CHAPTER 2

LITERATURE REVIEW

"The need for estimates of sediment yield are ubiquitous throughout water resources analyses, modelling, and engineering as sediment is a major pollutant, a transporter of pollutants, and sedimentation rates and amounts determine the performance and life of reservoirs, canals, drainage channels, harbors, and other downstream structures and improvements."

Leonard J. Lane *et al.* (1997)

According to the objectives, the following topics are reviewed in this chapter: a) soil erosion modeling, including the motivation and limitations, existing erosion models, and the importance of GIS to soil erosion modeling, b) geovisualization and time series animation techniques are described and their advantages as powerful data exploration techniques are enumerated and, finally, c) the last section revisits the findings of the grid cell size effects on the landscape representation, simulated flows and soil erosion predictions.

2.1. SOIL EROSION MODELS

2.1.1. Rationale and Limitations

Soil erosion and sedimentation by water involves the processes of detachment, transportation, and deposition of sediment by raindrop impact and flowing water (Foster and Meyer, 1977; Wischmeier and Smith, 1978; Julien, 1995). Erosion and sedimentation represent on-site and off-site problems. On-site, erosion can degrade the productivity of the soil necessary for crop and food production (Pimentel *et al.*, 1976 and 1995; Meyer *et al.*, 1984; Kimberlin and Moldenhauer, 1977). Off-site, sediment deposited in stream channels, reservoirs and other hydraulic structures reduce their capacity and need to be removed. Sediment is a pollutant by itself and may carry soil-absorbed pollutants (Stone, 2000; Lane et al, 1983; Hadley and Ongley, 1989;). Soil conservation specialists have for many years attempted to estimate soil loss from individual fields or slopes to determine land use practices which will ensure long-term productivity of the soil (Walling, 1982; Hadley, 1986; Hadley and Mizuyama, 1993;

Walling and Webb, 1996; Walling and Probst, 1997; Summer *et al.*, 1998). The ultimate objective of research on soil erosion is to solve erosion problems by adopting suitable conservation measures (Painter, 1981). Location of the sediment source areas, volume of sediment eroded, transported and delivered and rate of sediment delivery and transport after treatment are some of the factors that should be quantified before deciding what erosion control treatment is best suited for a problem (Madej, 1981). In this context, erosion models and, more specifically, 2-D erosion models provide the necessary tool to predict excessive soil loss and help in the implementation of an erosion control strategy (Julien and Frenette, 1987; Sharma *et al.*, 1996; Doe *et al.*, 1996; Marston and Dolanb, 1999).

The measurement of erosion rates is one of the limitations of erosion modeling. While direct surface measurements are preferable, these are often difficult to obtain from a logistical, observational and instrumental point of view. Many land surfaces change only imperceptibly and only highly accurate measurements over long periods of time may produce meaningful results (Campbell, 1981). Furthermore, Lane (1995) states that "the lack of adequate technology enabling measurements of erosion processes simultaneously in time and space limits our ability to parameterize, evaluate and thus validate process-based erosion".

A second limitation comes at the erosion modeling stage. Since the erosion components are subsidiary to a hydrologic model, the difficulties encountered when modeling rainfall-runoff relationships are magnified when modeling erosion and sediment production (Bennet, 1974; Clarke, 1994; Rojas and Woolhiser, 2000). Because the calculation of sediment-transport rate in most cases is dependent on the prior estimation of the hydraulics of overland flow, any errors in the predictions of the hydraulic will propagate through the erosion estimation process (Wainwright and Parsons, 1998).

Nevertheless, due to the complexity of the natural systems, watershed erosion modeling represents a powerful tool to predict the consequences of natural as well as man-induced environmental changes and impacts on the sediment dynamics.

2.1.2. Erosion Models Listing

Soil erosion computer models use mathematical expressions to represent the relationships between various factors and processes occurring on the landscape. These factors generally include topography, meteorological variables, soil properties, and land use and land cover features. One classification of models distinguishes between theoretical or physically based models and empirical models. However, most erosion models are of a hybrid type including both theoretical and empirical components (Haan *et al.*, 1994). The emphasis in erosion research on strictly empirically based models is declining. The trend in erosion prediction technology is toward the development of process-based simulation models (Morgan 1980; Nearing *et al.*, 1990). Many physically based upland erosion models in the past have used lumped or semi-distributed techniques for their hydrologic modeling component.

Most of the erosion models are based on the Universal Soil Loss Equation (USLE) (e.g. AGNPS (Young *et al.*, 1989), ANSWERS (Beasley *et al.*, 1989), EPIC (Sharpley and Williams, 1990), and SWAT (Arnold *et al.*, 1996)), on the partition of the watershed in planes and channel elements (i.e. KINEROS (Woolhiser *et al.* 1990), and EUROSEM (Morgan, 1990)) or they are not intended for basin-scale use (i.e. CREAMS

(Knisel, 1995)). An extensive description and discussion on these models can be found in Singh (1995), and Doe *et al.* (1999).

The USLE (Wischmeier and Smith, 1978) is the most widely used and accepted empirical soil erosion model. It was developed for sheet and rill erosion based on a large set of experimental data from agricultural plots. Yet, the equation was derived on single agricultural plots and is only valid when applied to an area up to 1 ha. The USLE equation takes into account slope length (L factor), steepness (S factor), climate (R factor), soils (K factor), cropping (C factor) and management (P factor). This model was specifically designed and tested to predict the average annual soil movement from a given field plot under specified land use and management conditions. The USLE has been enhanced during the past 30 years by a number of researchers. MUSLE (Williams, 1975), RUSLE (Renard *et al.*, 1996; Stone *et al.*, 2000), ANSWERS (Beasley *et al.*, 1989) and USPED (Mitasova *et al.*, 1996) are based on the USLE and represent an improvement of the former. The use of the USLE and its derivatives is limited to the estimation of gross erosion, and lack the capability to compute deposition along hill slopes, depressions, valleys or in channels. Moreover, the fact that erosion can occur only along a flow line without the influence of the water flow itself restricts direct application of the USLE to complex terrain within GIS. The history of the development of the USLE and its modifications can be found in Peterson *et al.* (1979), Lane *et al.* (1992) and Renard *et al.* (1997).

Developed by the USDA, the WEPP model (Flanagan and Nearing, 1995) is intended to replace the USLE family models and expand the capabilities for erosion prediction in a variety of landscapes and settings. This model is a physically based, distributed parameter, single-event simulation erosion prediction model. Processes within the model include erosion, sediment transport and deposition across the landscape and in channels via a transport equation. The WEPP model, in its current form, does not facilitate the integration with raster-based GIS.

The KINEROS model (Woolhiser et al, 1990; Smith *et al.*, 1995) is a single-event, physically based model that uses the Smith/Parlange infiltration model and the kinematic wave approximation to route overland flow and sediment. The EUROSEM model (Morgan, 1990) is a single-event, physically based model for predicting soil erosion by water from fields and small catchments. There are several sediment transport equation options implemented in both models. The representation of a catchment by a cascade of plane and channel elements in the WEPP, KINEROS, and EUROSEM models necessitates lumping of some parameters for small areas. This represents a drawback when representing large watersheds.

SHESED (Wicks and Bathurst, 1996) is based in the European raster SHE model. It simulates soil erosion by raindrop impact, leaf drip and sheet overland flow. Eroded material is transported across the landscape via overland flow. Erosion in channels is modeled as bed erosion. The sediment routine can handle the transport of fine and coarse material. The SHESED model has been applied successfully in Europe and the USA. The LISEM model (De Roo, 1996a; De Roo *et al.*, 1996a, 1996b) is a physically based hydrological and soil erosion model that is completely incorporated in a raster GIS. It can simulate splash erosion and rill and inter-rill erosion. The transport capacity of overland flow is modeled as a function of the unit stream power (Govers, 1990) and depends on the value of the median grain size.

Developed at CSU, CASC2D-SED (Julien and Sagahfian, 1991; Sagahfian, 1993; Julien *et al.*, 1995; Ogden, 1997a, 1997b; Johnson, 1997; Ogden, 1998; Johnson *et al.*, 2000) is a physically-based, distributed, raster, hydrologic and soil erosion model that simulates the hydrologic response of a watershed subject to a given rainfall field. Input rainfall is allowed to vary in space and time. CASC2D-SED can simulate the upland sediment production and deposition by size fraction at any point in a watershed. The sediment is transported from one cell to the next using the 2-D diffusive wave overland flow routine scheme present in CASC2D. For a full description of the CASC2D-SED model, see Chapter 3.

2.1.3. Soil Erosion Modeling and GIS

The ability to represent elevation in terms of topographic surfaces is central to geomorphological analyses and thus to the importance of representing topography using DEMs. It is through the distribution of soil that the land surface changes over the long term and so the ability to link sediment transfer with DEM changes (Schmidt, 2000). The redistribution of sediment will drive the long-term landscape change, which in turn will affect the hydrological processes acting within and over individual hillslopes (Brooks and McDonnel, 2000).

Soil erosion is influenced – among other factors – by the spatial heterogeneity in topography, vegetation, soil properties, and land use. All too often, however, predicative soil erosion models do not examine the problem in a spatial context. This is where a Geographical Information System (GIS) becomes a valuable tool. A GIS is "an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced data" (ESRI, 1994). Therefore, a GIS is a useful technique for coping with the vast number of spatial data and the relation between data from various sources in the erosion modeling process. The advantages of linking soil erosion models with a GIS include the following:

(1) The possibility of rapidly producing input data to simulate different scenarios. A GIS provides an important spatial/analytical function performing the time-consuming georeferencing and spatial overlays to develop the model input data at various spatial scales (Sharma *et al.*, 1996).

(2) The ability to use very large catchments with many pixels, so the catchment can be simulated with more detail (De Roo, 1996b).

(3) The facility of displaying the model outputs (visualization). Visualization can be used to display and animate sequences of model output images across time and space. Therefore, visualization enables object to be viewed from all external perspectives, and to invoke insight into data through manipulable visual representations (Tim, 1996).

There are different strategies for linking erosion models with GIS, ranging from loosely coupled to tightly coupled arrangements. Pullar and Springer (2000) categorize three levels of integration:

(1) Loose coupling: the GIS system and the erosion model are separated, and the files must be transferred back and forth externally between the GIS and the model.

(2) Tight coupling: the GIS (typically) provides the shared interface to move the spatial data between the GIS and the separated modeling program.

(3) Fully integrated: the model is fully integrated as a component in the host GIS application.

Most of the current integrations of soil erosion models with GIS are examples for level 1 and 2 types. Category 3 type linkages are problematic because of the lack of an efficient temporal dimension in most GIS systems (Kaden, 1993; Doe, 1999).

Erosion potential prediction is becoming a more and more widely applied GIS operation. Several examples for the integration of GIS with erosion models can be found in the literature: De Roo *et al.* (1989) combined ANSWERS with GIS technology; later, De Roo integrated LISEM (De Roo, 1996a,b; De Roo *et al.*, 1996a, 1996b) and LISFLOOD (2000) with a GIS; Mitchell *et al.* (1993) linked AGNPS with GIS. Other integration examples are described in Mallants and Feyen (1989), Lin (1991), Dryer and Frhlich (1994), De Jong (1994), Mitasova *et al.* (1996), Harrison and Doe (1997), Adler *et al.* (1997), Warren *et al.* (2000), Wijesekera and Samarakoon (2001)

2.2. GEOVISUALIZATION AND TIME-SERIES ANIMATION.

The ever-changing natural world involves the interaction between many environmental components. It is becoming increasingly important to understand the processes behind these changes to be able to better manage the anthropogenic effects on the environment. The exploration of complex spatio-temporal environmental data demands creative methods of analysis and assessment (Lane and Richards, 2001). Thus, the importance of the visualization of all environmental data to facilitate improved understanding of the data and better predictions through modeling.

Visualization of geographical information has been termed geovisualization (Thurston, 2001). **Geovisualization** is a powerful data exploration technique, exploiting the ability of current computing technology to analyze and display dynamically large amounts of information (Edsall *et al.*, 2000). Geovisualization involves the use of computer graphics to stimulate the human visual system to recognize patterns that would not otherwise be obvious (APOALA project, 2001). Geovisualization refers not only to a set of graphical images but also to the interactive process of visual thinking and interaction with the images (Dibiase *et al.*, 1992a, 1992b).

Scientific research can be described as a process in which a scientist receives an insight into an investigated phenomenon, verifies a derived hypothesis and finally communicates the results. Geovisualization is useful for exploration analysis (MacEachren and Kraak, 1997, 2001; Uhlenküken *et al.*, 2000; Blaser *et al.*, 2000; Steiner, 2001) and the communication of knowledge about spatial information (Kraak and Ormeling, 1996). Lane and Richards (2001) list visualization as an alternative type of model assessment allowing the modeler to reproduce in time and space processes that can be observed through experimentation or in the file, but not necessarily readily measured. They further state that while convectional empirical validation relies on measurement, visualization relies on observation and perception.

Visualization techniques are applied to the scientific research in two ways: a) as visual thinking or cognitive visualization, for exploration and verification of spatial data, and b) as visual communication, where the scientist communicates with other people to present and discuss results (Dransch, 2000).

Visualization techniques have been used widely in a variety of cases, i.e. Kreuseler (2000) used virtual 3-D scenes to explore oceanographic ecosystems and Fuhrmann (2000) as a system for visualizing hydrological data.

Time-series animation is a visualization technique ideally suited for displaying temporal geographic data. Animation leads to faster and easier comprehension of spatial patterns, trends and rates of change of data: "Just as a picture is worth a thousand words, an animation is worth much mere than the input static images" (Acevedo and Masuoka, 1997). Dykes (1997) states that while dynamic maps are particularly appropriate for exploratory analysis, short-term, slightly different, views of a data set are an essential part of the analytical process.

Frame-based raster animations are produced by showing a series of images one after the other in temporal order (Peterson, 1995). When creating a time-series animation one must consider the following issues:

(1) Number of data frames: the greater the number of frames, the better the representation of the process. Correspondingly, the more the number of frames, the bigger the animated file will be.

(2) Starting and ending time of the representation: to capture only the most significant sequence of the animation.

(3) Animation display speed: this will depend on many factors such as understanding of human visual perception and cognition, the intended purpose or objective of the animation, and the rate of change within the data itself.

(4) Media where the animation will be played: on computer screens, recorded to video tape, or put on the World Wide Web (Dykes, 1997; Cartwright, 1997).

Time-series animation techniques has been used, among others, for predictions from an orographic precipitation model (Hay and Knapp, 1996); representation of model uncertainties (Ehlschlaeger *et al.*, 1997; Davis and Keller, 1997; Evans, 1997); the visualization of urban growth (Acevedo, 1997); animation of time-varying three-dimensional groundwater model output (Predmore, 1999); support of development and evaluation of a soil erosion model (Mitasova *et al.*, 1996; Mitas *et al.*, 1997; Mitasova *et al.*, 2000); the properties of spatial and temporal periodicity (Edsall *et al.*, 2000); fluxes of materials in the coastal zone (Morris, 2000); and the representation of statistical sociological data (Adrienko *et al.*, 2000).

2.3. CELL SIZE EFFECTS

2.3.1. On Landscape Representation

Topography defines the movement of water in a watershed and therefore it greatly controls fluxes of energy, nutrient distribution and mass movement in a watershed. Landscape representation will affect the hydrologic response of a watershed at any scale (Schmidt, 2000) and thus it becomes an important factor in hydrological modeling. Characteristics such as slope angle and upslope drainage area will affect the water flow-path geometries, flow velocities and channel network (Thieken, 1999). The hillslope form and soil properties will dominate the runoff production at the hillslope scale. On the basin scale, the hydrograph is influenced by the catchment height distribution, length and form of the basin, and parameters describing the drainage network.

Topography is one of the factors affecting the hydrologic response of a watershed and so inaccuracies in the topographic model will propagate into errors in the prediction of the hydrologic output (Lagacherie *et al.*, 1996; Lee and Chu, 1996). One of such inaccuracies derives from cell aggregation in a raster model.

Resampling is the process of determining new values for cells in an output grid that result from applying some geometric transformation to an input grid. Spatial data aggregation or resampling to coarser scales is often used in the environmental sciences to "scale-up" from local to regional or global scales when modeling a system (Bian and Butler, 1999). The aggregated data is referred as having a coarser resolution or, in the specific case of raster data, as having a larger grid spacing or larger grid cell size.

Arc/Info (ESRI, 1982-2001) GRID module utilizes resampling for geometric transformations and for converting grids to other resolutions (ESRI, 1994). Some techniques have been developed to determine the output value depending on where the point falls relative to the center of cells of the input grid and the value associated with these points (Richards, 1993). The three processes for determining output values in GRID are nearest neighbor, bilinear interpolation, and cubic convolution.

The nearest neighbor is the resampling technique of choice for categorical data as it does not alter the value of the input cells. Once the location of the cell's center on the output grid is located on the input grid, the nearest neighbor assignment will determine the location of the closest cell center on the input grid, identify the value that is associated with the cell, and assign that value to the cell that the output cell center is associated with. The bilinear interpolation and the cubic convolution uses respectively the 4 and 16 nearest input cell centers and their values to determine the output cell. The last two methods should not be used on categorical data since the categories will not be maintained in the output grid. The bilinear and cubic interpolation methods also tend to smooth the data.

Zhang and Montgomery (1994) found that the spacing of the original data used to construct a DEM effectively limits the resolution of the DEM. For that purpose, they obtained digital elevation data from low altitude aerial photographs using a stereo digitizer at a density about every 10 m. Then, they gridded spot elevation data at scales of 2, 4, 10, 30, and 90-m using the GRID module of Arc/Info. In their study, they found that decreasing the cell size beyond the resolution of the original survey does not improve the accuracy of the DEM but potentially can introduce interpolation errors. In their case study, cell sizes smaller than 10-m gave only marginal improvement in slope representation.

Kienzle (1996) studied the effect of the grid size on the division of a catchment in South Africa into individual terrain units (valley bottom, footslope, midslope, scarp and crest). The simulation of terrain units with DTMs was shown successful with the 100- and 50-m grids, both spatially and proportionally. The 250-m grid gave good proportional results, but performed weaker with respect to spatial representation. The simulation with the 400-m grid failed to represent terrain units.

Terrain slope values are usually computed from DEM gridded data by using elevations of the four immediately adjacent pixels (Ritter's algorithm, 1987) or from the eight surrounding elevations in a 3x3 window (Sharpnack and Akin's method, 1969). Slope is an important variable affecting processes such as water flow routing and erosion rate predictions in a watershed. Slope mapping can be affected by the used computational algorithm, DEM resolution, topographic complexity and DEM data quality.

Zhang and Montgomery (1994) found that the percent of a catchment steeper than a given slope systematically decreases as the DEM cell size increases and that this effect is larger for steeper terrain. They concluded that since the slope of a grid cell represents the average slope for the area covered by the cell, an increase in the cell size will decrease the ability of the model to describe the characteristics of the steeper and more dissected topography. Wolock and McCabe (2000) agree in that the smoothing effects are greatest on DEMs with the most amount of terrain information, the ones with short terrain features and steep slopes.

Analyzing six independently created DEMs from 1/10000 contour data (20- to 100-m cell size), Bruneau *et al.* (1995) found that the relative frequency of low slope angles decreased for increasing cell sizes and vice-versa. Observed minimum and maximum elevation values were higher and lower respectively as the cell size increased.

Yu (1997) examined the effect of DEM grid cell size on the land surface representation. He found that the range of slopes increases as the cell size decreased and that the slopes distributions for cell sizes less than 300-ft did not differ from the distribution for 300-ft.

In general, the following relation has been observed between DEM spatial resolution and the computed slope angles (Kienzle, 1996; Gao, 1997; Chang and Tsai, 1991; Molnar, 1997):

(1) Derived slope values decrease with lower grid resolutions. This effect of DEM resolution is more apparent along topographic discontinuities such as valleys, ridges, and minor landforms.

(2) Slope mean and standard deviation decrease with increasing grid cell size.

(3) Coarsening of the DEM resolution causes the disappearance of extremely large gradients and the reduction in gradient range for simple and complex terrain units alike. This effect results in a change in slope distributions with decreased skewness and values aggregated around a lower mean.

DEM spatial resolution also affects the derived channel network. In general, the number of channel links, total channel length, link slope and drainage density decrease with increasing grid size (Garbrecht and Martz, 1994; Thieken, 1999; Wang, 2000). This decrease is the result of:

(1) The inability of a coarse grid to reproduce the channel sinuosity and

(2) The channel and drainage area capturing effect i.e. the DEM grid can no longer resolve the separation between channels or drainage boundaries.

2.3.2. On Simulated Flows

The results of hydrological models are not independent of the DEM grid resolution used in the model formulation. In distributed models, the cell size will have a direct effect on the information content and the accuracy of the simulated output. In general, researchers agree in that the finer cell size gives more accurate results. However, there is no consensus in the selected cell size and the recommended one depends in each study on the used hydrological model, initial conditions and assumptions, magnitude of the rainfall event and watershed and objective of the study.

The cell size effect on the output of the a hydrological model has been most studied for the TOPMODEL framework (Beven and Kirkby, 1979). Quinn (1991), Wolock and Price (1994), Zhang and Montgomery (1994), Bruneau *et al.* (1995) and

Saulnier *et al.* (1997) studied the effect of grid cell size to the computed topographic characteristics, wetness index and outflow.

The topographic index (α / tan β) is an important component of many physically based geomorphic and hydrologic models. It reflects the spatial distribution of soil moisture, surface saturation, and runoff generation processes. The variable α represents the specific catchment area, which is the area upslope from a specified contour segment divided by the length of the contour segment. *Tan* β is the slope gradient. TOPMODEL relies to such topographic index. Due to increased specific catchment area and decreased slope values with increasing cell sizes, the topographic index increases with coarser resolution DEMs (Zahng and Montgomery (1994), Wolock and Price (1994), Bruneau (1995), Saulnier (1997),Wolock and McCabe (2000)). As a consequence, the magnitude of the peak runoff rate and therefore the runoff volume predicted are higher for the coarser resolution. Zahng and Montgomery (1994) found that this change was larger for the case of the watershed with steeper slopes and that the effect of the cell size on computed hydrographs depends on both rainfall intensity and initial base flow. They concluded that "the runoff processes are governed neither by the finest, nor by the coarser resolution" and they suggest that "the most appropriate DEM cell size for topographically driven hydrologic models is somewhat finer than the hillslope scale identifiable in the field". While a 10-m cell size represented a significant improvement over 30-m or coarser cell sizes, finer cell sizes provided relatively little additional resolution.

Yu (1997) examined the effect of DEM grid cell size on the land surface representation and hydrologic simulation using the Basin-Scale Hydrologic Model (BSHM). In this model, an algorithm with unidirectional flow is used in the calculation of the spatial distribution of the runoff travel time and the prediction of simulated hydrographs for different cell sizes. In his study, infiltration along the overland flow path was not considered. Using a digital elevation generator (DEG) in BSHM, Yu produced DEMs of a 555-mi^2 basin with a regular grid ranging from 3600 to 120 feet. He found that the resolution of patterns of calculated runoff travel time improves as the cell size gets smaller but for cell sizes smaller than 300 ft. For cell sizes smaller than 300-ft, the frequency distribution of travel times and peak flows were almost identical. They considered the 600-ft spacing to be efficient in terms of CPU time and the quality of the simulation.

KINEROS (Woolhiser *et al.*, 1990) is a event-based, distributed model that calculates surface runoff and erosion in small agricultural an urban watersheds. Using the KINEROS model, Thieken *et al.* (1999) observed that watershed configurations generated with the same contributing threshold area but from different DEMs produce an increase in runoff volume as well as in peak flow rate for a given storm as cell size increases. The time to peak was observed to decrease as the DEM resolution was increased. They were able to correlate drainage density and areal mean lengths with outflow depth and conclude that both descriptors strongly influence the hydrological modeling results.

Using a spatially-explicit, variable source area hydrology model, Kuo *et al.* (1999) studied the effect of different cell sizes on soil water content and the sensitivity of the model to aggregation of specific types of input data by increasing the grid cell size. Their model works in areas of impermeable sloping sub-soils at shallow depth and includes unsaturated flow. They tested elevation, soil and land use digital models with grid cell sizes ranging from 10- to 600-m. They found that the spatial variability of soil type and land use were not affected by the grid cell size. They also found that while the spatial variability of the slope decreased slightly, the Laplacian (or curvature of the landscape) decreased greatly. This resulted in higher soil water content and higher evaporation rates for large grid cell sizes. The runoff in a wet year was not affected by the grid cell size but for a dry year it was greatest for smallest grid cell size. Kuo *et al.* (1999) and Beven (1995) agree that the aggregation approach using averaged parameter values toward macroscale modeling is inadequate for representing hydrological processes at large scale.

Although CASC2D has been applied to a wide range of grid sizes, Ogden (1997b) has found that grid cell sizes smaller that 200-m produce more robust calibrations. Ogden (1997a) further states that the selection of the grid cell size will depend both on the existing relevant data and the computational effort required. Ogden (1997b) estimates that approximately 250 bytes of memory is required for each grid cell cell, thus decreasing the grid cell size will increase the computational time. At the same time "the higher the resolution, the more accurate the solution will be" (Ogden, 1997b). Grid cell size affects the computational time step in that the later is shorter for finer grid cell sizes. Too long time steps will produce instabilities in the hydrological model and eventually will result in a crash.

Molnár (1997) applied the CASC2D model to two basins in Mississippi of approximately 21 km^2 (Goodwin Creek) and 560 km^2 (Hickahala-Senatobia). The effects of grid cell size were evaluated using grid cell sizes ranging from 127- to 380-m in Goodwin Creek and from 30- to 914-m in Hickahala-Senatobia. Using the nearest neighbor technique, the aggregation process led to an increase in the percentage of channel cells as compared to the total number of cells. Due to the representation of the watershed at larger grid cell sizes, runoff from upland regions reached the channels more rapidly and transmitted more quickly to the outlet. As a result, coarser resolutions resulted in higher runoff rates and shorter times to peak. Molnár found that to compensate for larger grid cell sizes, overland and channel roughness coefficient had to be increased. Molnár concludes that the selected grid cell size should small enough to preserve essential characteristics governing rainfall-runoff processes, but large enough to be used effectively and efficiently.

2.3.3. On Soil Erosion Prediction

Investigation of the effect of the input DEM on the prediction of erosion has been very limited until now. Studies of grid cell size effects the erosion/deposition prediction are almost non-existent and they are limited to the application of the USLE equation. However, the USLE was originally developed to predict long term average annual erosion and thus, it is not designed to predict event erosion well. Kinnell (2000) points out how procedures available to determine the slope length factor for a cell does not enable the impact of variations in upslope runoff on cell erosion to be determined adequately.

Julien and Frenette (1987) performed studies on the Chaudiere basin (5830 km^2) in Canada in order to examine the applicability of the USLE to large areas. They were able to extend the applicability of the USLE to the large watershed by applying a correction factor. This correction factor depended primarily on the average slope gradient. The same method was latter applied by Julien and González del Tanago (1991) in Spain, validating the use of the grid size factor. In both studies, it was concluded that unbiased estimates of soil erosion losses are obtained for grid cell sizes less than about 350 m.

Kienzle (1996) used the RUSLE (Revised USLE) to study the effect of grid ell size on the estimation of soil loss potential. It was determined that the soil loss was very sensitive to slope. Mean annual erosion values increased up to 67% when computed with the 400- and 50-m resolution grids while this increment was much larger (430%) when the maximum erosion rates were compared.

A fourth study is done by Molnár and Julien (1998) relating cell size and erosion prediction using the USLE in two basins (21 km^2 and 304 km^2). In this study, it is concluded that at grid cell sizes exceeding 100-m, a correction factor must be included in the calculations. With the use of this correction factor, the USLE can be applied directly at macroscales.

The effect of grid cell size produced when modeling rainfall-runoff processes are magnified when modeling erosion and sediment production (Rudra *et al.*, 1998; Wainwright and Parsons, 1998). One of the sources of error in the prediction of erosional / depositional processes is the accuracy of the input elevation data. DEM errors impact terrain attributes (such as slopes and slope lengths) that affect the erosion prediction the most. Mitasova *et al.* (1996) demonstrated that the "digitized contours from 1:24000 topographic map along with a reliable interpolation is more suitable for erosion / deposition modeling than the standard 30-m DEM, which has insufficient resolution and several levels of systematic errors and artifacts".

The selection of the grid cell size will also depend on the established objectives and the resources availability to model the watershed system. Using the same mathematical representations of physical processes for runoff and sediment transport, Hong and Mostaghimi (1997) concluded that a 2-D model provides better representation of spatial distribution of flow depths and sediment concentration that the 1-D model. However, the 2-D model provided little improvement when simulating the total runoff volume and sediment yield at the outlet. This fact could make it difficult to justify the additional computational cost and increased number of input parameters required for the 2–D model. It becomes apparent that either the 1-D or 2-D models could be used, based on the specific objectives. When using a 2-D model the same type of philosophy should be applied in the selection of the model resolution.

Holmes *et al.* (2000) suggested that although the global (average) error in a 30-m USGS DEM is small, local error values can be large and even small amounts of elevation errors can greatly affect derivative calculations. In this study, it is shown that errors in a 30-m DEM can lead to predict only half of the area prone to potential debris flow. Holmes *et al.* (2000) and Mitasova *et al.* (2000) agree that the error propagation is most dramatic in valley bottoms (low lands) and along streamlines. Mitasova *et al.* conclude that the computation of net erosion/ deposition as a change in transport capacity is very sensitive to artifacts in the DEM.

Molnár and Julien (1997) used the USLE equation for estimating soil loss at different grid resolutions (from 30-m to 2-km grid cell size). They found that large grid cell sizes tend to underestimate soil losses because of a decrease in the terrain slopes.

They proposed a correction factor to compensate for the underestimation of soil loss when applying the USLE at macroscales.

2.4. SUMMARY

From the literature review we have learned that:

(1) Watershed erosion modeling provides the necessary tool to predict excessive soil loss or deposition and helps in the implementation of an erosion control strategy. CASC2D-SED is a raster, physically-based hydrological and soil erosion model that allows the prediction of the location of erosion source areas. This model predicts erosion rates and deposition on an event basis, taking into account the spatial distribution of the hydrological and erosional model variables.

(2) GIS is an increasingly important tool in environmental models allowing rapid data pre-processing, data input, and analyses and display of results. Applied to the scientific research, geovisualization is a powerful data exploration technique utilizing the ability of the computing technology to analyze and display dynamically large amount of information

(3) In raster models, the grid cell size affects the landscape representation by affecting primarily the terrain slopes and the channel network definition. With increasing grid cell size, hydrological simulations are affected by the lost in information content and accuracy of the simulated output. Process-based erosion models, depending on both landscape representation and hydrological variables, have a magnified dependency on the input data spatial resolution.