AUTOMATED MAPPING OF THE POTENTIAL FOR EPHEMERAL GULLY FORMATION IN AGRICULTURAL WATERSHEDS

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Abstract Erosion due to ephemeral gullies in cultivated areas contributes significantly to soil loss and sediment yield from arable watersheds. Despite this, no readily applied, automated method for mapping the potential for ephemeral gullies to form currently exists. This presentation outlines how the capability to perform these tasks within a GIS environment adds value to the utility of catchment erosion and sediment yield models, and demonstrates how the potential for ephemeral gully locations may be mapped within the USDA-ARS's AnnAGNPS model, to support prediction of the impacts of ephemeral gully initiation and subsequent growth.

The approach adopted builds on the results of long-term research performed at the USDA-ARS National Sedimentation Laboratory that began in the 1980s and which used the manual, field-based calculation of a Compound Topographic Index (CTI) as a predictor of ephemeral gullying potential. More recently, joint research between the NSL and Nottingham University has examined the ability of a GIS-based version of the original CTI to correctly predict the locations of ephemeral gullies based gridded altitude data obtained by remote sensing. The new technique has been tested at the field scale through direct comparison with ephemeral gullies observed at a number of experimental monitoring sites.

The results of the study demonstrate that the technique developed works effectively where gridded altitude data are available, and with the current rate of increase in the availability of such data the method should become nationally applicable it in the near future. On this basis, the alogorithms necessary to support prediction of potential sites for ephemeral gully formation have been programmed in to the latest version of the AnnAGNPS software.

INTRODUCTION

Soil loss from arable fields is a serious problem to agricultural producers and action agencies concerned with erosion control and maintenance of the productivity of the land (Thorne et al., 1984). Soil erosion in agricultural fields from water runoff occurs predominantly by three processes: sheet erosion, rill erosion, and ephemeral gullying (Smith, 1993). A sound understanding and quantification of these processes is a vital prerequisite for developing methods to minimize the damages associated with soil erosion (Zevenbergen, 1989). This study focuses on the latter of these three processes since despite the threat that ephemeral gully development poses to agricultural productivity, and the serious downstream sediment problems that they can cause in the watershed, the contribution of ephemeral gully erosion is frequently overlooked in many soil erosion estimates (Vandaele et al., 1996). An evaluation of the effect of agricultural conservation practices on watershed sediment loads should include the contribution from ephemeral gully erosion.

Zevenbergen (1989) describes five factors as influencing ephemeral gully formation including:

1. Overland flow discharge and duration, without which ephemeral gullies could not exist;
2. Slope and flow depth, which determine the magnitude of the flow's downslope component of weight and, therefore, the boundary shear stress exerted by the flowing water on the soil;
3. Planform curvature, which determines the local flow convergence and, therefore, the concentration of stress along a flow path or swale;
4. Soil characteristics, which affect both overland flow rates (through controlling infiltration capacity) and determine the erodibility of the soil;
5. Vegetation characteristics, which affect overland flow rates through interception and flow resistance and provide cover for the soil, reducing its susceptibility to erosion.

Recent work on the controlling influences of gully development has identified enlargement of pipes through subsurface flow as a critically important soil erosion process which can be responsible for exceptionally high soil losses (Faulkner, 2006). While this study is aware of this process it is beyond the scope of the technique developed here which aims to focus solely on topographic controls of overland flow important in influencing ephemeral gully development.
In terms of topographic influence Thorne et al. (1984: 2) identified that "the formation of an ephemeral gully depends on the generation of concentrated surface runoff of sufficient magnitude and duration to initiate and maintain erosion, leading to channelisation". From this, the first three of the above factors listed by Zevenbergen: discharge, slope and planform curvature, are key topographic controls in the formation process.

The importance of these three factors can be theoretically considered using stream power, a parameter commonly used to represent flow intensity and predict sediment carrying capacity (Bagnold, 1966; Yang, 1977). The concentration of surface runoff described by Thorne et al. (1984) can be physically represented by specific stream power, which is a function of discharge, slope and width. Drainage area is often used in geomorphic analysis as a surrogate for discharge and, consequently, drainage area multiplied by slope gives a parameter acting as a proxy for total stream power. This line of argument justifies the inclusion of both slope and drainage area (as an acceptable surrogate for discharge) in a technique responsible for predicting the formation of ephemeral gullies.

The third topographic factor, planform curvature, or convergence, contributes to ephemeral gully formation in multiple ways. Firstly, without convergence runoff volume and discharge are linearly proportional to slope length, while with convergence these values are related to slope length to a power greater than unity (Zevenbergen, 1989). Secondly, at any point along a swale in the downstream direction the degree of planform curvature determines local flow geometry, including the degree of flow concentration. This means that the level of convergence in the land surface is important in controlling the initial flow path geometry, and therefore, the initial channel location. In other terms, whilst the product of slope and discharge may adequately represent total stream power, planform curvature is necessary to represent the degree of concentration of this stream power and so enables it to become a representation of specific stream power, the key component of Bagnold's sediment transport theory.

Zevenbergen and Thorne (1987) developed a methodology for calculating slope, aspect, planform curvature and upstream drainage area for each point within an elevation grid matrix.

Thorne et al. (1986) used these parameters to calculate a Compound Topographic Index (CTI) for each grid cell within that matrix, which is used to identify potential locations for ephemeral gullies based on land topography. The CTI is defined by:

$$CTI = A \cdot S \cdot PLANC \tag{1}$$

where: A = upstream drainage area (L2) and provides a surrogate for runoff discharge since the two are generally strongly positively correlated; S = local slope (L/L), which together with upstream area provides an indication of the stream power per unit downstream distance of the runoff; and PLANC = planform curvature (1/L), a measure of the landscape convergence (negative for spurs and positive for swales) indicating the degree of concentration of the runoff and so allowing the CTI (L) to represent specific streampower (streampower per unit bed area). As a result, the CTI represents the major parameters controlling the pattern and intensity of concentrated surface runoff in the field.

This study aims to take the work carried out by Zevenbergen and Thorne during the 1980s forward, utilising the contemporary advancements of Geographical Information Science (GIS) to automate the derivation of the CTI parameter from Digital Elevation Models (DEMs). This paper describes the development and initial testing of the GIS based CTI process as well as considerations for the impact that DEM resolution and source can have over the process's results.

DEVELOPMENT OF THE CTI METHODOLOGY

The USDA Agricultural Non-Point Source (AGNPS) modelling system (Bingner and Theurer, 2001a) includes components necessary to determine the impact of watershed conservation practices on ephemeral gully erosion, but requires the identification of potential ephemeral gully locations throughout a watershed. The CTI methodology provides the information used within AGNPS, in simulating ephemeral gully erosion, through a more automated process then through the use of on-site visual determinations for ephemeral gully locations. To develop a means of generating the original CTI as defined by Equation 1 it was first necessary to find ways of generating the three components of the CTI (slope, upstream area and planform curvature) from a DEM. To produce the first two of these parameters, selected modules from the TOPAZ (TOpographic PAramateriZation) landscape analysis tool (Martz and Garbrecht, 1998) were used within an AGNPS / ArcView 3.55 interface (Bingner et al., 1997). These modules produced output grids of the required parameters 'terrain slope' and 'upstream area' based on the user-defined DEM. The final parameter, planform curvature, was obtained by means of the 'DEMAT' (Digital Elevation Model Analysis Tool) an extension to the ArcView 3.3 interface written by Thorsten Behrens (http://arcscripts.esri.com/details.asp?dbid=10222).

The steps necessary to generate the compound topographic index from a digital elevation model are summarized in Figure 1.

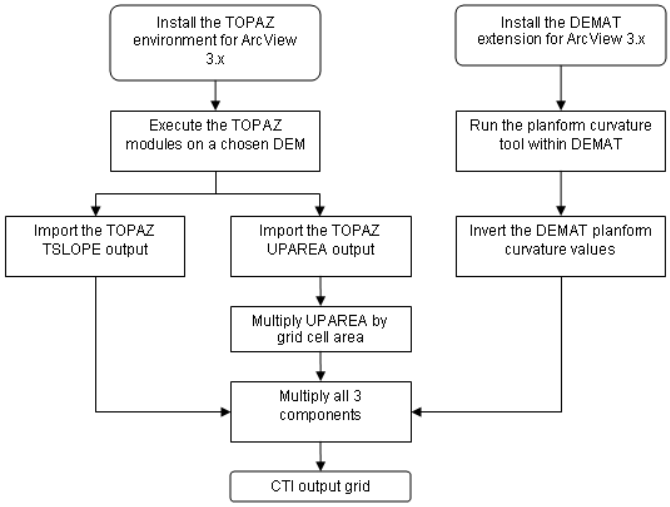
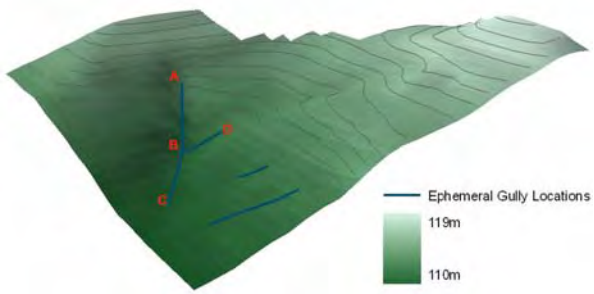


Figure 1 Flow diagram representing the steps necessary to generate the Compound Topographic Index from a Digital Elevation Model.

Testing the GIS-based CTI procedure Once an agreed methodology for generating the CTI had been determined, preliminary testing was performed through application to the field site used in Zevenbergen's original work on Ellis Farm Site A, Panola County, Mississippi (Figure 2).

a)



b)

Figure 2 Visualization of Ellis Farm Site A. a) Elevation grid and ephemeral gully locations measured by Zevenbergen (1989) [NE orientation]; b) Aerial site photo [SW orientation].

Figure 3 displays the values of the compound topographic index calculated for the Ellis Farm field site using the procedure outlined above compared with the CTI predictions originally reported in Zevenbergen's (1989) thesis. These results demonstrate that the new, automated methodology performed within a GIS environment and based on a DEM successfully recreates the results that were originally generated using field measurements and manual calculations. Of particular note in Figure 3 is that, in addition to the new methodology replicating the general location of gully sites predicted by Zevenbergen's method, the new GIS-based methodology also indicates similar breaks in gully lines to those predicted by Zevenbergen. These breaks in predicted gully locations are linked to areas of reduced flow convergence in the landform topography, the importance of which is investigated below.

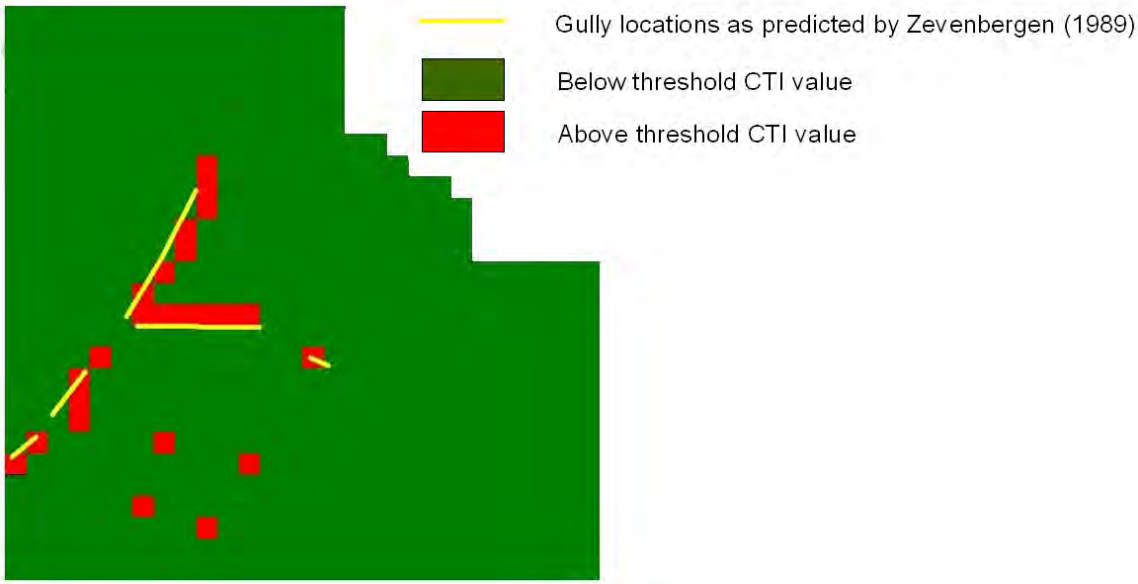


Figure 3 Results of GIS-based CTI process on Ellis Farm Site A compared with original predictions provided by Zevenbergen.

In order to test the significance of the inclusion of planform curvature [the parameter unique to Thorne and Zevenbergen's (1984) ephemeral gully predictor], the ability of the CTI to predict gully location was assessed against an alternative predictor composed of just upstream area and slope.

Figure 4 illustrates the results of this assessment, with the predicted patterns of potential gully locations seemingly similar for both predictors. This is due to a combination of the strong influence of slope and upstream area over both predictors and the strong positive correlation that occurs between upstream area and planform curvature.

Upon closer examination of the results important differences can be observed. Figure 4 shows a decrease in the cross-sectional area of the observed gullies at point X. The value of the index without planform curvature included does not fall in this area but the value of the CTI parameter does fall. The cause of this difference is a drop in planform curvature around point X caused by a decrease in swale concavity that is responsible for a reduction in flow concentration and therefore reduced gully erosion. A similar effect can be seen in Figure 5 that demonstrates how the index without planform curvature included overextends its prediction of the location of the ephemeral gully compared with the CTI. The planform curvature values drop significantly at the

end of the gully location, demonstrating the importance of planform curvature in influencing the presence of ephemeral gullies. Therefore the CTI is able to differentiate more clearly the limits of ephemeral gully locations than other indices that do not include the influence of planform curvature. Further examples of this phenomenon were observed at both this and other field sites. The absence of planform curvature in the alternative predictor means that it both predicts gullies where there are none, and fails to predict gullies where they are present because it fails to pick up the converging influence of high planform curvature. On the other hand the CTI, because of the inclusion of planform curvature, is able to pick up the location of gullies whilst managing to recognise that gullies are not present in other areas despite upstream area and slope values being high.

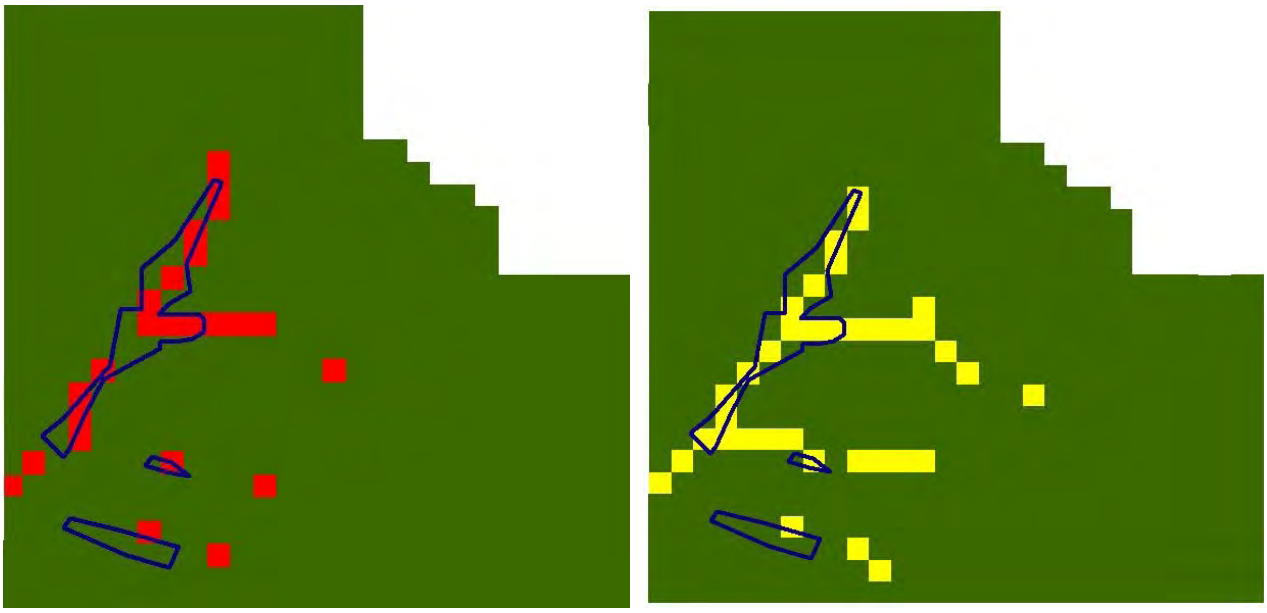


Figure 4 Results of a) the GIS-based CTI process (left) on the Ellis Farm site compared with b) an index composed of solely drainage area and slope (right). The highlighted cells represent index values above the threshold for this site. The polyline is a representation of the cross-sectional area of the gullies.

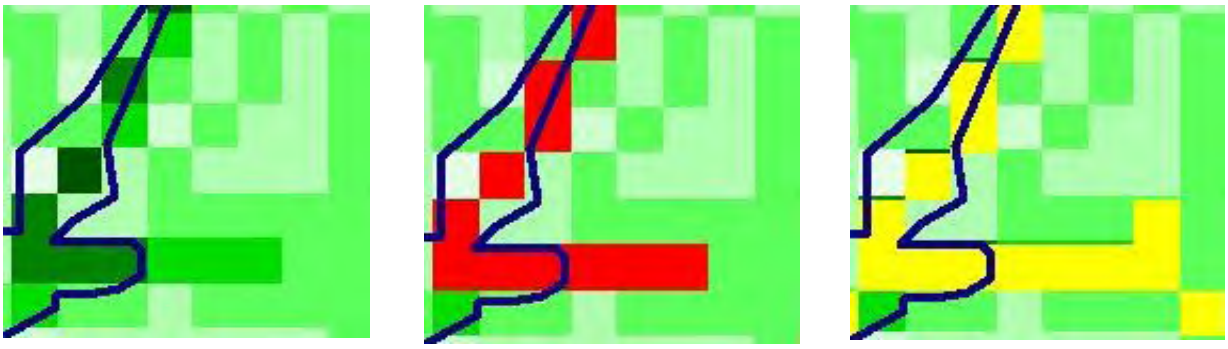


Figure 5 Close examination of the differences between the results of the CTI index (centre) and the alternative upstream area and slope index (right) for the Ellis Farm site. The far left image represents planform curvature values (with darker cells having a higher / more concave curvature). The blue polyline represents the cross-sectional area of gullies present.

Finding a threshold CTI value While the Compound Topographic Index offers the opportunity to define the topographic controls on the location and extent of ephemeral gullies, the likelihood of an ephemeral gully actually forming at a given location is not dependent on topography alone. The susceptibility of the soil to erosion, which is controlled by soil type, underlying geology, organic matter, tillage, crop type and stage and conservation practice, also markedly controls the probability of channel initiation and enlargement. However, no theoretical basis exists for predicting the susceptibility of the surface of a particular field to gully erosion, and so a pragmatic approach was adopted by Thorne and Zevenbergen (1990), based on empirical derivation of a critical or threshold CTI value for ephemeral gully formation unique to a particular region / soil / management / crop combination. This critical value represents the intensity of concentrated overland flow necessary to initiate erosion and channelised flow under a given set of circumstances. Portions of swales where the CTI values fall below the critical CTI values would not be expected to contain ephemeral gullies, while gullies would be expected in those areas with CTIs higher than the critical value.

Since critical CTI values cannot currently be calculated reliably from basic principles, Thorne and Zevenbergen (1990) instead calibrated them for each study site, using measurements of CTI at locations with conditions known to be critical to gully formation – that is around gully heads where erosion is initiated. An approach based on vernacular knowledge of the sites in question was adopted, with consultations with local agricultural producers used to locate points at which gully heads formed in an average year. Thorne and Zevenbergen then calculated the CTI for these points with the averaged values across a number of gullyheads considered to provide a robust estimate of the critical CTI value for the site in question.

Due to the inefficiency of performing Thorne and Zevenbergen's approach at a broad scale an alternative means of attaining critical CTI values is necessary for use within an automated framework. In order to use a threshold value for the Compound Topographic Index successfully in an automated methodology it is necessary to have a selection of critical CTI values for a range of certain land use/climate/soil type conditions. However, to do so requires the determination of threshold CTI values for a large number of sites of different land use/soil/climate conditions to base these condition-specific critical CTI values on. Whilst Thorne et al. (1986) describe how critical CTI values have already been found for a large number of sites in Mississippi with the purpose of building a database of critical values, unfortunately this collection of data is no longer available and, therefore, it is necessary to compile new critical threshold data.

Due to the difference in format between the CTI grid produced by this new GIS based CTI and the output of Thorne and Zevenbergen's (1984) methodology an alternative means of finding a site's critical CTI value was required. The chosen procedure involves iteratively adjusting the threshold until a value is found that best represents the location of gullies.

The results of this procedure for the Ellis Farm field site are illustrated in Figure 6. This figure demonstrates how, as the threshold CTI value is increased, the areas predicted to be potential ephemeral gully sites reduce in size. After iterating, a threshold value was found for which those areas predicted to be potential gully sites (in red) best matched the actual known gully locations (in blue). In the case of the Ellis Farm site in Figure 7 this critical CTI value was found to be 75.

Interestingly this value is very similar to the value found by Zevenbergen (1989) in his thesis of 76, despite his usage of a completely different methodology.

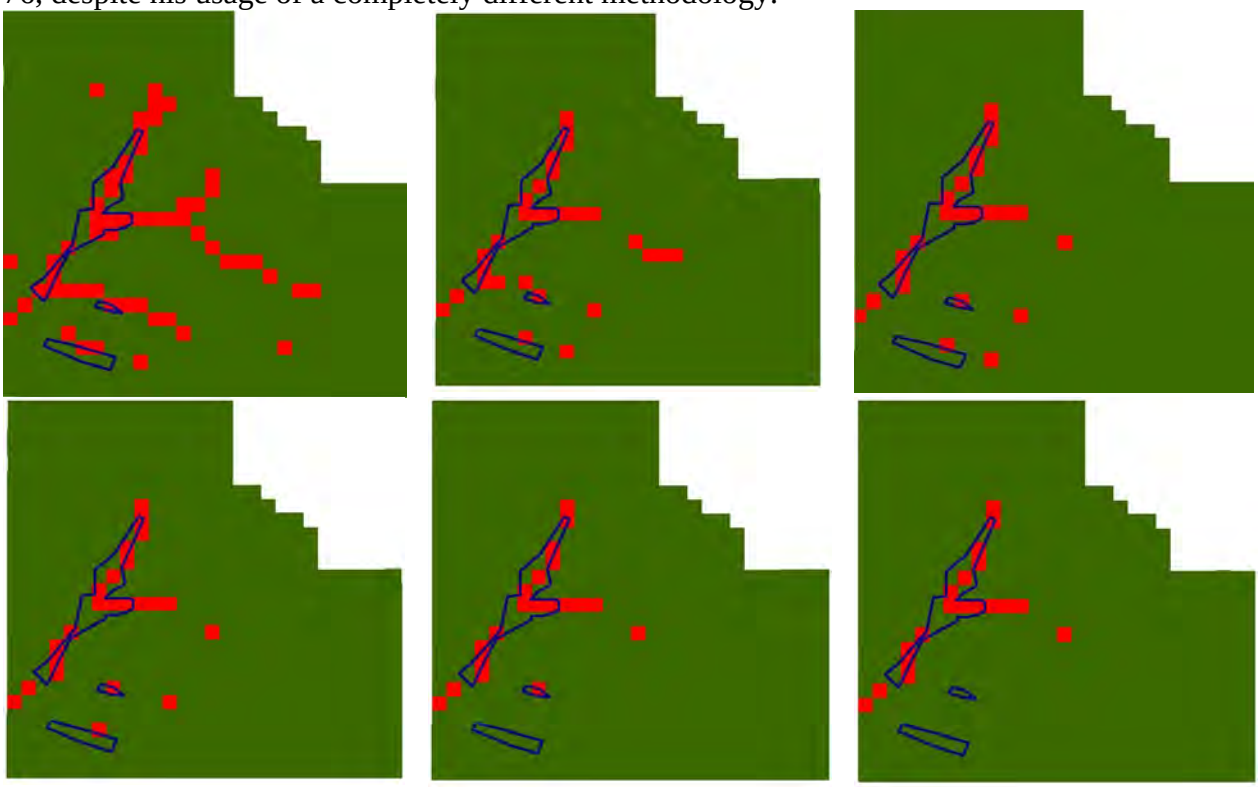


Figure 6 Highlighted cells display CTI values above a range of different thresholds compared against known gully locations on Ellis Farm Site A. Threshold values applied are a) 10, b) 50, c) 62, d) 75, e) 87, f) 100.

This technique was repeated for a number of field study sites for which elevation data and ephemeral gully locations were available. The results displayed in Table 1 highlight a wide range of critical CTI values from 5 to 75, supporting the finding of Thorne and Zevenbergen (1990) that factors other than topography play a significant role in ephemeral gully initiation. Unfortunately, due to a limited number of sites and limited information regarding the characteristics of the field sites, this study has been unable to derive a relationship between these critical values and site character. This is likely due to the influence of factors aside from soil type and land use impacting the threshold value for the study sites. For example climate, conservation practices and land management are all thought to have important influence (Thorne et al., 1986), and recent developments in research into subsurface flows has highlighted piping as a critically important origin of gully development (Faulkner, 2006). Nevertheless, whilst not a complete database in itself the data collected in this study provides a starting point for further work on determining critical CTI values for different site types by presenting an idea of the kind of critical CTI values to expect.

Table 1 Critical CTI vales found for each of the sites in the study with any information on crop and soil type available.

Site	*Land Use*	*Soil Type*	*Critical CTI value*
1. Melton Farm	-	Alligator–Sharkey - Dundee	36
2. Ellis Farm Site A	Broadcast Soybeans	Loring	75
3. Ellis Farm Site B	Corn	Loring	32
4. Flannigan	Milo	Loring	35
5. Henson	Corn	Loring	12
6. New Hampshire Site	-	-	9
7. Herbert Downey A	Soybeans	Memphis	8
8. Herbert Downey B	Soybeans	Memphis	7

An automated method of determining CTI values throughout a watershed system can provide information on where potential ephemeral gullies may occur, but the critical CTI value is necessary to define the downstream mouth of the ephemeral gully for use in the Annualized AGNPS (AnnAGNPS) watershed model (Bingner and Theurer, 2001b). The application of AnnAGNPS on a watershed system provides a mechanism to determine if a potential ephemeral gully would turn into an actual ephemeral gully, through the combination of climate, soil properties, land management, and the resulting runoff through the landscape. Action agencies can then apply this technology at a watershed scale in determining the long-term effects of conservation practices on erosion.

THE IMPORTANCE OF DEM SPATIAL RESOLUTION

An important consideration when performing topographic analysis on raster digital elevation models is the impact of the grid data quality on the resulting parameters (Holmes et al., 2000). An investigation into how the GIS-based CTI methodology developed within this study was impacted on by the elevation grid used was performed.

Evaluating the impact of DEM resolution While the authors recognise that numerous types of DEM resolution are important in terrain analysis, including temporal, vertical and horizontal, it is felt that it is of most interest to the purposes of this study to consider the impact of horizontal spatial resolution in isolation. Whilst an elevation grid's horizontal spatial resolution can be too low, resulting in the exclusion of significant slopes and land features, the resolution can also be too high, since micro-relief and elevation measurement errors can become more significant than is appropriate for a given purpose (Gerrard and Robinson, 1971). In order to investigate how either of these error forms may cause an elevation grid's resolution to impact on the predictive ability of the CTI, a number of grids with resolutions ranging from 1m to 20m were interpolated from the same contour map of a field site in New Hampshire. The CTI process [as described in Figure 1] was performed on each of these elevation grids to assess how the performance of the

CTI responded to changes in the resolution. Examination of the resultant output grids [Figure 7] reveals that the predictive ability of the CTI gradually degrades as horizontal spatial resolution lowers and becomes extremely poor at a grid size of approximately 10m. This provides a graphical demonstration of the principle of truncation error as described by Zevenbergen (1989).

In an analysis of the effect of elevation grid resolution on terrain attributes, Thompson et al. (2001) found that decreasing the horizontal spatial resolution of an elevation grid produced lower slope gradients on steeper slopes, steeper slope gradients on flatter slopes and narrower ranges in curvatures. A similar outcome was identified within this study with the result that, at lower resolutions, the topographic features responsible for forming the ephemeral gullies were not properly represented and therefore the CTI analysis did not identify gullied areas correctly.

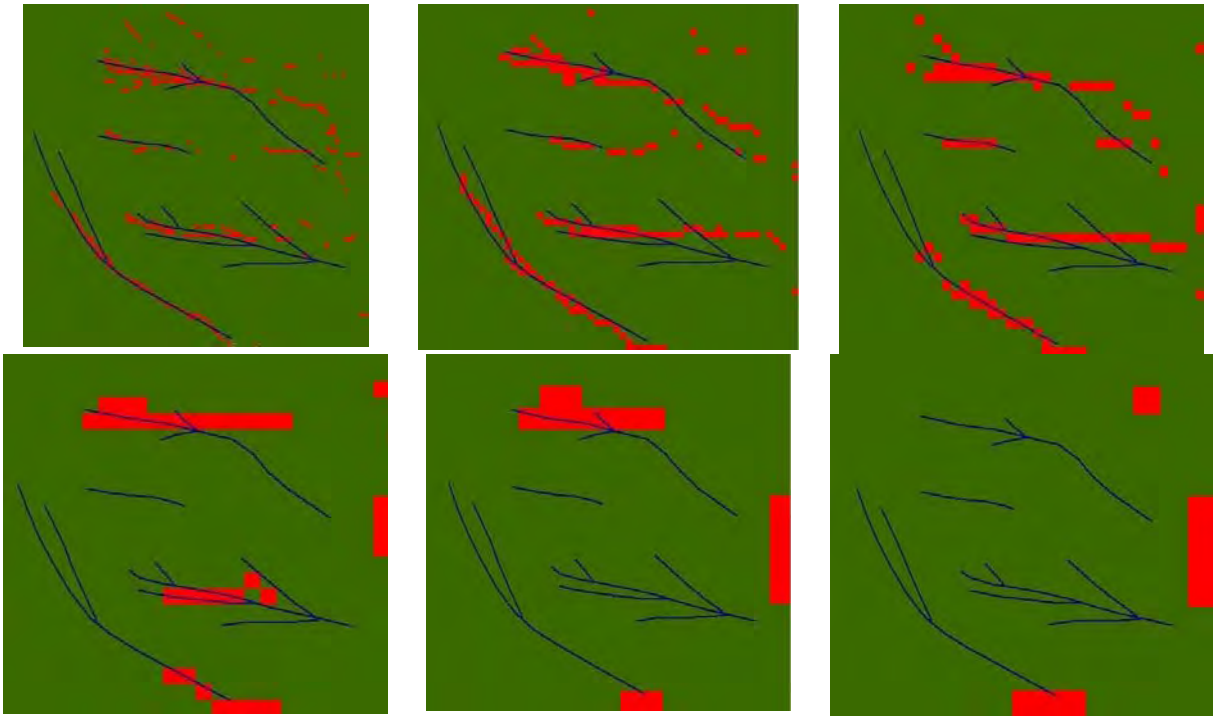


Figure 7 CTI values above 10 (highlighted) compared against known gully locations (polylines) for a selection of the various elevation grids used to investigate the impact of resolution on CTI output for the New Hampshire field site. Elevation grids displayed at resolutions of: a) 2m, b) 4m, c) 6m, d) 10m, e) 14m, f) 18m.

Thompson et al. (2001) describe how the accuracy of digital elevation models depends not only on their resolution, but also on the source of the elevation data. The results of the latter part of this study have exemplified this with regards to the usage of elevation grids in predicting the location of ephemeral gully locations.

CONCLUSIONS

A methodology to apply Thorne and Zevenbergen's (1990) CTI technique within a GIS environment, has been achieved. This is an important step as it demonstrates the potential for incorporating the CTI approach into digital terrain analysis tools such as TOPAZ, which would

allow rapid identification of potential locations for ephemeral gully channels. Further, because of the automatic and rapid nature of the technique, and its GIS-based nature, it has the potential to be expanded to the catchment scale and incorporated into models like AGNPS, which currently lack the ability to automatically locate potential ephemeral gullies and instead rely on manual inputs.

As well as showing that the GIS-based technique successfully replicates the results of Zevenbergen (1989) the analysis also re-iterates the accuracy with which the Compound Topographic Index can locate potential ephemeral gully locations, and demonstrates the importance of including planform curvature in such an indicator. Whilst upstream area and planform convergence may not be independent of each other, the CTI is not an empirical regression fit and so its validity does not depend on independence of the input variables. In fact, the CTI is a rational equation that predicts the potential for ephemeral gullying on the basis of local values of specific stream power. As such, inclusion of planform curvature is important in representing specific rather than total stream power by indicating the degree of convergence as demonstrated in the above analysis.

A need to define the threshold CTI value at which ephemeral gully initiation occurs led to the development of an iterative procedure to define this threshold value for a number of sites. This critical CTI value is necessary for each site to define the downstream mouth of the ephemeral gully for use in the AnnAGNPS watershed model. Further development of this process should assist in the extension of the CTI methodology to applications at the catchment scale.

The results of the latter part of the paper have clearly demonstrated that as well as the elevation grid resolution having a clear influence over the CTI predictor's performance. The original source of that data is also in important influence. Unfortunately the datasets that are currently the most widely available across large geographic areas, the USGS 10 and 30m DEMs are those that result in poor performances from the CTI predictor. This demonstrates a need for more widespread availability of accurate elevation data before the CTI technique can be applied effectively at the catchment scale, whether this improved data is from LiDAR or some another source.

In closing, this study has shown how the CTI technique works effectively where accurate data sources are available and, with the current rate of increased data availability, there will be a key role for it in the near future. With these developments the CTI technique described in this paper can then help in the understanding and quantification of ephemeral gullying, and thus assist in the conservation of agricultural resources.

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