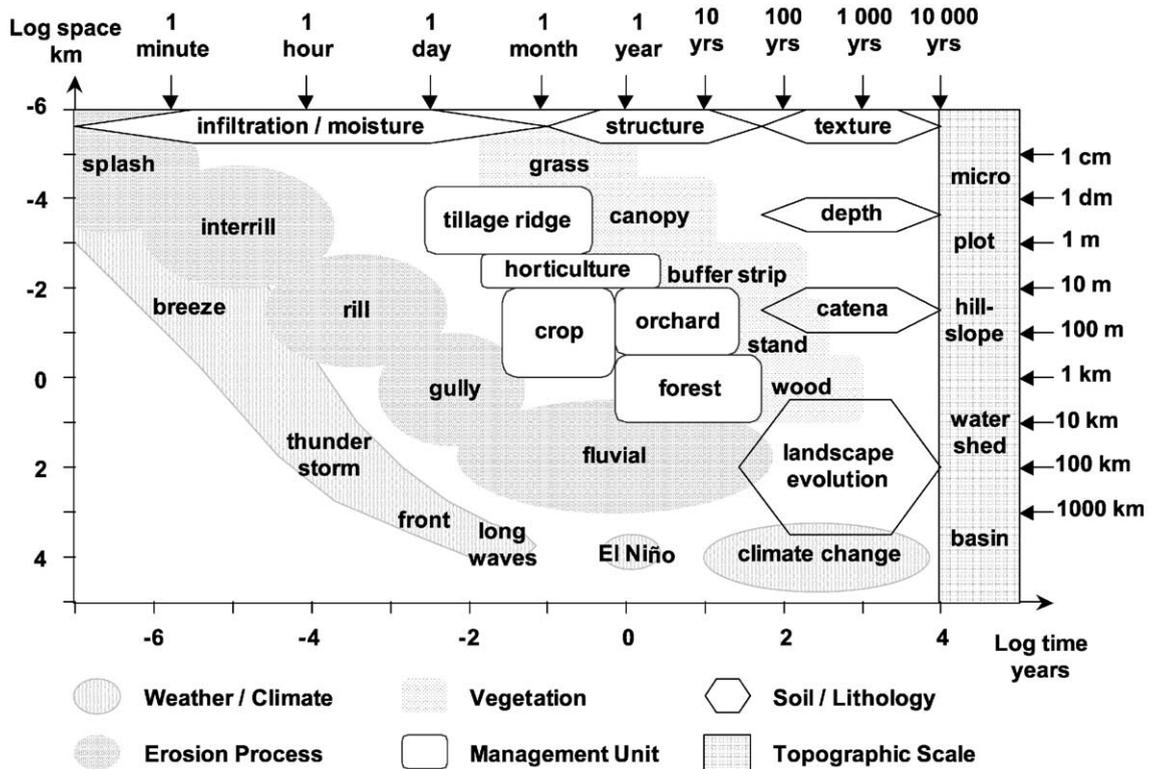


Fig. 3. Time and space extent of atmospheric, topographic, soil, and vegetation phenomenon important for dominant soil erosion processes. The management units indicate extent of human interest and impact.

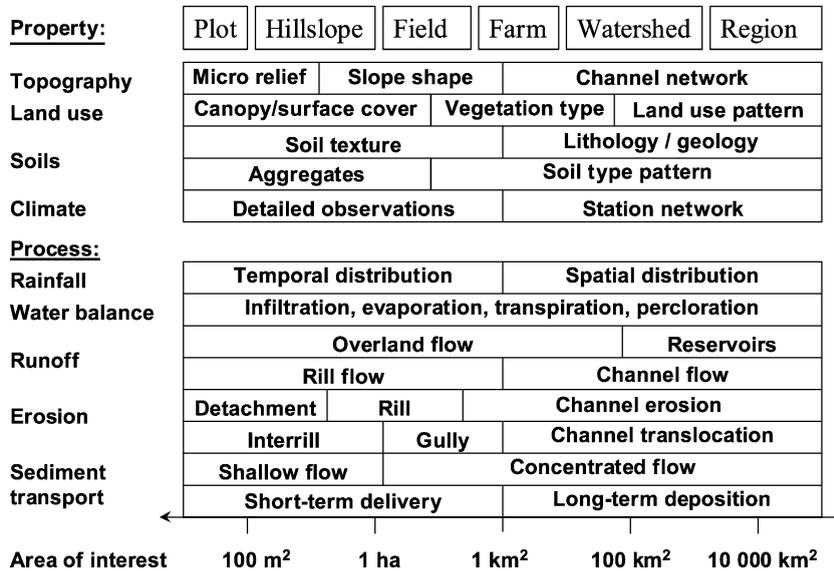


Fig. 4. Scales of interest, spatial, and temporal variable properties important for dominant processes at an indicated scale.

hydrologic processes are described in ways that depend on the model’s scale, and the scale in which the model is designed to operate influences decisions about the level of spatial aggregation in input data, analysis, and model output. However, when the problem of interest is not at the scale of the model, scaling both data and model results is very complex (Renschler et al., 1999). For example, empirical, process-based approaches to predict sheet and rill erosion rates can provide reasonable results to evaluate environmental and economic impacts of agricultural policy on a large scale (Carriquiry et al., 1998), but do not yield accurate predictions of erosion variability on the field scale.

3.4. Implementation process and user acceptance

Success in implementing a soil erosion prediction tool depends ultimately on a sensitive decision-making process that balances environmental and economic concerns in a policy framework and the need for broad scientific and public acceptance. A scientifically powerful model that cannot be used is no more useful in a policy context than a simple model that is deemed unacceptable by the scientific community that advises policy makers. Rapid implementation of conservation tillage, for example, occurred because the

practice had all the elements of success (Tweeten, 1995): achievable technology, efficient use of human resources, support from scientists and policy makers, and most of all, economic benefits that were clearly perceived by the users. However, for many soil conservation practices, such as no-till, adoption is more difficult without regulatory incentives based on widely accepted measures of soil erosion prevention. Soil and water conservation practices must fit into the household- and watershed-level socioeconomic system within a local, regional, and national economic framework, but the practice that stands the best chance of success may not be the most effective from a technical standpoint (Kerr, 1998). Social, economic, and ecological effects of these model applications in real world settings have to be investigated in terms of their impact on policy, and this in turn affects how scientists should approach model development and evaluation.

3.5. Geographic information systems

Graphical tools (maps, aerial photographs, and digital imagery) play an important role in the interaction between a user/decision maker and a model. Geographic Information Systems (GIS) have emerged as a powerful tool for handling spatial geo-

referenced information for preparation and visualization of input and output, and for interaction with models. Combined with modern information technology, which enables users to operate GIS applications through the Internet, GIS applications can be used to solve problems and to provide meaningful answers in formats usable for decision-makers (Gallaher, 1999). However, to achieve this potential, each GIS-based model application has to be evaluated in terms of its ability to provide the user with useful visual information and analysis tools while fulfilling the model's data quality standards and preprocessing requirements (Renschler, 2000). Poor spatial data quality, data processing induced errors in data conversion, and error levels introduced by model assumptions and methods need to be evaluated carefully in terms of their potential effect on results and the decision-making process (Goodchild, 1996). Statistical modeling and accuracy visualization provide ways to show users how data accuracy and model choices affect results and, thus, decisions (Goodchild, 1996; Ehlschlaeger et al., 1997; Wechsler, 1999). An appropriate goal of model development should thus be to develop a user-friendly and scientifically accepted prediction tool with spatial distributed model and visualization capabilities accessed through GIS.

4. Development of an assessment tool for point to regional scales

One of the major challenges in soil erosion modeling, which has become even more important with increasing use of models linked to GIS, is the mismatch between the small spatial and temporal scales of data collection and model conceptualization, and the large spatial and temporal scales of most intended uses of models. A promising alternative approach to scaling model applications involves efforts to base analyses at large scales on regionalization of results of fine-scale simulations. Regionalization of effective and representative model parameters based on the most detailed data available allows use of a single process-based model concept across a range of scales (Renschler, 2000). In addition, the use of representative model parameters and consideration of heterogeneity based on the finest

data available avoids data limitations related to aggregation procedures that traditionally precede model runs at large scales. Therefore, hydrologic conditions and erosion processes can be simulated at a small scale using process-based models and then aggregated to the watershed or regional scale. The primary goal of the case study presented here is to demonstrate the development of an assessment tool and how assessment results may change in response to variations in input data ranging from high resolution (research grade) to low resolution (commonly available data).

4.1. Model: spatially distributed process-based modeling

The soil erosion model used here, WEPP, was selected because it is being considered by the USDA for selection as the primary soil erosion assessment tool that will be used in the future to support regulatory requirements. Thus, WEPP is likely to be critically important in real-world decision making. WEPP has been validated for single event and continuous simulations at several scales, ranging from plots (Zhang et al., 1996) and hillslopes to small watersheds (Liu et al., 1997). The WEPP model's process-based nature enables its transfer to ungauged watersheds without any further calibration, unlike many other existing models. The performance of the WEPP hillslope version (Flanagan and Nearing, 1995) is investigated here in terms of its ability to predict spatially distributed soil loss for raster cells along flow paths on hillslopes (Cochrane and Flanagan, 1999) and to support management decisions on agricultural land for a complex landscape within a region. This involves using regionalization methods that are necessary to use the most detailed and recent commonly available, standardized data sources.

4.2. Data: commonly available U.S. data sources

Although models can be developed and refined using the data from carefully monitored and surveyed plots or watersheds, if such models are to be used widely in support of policy and conservation efforts, they must be able to produce useful results using only the data that are commonly available to potential

users. Thus, an important concern is to identify the data actually available to a wide range of users.

4.2.1. Soils data

The NRCS publishes county soil survey maps at a 1:24,000 scale as an overlay on aerial photographs, and this is the limit of soil data available to the vast majority of potential users. Recently, the agency started providing detailed spatially distributed soil information in digital format at the county level, together with orthophotos on CD-ROM (Soils Explorer only for selected counties) and as digital GIS files from the National Soil Survey Geographic Database (SSURGO) (Natural Resources Conservation Service, 1999b).

4.2.2. Climate data

The quality of spatially and temporally distributed weather information is critical in soil erosion model results because of the primary influence of rainfall intensity on runoff and initiation of soil movement. Detailed climate data for WEPP can be generated by a climate generator (CLIGEN) (Nicks et al., 1995) based on long-term statistical parameters for more than 1000 locations in the U.S. A Break Point Climate Data Generator (BPCDG) derives WEPP climate input from detailed observed weather data (National Soil Erosion Research Laboratory, 1999). However, from a small-scale impact assessment perspective, use of a non-spatially distributed climate data set is appropriate to analyze the response from single hillslopes within a region of homogenous climate. Because both CLIGEN and BPCDG are available with WEPP, these can be considered to be commonly available data and approaches.

4.2.3. Land use data

Sources of commonly available data describing spatial and temporal variability in land use are rare (although most communities have some sort of land use or zoning map available, at least in printed format). However, most users and landowners at a local scale have or can create a map of current and planned land use at the scale of interest. While most of the users are interested in variations of land management, the topography, soil, and climate properties form the basis of input to design specific assessment scenarios to support decision making.

4.2.4. Topographic data

The U.S. Geological Survey (USGS) provides digital, nationwide, topographic information through a publicly accessible data server (U.S. Geological Survey, 1999). Topographic information can be derived by digitizing the contour lines of Digital Raster Graphs (DRGs) or directly as line information from hypsographic Digital Line Graphs (DLG) available for some areas. The 10- or 20-ft (3.04- or 6.08-m) contour lines from DRGs have an average vertical accuracy of 1.5 ft (0.46 m). Digital Elevation Models (DEMs) at the 1:24,000 map scale are available nationwide with a 30-m pixel size, with some areas available at a 10-m pixel size scale. The DEMs vary in resolution and accuracy depending on the method used to derive them. Level 1 DEMs are derived from high altitude photogrammetry with a vertical resolution of 1 m and an average vertical accuracy of 7 m. Level 2 DEMs are interpolated from DLGs with a vertical resolution of 1.5 ft (0.46 m).

4.3. Study area: Treynor, IA, USA

The WEPP method was applied to three HEL-classified experimental watersheds in the steeply rolling deep loess in SW of Treynor, IA. Except for topographic characteristics, identical data input parameters as prepared for watershed W-2 (30 ha) were used to simulate neighboring watersheds W-1 (21 ha) and W-11 (6 ha). Precipitation and climate input for a 6-year period (1985–1990) were taken from detailed breakpoint measurements. Soil parameters for a silt loam soil series (Marshall–Monona–Ida–Napier) were taken from soil surveys and the WEPP soils database. Soil surveys indicate three soil mapping units within the watershed, but soil variations in soil characteristics within the watershed were assumed to be negligible for modeling purposes in contrast to variations in topography (Kramer, 1993). Management practices were taken from management schemes for a 6-year corn (*Zea mays* L.) rotation with a conventional tillage system consisting of heavy disking in mid-April followed within a fortnight by a shallow disking and harrowing. Despite the fact that runoff and sediment yield measurements at the three watershed outlets have been collected since 1965 (Kramer et al., 1999), this evaluation study focused on the effect of data processing on assessment results rather than a spatially dis-

tributed validation of the approach; therefore, only a relatively short time period (1985–1990) was simulated.

4.4. *Methods: accuracy of available elevation data*

As an example drawn from a larger study (Renschler, 2000), we want to emphasize here the sensitivity of model results to different resolutions and accuracy standards of three elevation data sets, described above. The Topography Analysis Software System (TOPAZ) (Garbrecht and Martz, 1997) was initially used to divide hillslopes and watersheds into a network of discrete flow paths based on each data set. The effect of different elevation data sources on watershed discretization and topographic characteristics, as well as their impact on soil erosion simulation results, were then evaluated against each other and in comparison to empirical results. Model input for variables, such as climate, was prepared for a specific watershed and then transferred and applied to watersheds in the same region without any calibration. Thus, climate differences are not a source of variation in the results. To evaluate the effect of geo-referenced commonly available elevation data, sources of different resolution and quality were prepared and model results from these were compared to each other and to field measurements. The following sources of commonly available elevation data were used: (i) USGS 30-m raster DEM Level 1, (ii) USGS 10-m raster DEM Level 2, (iii) USGS 10-ft contour lines from DRG, and (iv) detailed point measurement as Triangular Irregular Network (TIN) from ARS aerial photogrammetry.

4.5. *Results: data preprocessing and assessment*

A schematic overview of each data source (Fig. 5a) with derived discretization in 3-m contour lines (Fig. 5b) demonstrates the decreasing accuracy of the topographical input from point and contour to raster data. The 10-ft contours and the contours derived from the 10-m DEM are almost identical. The 30-m raster data appear to be less accurate for representing the topography on this 1-km² scale. After running the sink-hole removal and watershed discretization algorithms of TOPAZ, the slopes for each cell show the differences in the topography of each data source (Fig. 5c).

On the 10-m raster level, the detailed TIN data have less steep areas than either USGS data. The interpolated contour lines provide a smoother surface, whereas the 10-m DEM interpolated from the same contour lines has more variability in slope classification. The USGS 30-m raster gives very basic topographic information about the watersheds, but fails to provide the information required to delineate the smallest watershed W-11.

The DLG contours and the TIN data were processed with an interpolation algorithm (Arc/Info TOPGRID tool) to prepare raster maps in raster sizes of 30, 20, 15, 12, 10, 6, 5, and 4 m. Analog raster sizes except for the original 30-m DEM were produced by a simple approach based on weighted averaging of the 10-m raster DEM. Results for the watershed area discretization provide good mapped watershed areas in the field for grid sizes of 20 m and smaller (Fig. 6a). Using these data, the model generally under-predicted storm event surface runoff, but the runoff increased with a decreasing raster cell size (Fig. 6b). Best results in comparison to observed long-term observations are for cell sizes smaller than 10 m. The USGS data produced better long-term average results for surface runoff than the detailed TIN data. However, the TIN data produced results for average annual sediment yield that are more stable across the different raster cell sizes (Fig. 6c). The simulated spatial distribution of soil loss can be shown as output (Fig. 5d), but because there are no field observations or maps of erosion features, there are no empirical data against which to evaluate model results. In general, the coarser resolution data resulted in model runs that predicted more erosion than the finer resolution TIN topography (Fig. 5d). Note that observed values of sediment yields are measured at the watershed outlet and implicitly include channel erosion, whereas WEPP does not include channel erosion (Cochrane and Flanagan, 1999), so the simulation results for the watersheds represent only the runoff and sediment yield entering the channels.

4.6. *Discussion: implementation of assessment results*

The case study suggests that variations in input data resolution do affect model results and that in this specific case, coarser data overestimated erosion loss compared to high resolution data. Data resolution also

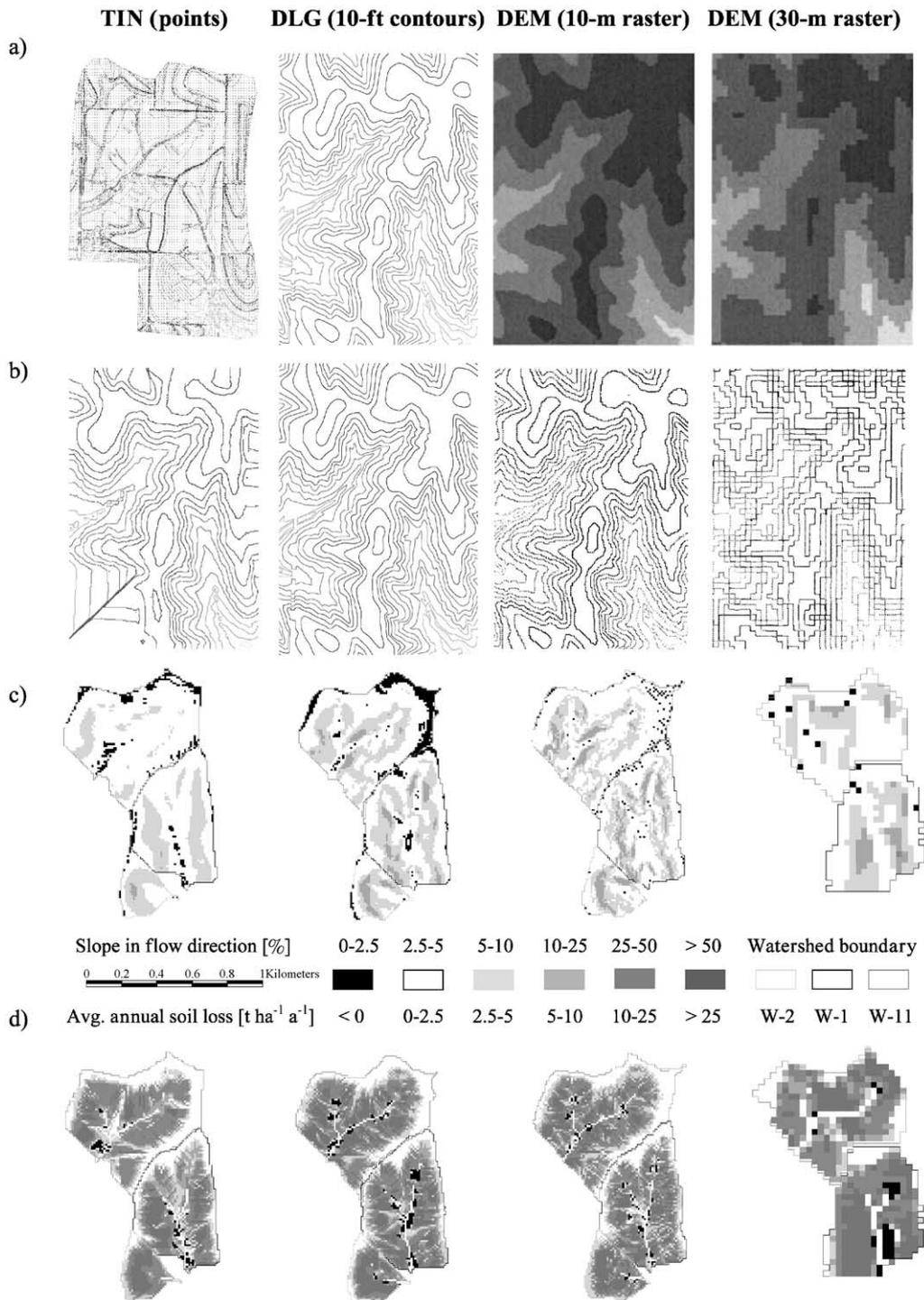


Fig. 5. Comparison of (a) topographical input sources, (b) derived 3-m contour lines, (c) slope discretization, and (d) soil erosion model results for three experimental watersheds at Treynor, IA. Input sources are points of Triangular Irregular Network (TIN), contours of a Digital Line Graph (DLG), and two raster sizes of Digital Elevation Models (DEM) (both U.S. Geological Service).

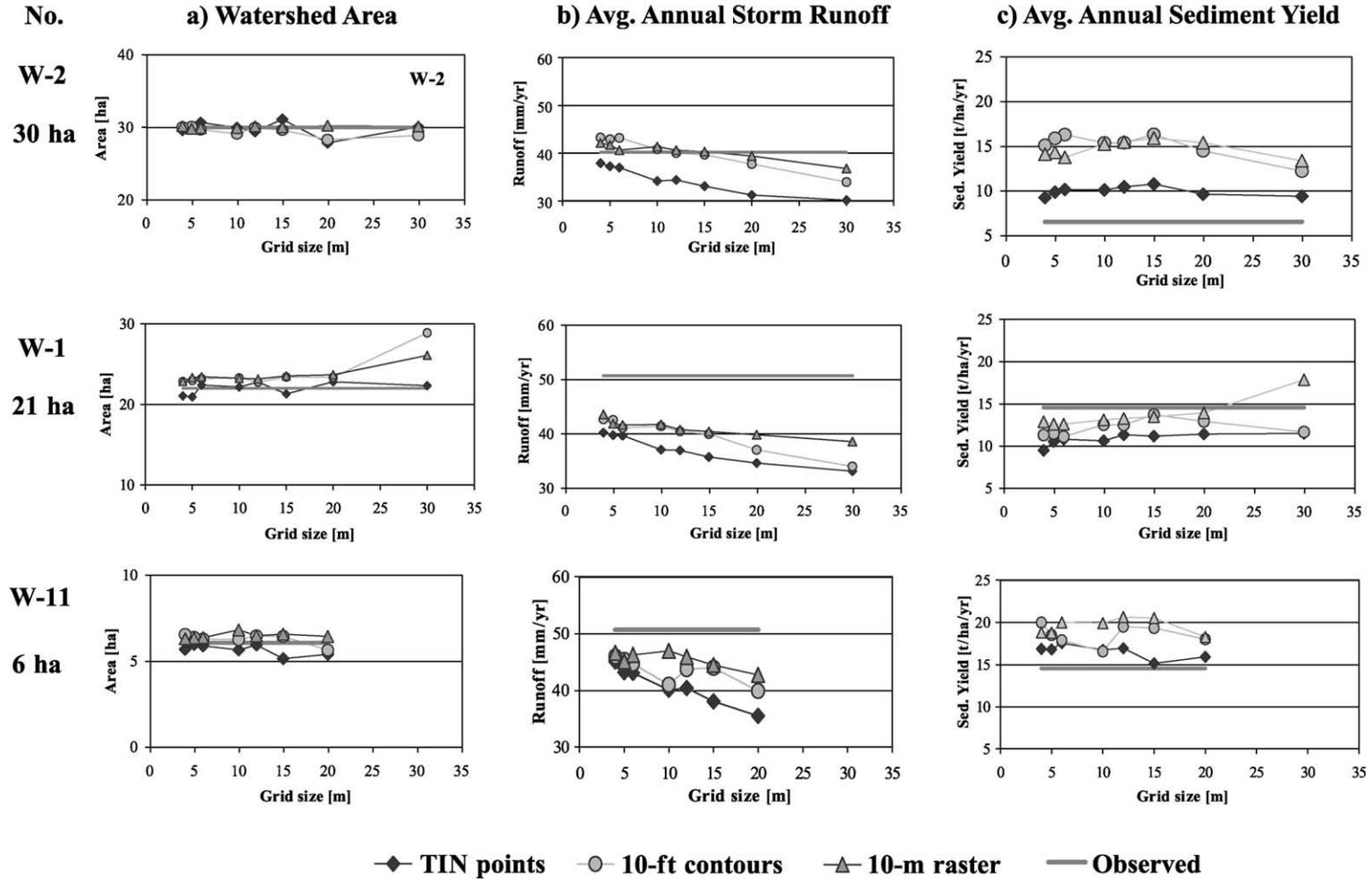


Fig. 6. Comparison of (a) watershed area, (b) average annual storm event surface runoff, and (c) average annual sediment yield for watersheds W-2, W-1, and W-11 at Treynor, IA (1985–1990) and different sources of topographic input (compare Fig. 4). Note that topographical input was interpolated from TIN points, 10-ft (30.5 cm) contours and 10-m raster for different grid sizes (10- and 30-m raster are original). Regionalization method produces acceptable runoff and soil loss results without considering the effect of channel characteristics.

affects the average annual storm runoff and sediment yields, as well as the details of where erosion is predicted to be occurring, all of which have significant management implications. Based on the NRCS assigned T values for the soil units in the study watersheds ($11.2 \text{ t ha}^{-1} \text{ year}^{-1}$; [Natural Resources Conservation Service, 1999b](#)), the simulated (and measured) average annual values of the 6-year period would indicate a need for a change of management in W-11 (high priority) and W-1 (lower priority), while W-2 results are within ‘tolerable’ limits, if the TIN data are chosen as input. Despite the fact that spatially distributed soil erosion measurements were not available, simulation results based on the TIN data do indicate the locations of patches within the watersheds with erosion problems, and it is important to note that these are not all the same as the problem areas identified using only commonly available data. However, the large-scale patterns are similar. This case study demonstrates that the WEPP soil erosion assessment tool produces useful results concerning soil loss on hillslopes and sediment yields that can be used in decision support for soil and water conservation, even when the model is run solely with commonly available topographical data. However, the results are not identical between different data levels, so in using a model, such as WEPP, one must be prepared to accept some different outcomes in decision making with the use of commonly available data as a trade-off for avoiding prohibitively expensive additional data collection. More information and details of the case study are provided in [Renschler \(2000\)](#).

5. Addressing future research and implementation efforts

5.1. Modeling

Historically, soil erosion modeling has used a number of different approaches, ranging from almost entirely empirical to largely theoretical physical or stochastic models. Multiple model styles are needed, depending on potential applications. However, in support of policy decisions, arguably the greatest need is for models that can produce robust results using readily available data. In determining if models are accurate and reliable, a common approach is to

compare model results with observational data; however, model predictions rarely match observations exactly. Does this mean that the models are insufficiently reliable? [Nearing et al. \(1999\)](#) evaluated coefficients of variation of soil erosion data of replicated plots to determine better ways to design experiments and enhance capabilities of prediction models to handle variability of results (see also [Nearing, 2000](#)). The results prompted him to note that because the physical data from a large set of observations of 15 replicate plots (Kingdom City, MO) produced an r^2 value of 0.76, it is unreasonable to expect a deterministic erosion model to do better than this. Rather, to encompass natural variability in observations, assessment tools should include probabilistic elements.

5.2. Data availability

The types of data required to run simple erosion models are already widely available. Digital databases and more complex models with user-friendly front ends accessible through the Internet will increase the number of people making use of more sophisticated environmental assessment tools at a local and regional level. This will, for example, allow landowners to investigate policy implications through access to information and models. However, most users will not critically evaluate data sources, quality, or resolution; rather, there is likely to be widespread use of whatever data are readily available, without careful consideration of the implications of these data set choices. Thus, the access and applicability of environmental models have to be critically evaluated in terms of model performance under these conditions, as well as the likely response users will make to model results. Geomorphologists have to carefully evaluate models and assessment approaches in terms of how results will be generated and used, to avoid serious mistakes being made on the basis of faulty results or interpretations. Thus, there is considerable need for more practical approaches to assess the risk associated with certain levels of data accuracy ([Agumya and Hunter, 1999](#); [Hunter, 1999](#)).

5.3. Process-based approach for tolerable soil loss

There is continued need for discussion about approaches used to determine ‘tolerable’ soil losses,

as these are critical in the decision-making process used to implement conservation techniques (Johnson, 1987). Similar to soil erosion modeling efforts, soil profile development and tolerable soil losses should be determined by process-based model approaches rather than a simplified estimation approach that meets politically motivated criteria. What is the use of a successful implementation of a scientifically accepted erosion assessment tool if its results are then evaluated by comparison with T and HEL limits derived by vague estimation procedures?

There is considerable concern that current T values may significantly overestimate sustainable tolerable soil loss. Kramer (1999) measured mean long-term annual sediment yields (1974–1992) of $11.5 \text{ t ha}^{-1} \text{ year}^{-1}$ for conventional tillage with contouring, $1.5 \text{ t ha}^{-1} \text{ year}^{-1}$ ridge-tillage with contouring, and $0.7 \text{ t ha}^{-1} \text{ year}^{-1}$ for ridge-tillage on terraces. These measurements in several small watersheds in Iowa show that sheet erosion rates under conservation practices can be much higher than these soil development rates. For example, the annual soil replacement rate in Iowa has been estimated to be $10.5 \text{ t ha}^{-1} \text{ year}^{-1}$ for prairie, $2.7 \text{ t ha}^{-1} \text{ year}^{-1}$ for forest, and $0.7 \text{ t ha}^{-1} \text{ year}^{-1}$ for conventional agricultural conditions (Glanz, 1995). These data suggest that although even conventional tillage is close to the defined T value, soil development is actually an order of magnitude less than soil loss rates. Only ridge-tillage on terraces produced erosion rates comparable to soil replacement rates.

6. Conclusions

Soil erosion is a critical issue in many countries in terms of its impacts on crop yields, infilling of navigable waters and drainage structure, and ecological impacts on receiving waters and water quality. Geomorphologists are well placed to play a significant role in policy discussions and to provide tools and expert opinion that help in the formulation and implementation of policy. In the U.S., soil erosion research has helped advance understanding of the nature and scope of the soil erosion problem, has contributed to the development of practical management approaches, and has become institutionalized within the regulatory component of national soil erosion policy. Since 1985,

the Food Security Act has required determination of soil loss rates using the USLE model concept for comparison to tolerable soil losses from farm land and at the local level, some construction site erosion control ordinances require USLE calculations for comparison to allowable erosion rates.

Development of a newer generation of models that are slated to become part of the regulatory framework, RUSLE and WEPP, provides an opportunity to resolve some of the limitations of the USLE and to prepare for the challenges of an expanded user base. The increasing availability of online data, visualization, and analysis tools is allowing a wider range of users access to models, with opportunities for both more informed decision making, as well as opportunities for much wider misuse of models. Thus, there is considerable need for careful evaluation of model performance under conditions representative of real world users and the data they have access to. As geomorphologists become increasingly involved in model development to support policy implementation, it is important to move beyond complaining that users are not running models with sufficiently detailed, high quality data. Rather, as the case study illustrates, it is critical to develop models with real data availability in mind, test these models using both high quality and readily available data, and then examine the extent to which these data sources actually change decisions that rely on model results.

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