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AUTOMATED MAPPING OF POTENTIAL FOR EPHEMERAL GULLY FORMATION IN AGRICULTURAL WATERSHEDS

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Abstract

Erosion associated with ephemeral gullies in cultivated areas is known to contribute significantly to soil loss and sediment yield from arable watersheds. Despite this, no automated method currently exists for mapping the potential for ephemeral gully formation. This study identifies that the capability to perform these tasks within a GIS environment would be useful, and explores how such a methodology might be developed.

The approach adopted builds on the results of research previously performed at the USDA-ARS National Sedimentation Laboratory, which developed a Compound Topographic Index (CTI) to predict soil loss due to ephemeral gullying at the field level. In this study, the potential for a GIS-based version of the CTI to reliably predict the locations and extents of ephemeral gullies has been investigated using data from a number of field sites. At this field level it was possible to compare the predicted and the observed actual locations and extents of ephemeral gullies. The requirements for scaling up the automated technique to the watershed level were also explored.

The results of the study show that the automated CTI technique works reliably provided that topographic data of sufficient resolution and accuracy are available. While the limited availability of high resolution topographic data currently limits application of the CTI method to research sites, given the increasing level of data availability the CTI method should become practically applicable to erosion assessments at the field scale in the near future. However, investigation of the impacts of digital elevation model resolution, data source and data errors on the technique's results, and a consideration of the resolution and accuracy of readily available elevation data in the United States suggest that the widespread application of this method to predict ephemeral gullying at the watershed scale is currently unfeasible.

INTRODUCTION

Erosion due to ephemeral gullies in cultivated areas is known to contribute significantly to soil loss and, where ephemeral gullies are connected to the perennial drainage network, sediment yield from arable watersheds. Despite this, no automated method yet exists for mapping the potential for ephemeral gullies to form, or for locating the likely start points or mouths of ephemeral gully channels. The capability to perform these tasks within a GIS environment, using the power of GIS to perform spatial analysis, would be beneficial and would add value to the utility of watershed models such as the USDA-ARS AnnAGNPS.

Recognising this, the USDA-ARS National Sedimentation Laboratory and the University of Nottingham are developing preliminary research necessary to evaluate the use of GIS-based topographic analysis as a means of mapping ephemeral gully potential. The results of this research are reported herein.

This study builds on the results of earlier research performed at the USDA-ARS National Sedimentation Laboratory in the 1980s, which developed a method for calculating a Compound Topographic Index (CTI) as a predictor of ephemeral gully location, extent and soil loss. Future ephemeral gully modelling efforts by the USDA-ARS require the location of ephemeral gully start point to be known; therefore this study looks at the ability of the CTI to correctly predict the locations of ephemeral gullies. The capability for the CTI to predict the location of ephemeral gullies has been verified at the field scale through direct comparison with ephemeral gullies observed at a number of sites. However, the potential for the method to be fully and completely automated in a GIS environment remains to be explored, and will require the successful development of threshold CTI values and will also require topographic data of sufficient resolution and accuracy. Until this exploration is complete and the required information is available the expansion of the CTI analysis to the watershed scale will remain untested.

REVIEW OF LITERATURE RELATING TO EPHEMERAL GULLIES

The importance of soil erosion in agricultural land management.

Soil erosion is a major problem facing the world (Smith, 1993). As the principal resource base for the production of food, soil is a limited resource which has been severely depleted in many areas of the globe. Soil loss from agricultural land produces adverse impacts both on and off the site of erosion (Zevenbergen, 1989). In the source zone, removal of fertile topsoil reduces crop yields and can ultimately make crop production uneconomical or physically impossible while sediment that is deposited on a field can bury seedlings and impede drainage. Excessive sediment supplied to streams by field erosion is deposited further downstream in the fluvial system, increasing flood risk, decreasing navigability, reducing reservoir storage capacity, adversely affecting aquatic and wetland habitats and reducing water quality.

Soil loss from arable fields is a serious problem not only to farmers, but also to action agencies concerned with erosion control and maintenance of the productivity of the land (Thorne *et al.,* 1984). The United States Department of Agriculture (USDA) is charged with the responsibility of studying soil erosion and conserving agricultural resources in the United States. Improved land management should result from a thorough understanding of erosion processes, which will provide insights into methods to limit erosion and help to protect land as a resource (Zevenbergen, 1989).

To assess the damage caused by soil erosion, both at the site and downstream, the processes by which soil is detached, transported and deposited must be quantitatively described. These processes are controlled by climate, topography, soils, vegetation, and land management. A sound understanding and quantification of the processes responsible is a vital prerequisite for developing methods to minimize the damages associated with soil erosion (Zevenbergen, 1989). Soil erosion from water runoff in croplands occurs predominantly by three processes: sheet erosion, rill erosion, and ephemeral gullying (Smith, 1993). This study focuses on the latter of these processes.

Ephemeral gullies are larger than rills but are (usually) smaller than permanent gullies (Vandaele *et al.,* 1996), but the major distinction is that cultivation can periodically remove ephemeral gullies, thus providing the transient component. The most important differences between these channel forms are given in Table 1. They are all important contributors to the sediment yield from a field or small basin, as demonstrated by volumetric measurements of rill and ephemeral gully erosion in cultivated catchments carried out by Auzet *et al*. (1993) in northern France, and Vandaele (1993) and Vandaele and Poesen (1995) in central Belgium. Consequently, development of ephemeral gullies can cause a real threat to farm productivity and generate serious sediment problems lower in the watershed. Despite this, the contribution of ephemeral gully erosion is frequently overlooked in many soil erosion estimates (Vandaele *et al.,* 1996).

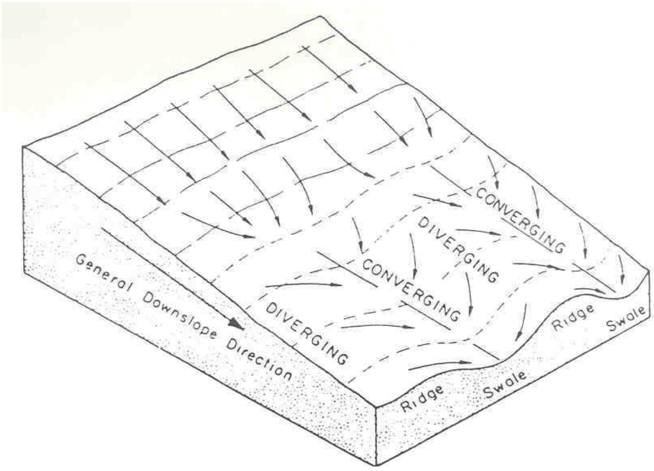
Table 1: Characteristics of different types of cropland erosion processes. After Laflen *et al.* (1985).

Sheet and rill erosion	*Ephemeral gully erosion*	*Gully erosion*
Occurs on smooth side slopes above concentrated flow paths.	Occurs along shallow concentrated flow paths upstream from incised channels or gullies.	Generally occur in well defined concentrated flow paths.
May be of any size but are usually smaller than concentrated flow channels.	Usually larger than rills and smaller than permanent gullies. Agricultural equipment is able to travel across these.	Usually larger than concentrated flow channels and rills. Agricultural equipment is not able to travel across these.
Flow pattern develops many small disconnected channels which end at concentrated flow channels, terrace channels or in depositional areas	Usually forms a dendritic pattern along water courses beginning where overland flow, including rills, converges. Flow patterns influenced by tillage, rows, terraces and other man made features.	Dendritic pattern along natural water courses. May occur in non-dendritic patterns in road ditches, terrace or diversion channels, etc.
Rill cross-sections are usually narrow relative to depth.	Cross-sections are usually wide relative to depth. Sidewalls not well defined.	Cross-sections usually narrow relative to depth. Sidewalls are steep. Headcut prominent. Eroding channel advances upstream.
Rills normally removed by tillage and usually do not reoccur in the same place.	Temporary feature, usually removed by tillage but reoccur in the same place.	Not removed by tillage.
Soil removed in thin layers or shallow channels. Soil profile becomes thinner over entire slope.	Soil removed along narrow flow path to the tillage depth if untilled layer is resistant to erosion.	Soil may erode to the depth of the soil profile and can erode into soft bedrock.
Low erosion rates not readily visible.	Area may or may not be visibly eroding.	Erosion readily visible.
Detachment and transport by raindrops and shallow flow.	Detachment and transport by concentrated flow only.	Detachment by flowing water, slumping of unstable banks and head cut retreat. Transport by flowing water.

The fundamentals of ephemeral gully formation.

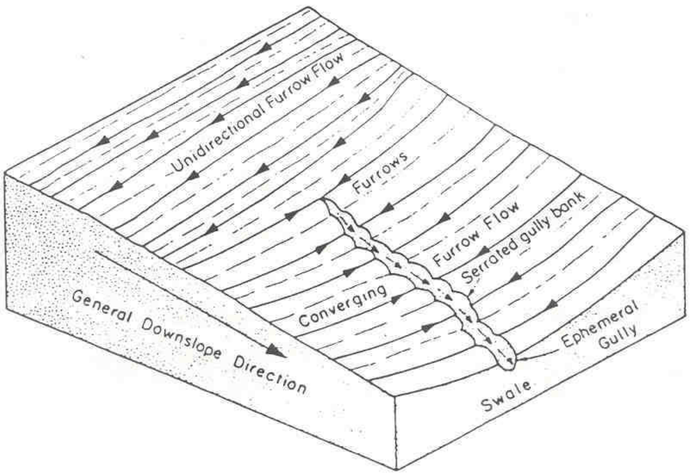
Ephemeral gullies are defined as small drainage channels which, if not filled in, would become permanent features of the drainage network (Smith, 1993). These features form in swales (washes), where concentrated runoff is sufficiently erosive to scour a channel. Precipitation events of great intensity and/or long duration can generate runoff over an entire field through Hortonian overland flow. This runoff then concentrates in swales by flow convergence from adjacent spurs [Figure 1].

Figure 1: The topographic control of surface runoff which produces concentrated flow in swales (from Thorne *et al.,* 1984).



In plowed fields, the ridge and furrow pattern is often oriented perpendicular to the main slope so overland flow in furrows generally converges at the low point in a swale, leading to overtopping into the next furrow down-slope, which also overtops producing a cascade of concentrated surface runoff down the swale [Figure 2]. The downstream headcut would then move upstream.

Figure 2: Converging furrow flow in a plowed field producing concentrated flow and an ephemeral gully (from Thorne *et al.,* 1984).



During storms of lower intensity or shorter duration, when rainfall is insufficient to produce Hortonian overland flow, surface runoff may still be generated in swales by saturation overland flow and/or saturation return flow, because levels of soil saturation are much greater in swales than they are on adjacent spurs. Consequently, the frequency of surface runoff is greater in swales than on spurs, so that overland flow is concentrated there in time as well as space (Thorne *et al.,* 1986).

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.

In terms of topographic influence, "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 channelization" (Thorne *et al.*, 1984). It follows that, the first three of the above five factors: discharge, slope and planform curvature, are key topographic controls in the formation process.

The importance of those three factors can be theoretically considered using stream power, the most general and successful parameter of flow intensity used to 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 which can be used to represent total stream power. This justifies the importance of both slope and discharge (or upstream area as an acceptable surrogate) in 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 equilibrium 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 (Zevenbergen, 1989). 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.

It is important to consider that, whilst the influence of topographic curvature is important for initial gully development, its importance has a transitory nature, since once an ephemeral gully is formed the gully's shape exerts its own control on flow concentration (Zevenbergen, 1989).

Aside from the physical explanation for their initial formation, a further reason why planform curvature can be significant in predicting the location of ephemeral gullies is that whilst ephemeral gully channels are obliterated periodically through the mechanical erosion of tillage, the swale responsible for the gully formation changes through time due to increased curvature over time – owing to side-slope material being used to fill the gully (Zevenbergen, 1989).

Past approaches to predicting ephemeral gully location and erosion.

The most widely employed procedure for predicting soil erosion on croplands has, historically, been the Universal Soil Loss Equation (USLE). The USLE was developed in order to estimate erosion on upland slopes above areas of deposition or defined channels (Zevenbergen, 1989). It takes the form:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

Where, R = rainfall erosivity factor, K = soil erodibility factor, L = slope length factor, S = slope steepness factor, C = cropping-management factor and P = erosion control factor. Whilst this equation can represent sheet and rill erosion, it cannot be expected to also account for concentrated flow erosion from ephemeral gullies (Zevenbergen, 1989). Smith (1993) concluded that this was the reason why the total amount of soil loss predicted by the USLE often significantly underestimates actual soil loss in fields affected by ephemeral gullying.

In fact, few soil loss prediction equations include the soil loss due to ephemeral gully erosion (Beasly *et al*., 1980; Borah, 1989; Bingner *et al*., 1989). Failure to include ephemeral gullies in the equations and models can lead to significant underestimates of the severity of soil loss. Further, it is important to understand ephemeral gully erosion and its relationship to other erosion and sediment transport processes in order to develop appropriate soil conservation solutions to erosion problems. Without this understanding, selection of effective conservation systems for the control of the appropriate erosion process is difficult. For instance, based on research using solely the USLE erosion prediction, conservation measures may address sheet and rill erosion concerns but not the issues associated with ephemeral gully erosion (Woodward, 1999).

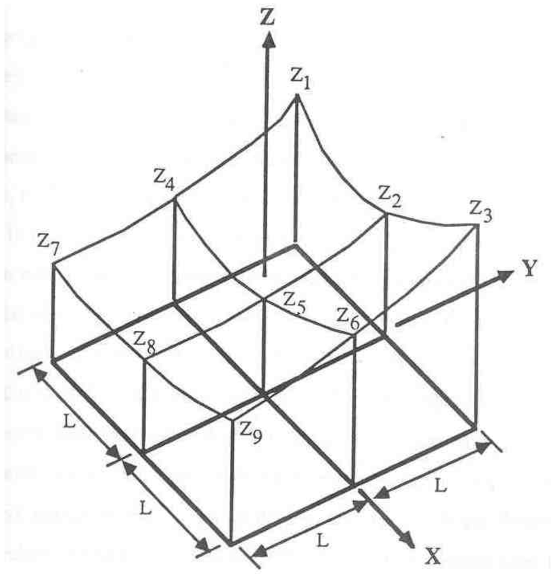
In studies of the formation of discontinuous classical gullies, Patton and Schumm (1975) found a threshold relationship between slope and drainage area, above which classical gullying is likely to occur. Whilst the study of ephemeral gullies differs from their work on classical gullies in that they form and are obliterated on an annual basis, the study of Patton and Schumm demonstrates the potential for using topographic parameters in developing relationships for predicting channel formation.

In addition to Patton and Schumm's (1975) study, upslope drainage area and slope gradient have also been used in more recent models predicting the initiation, location and erosion of gullies (Begin and Schumm, 1979; Thorne *et al*., 1986; Auzet *et al*., 1993; Montgomery and Dietrich, 1994). This is based on the fact that the location and size of gullies are essentially controlled by the generation of concentrated surface runoff of sufficient magnitude and duration to initiate and sustain erosion. In most of these studies, upslope contributing area is used as a surrogate for the volume of runoff because no runoff discharge data are available. This is justified by the observation that in landscapes where Hortonian overland flow dominates, runoff volume increases in proportion to catchment area (Leopold *et al.,* 1964).

Vandaele *et al.* (1996) investigated the links between ephemeral gully formation, slope and upstream area by examining the relationship between surface gradient immediately upstream of the incision head and the upstream area of the incision head for several datasets. They found that, for gullied sites, it was possible to draw a straight line on log-log paper through the lower-most points for each of the available datasets, representing a critical slope-area relationship for incision, below which no ephemeral gullies form. Whilst this study demonstrated empirically that the initiation of ephemeral gullies is related strongly to the upstream area and slope, it did not include planform curvature, the importance of which has been discussed above. Addition of planform curvature to such analyses should improve their reliability as this parameter allows the predictor to represent specific stream power (that is stream power per unit bed area) rather than stream power per unit channel length and so better represent the flow intensity responsible for ephemeral gully initiation and growth.

A study that did acknowledge the importance of planform curvature to formation of ephemeral gullies was performed by Thorne *et al.* (1986). Their study, reported in a series of papers (Thorne *et al.,* 1984, Thorne and Zevenbergen, 1984; Zevenbergen and Thorne, 1987; Zevenbergen, 1989; Thorne and Zevenbergen, 1990), was based on the earlier work of Evans (1979: cited in Zevenbergen, 1989). Evans was responsible for developing a topographic analysis based on the differentiation of elevation between points in a uniform elevation grid, which was used to determine the four topographic indices: slope, aspect, profile curvature and planform curvature [Figure 3].

Figure 3: 3x3 altitude sub-matrix used by Zevenbergen (1989) to derive topographic parameters from digital elevation grids.



Zevenbergen and Thorne (1987) used a modified version of Evans' approach to calculate the slope, aspect, planform curvature and upstream drainage area for each point within a grid matrix. These parameters were used by Thorne *et al.* (1986) to calculate a CTI for each grid cell, and use the CTI to identify potential locations for ephemeral gullies based on land topography. The CTI is defined by:

$$CTI = A \,.\, S \,.\, PLANC$$

Where: A = upstream drainage area (m^2) and provides a surrogate for runoff discharge since the two are generally strongly positively correlated; S = local slope (m/m), which together with upstream area provides an indication of the stream power per unit downstream distance of the runoff; and PLANC = planform curvature (m/100), a measure of the landscape convergence (negative for spurs and positive for swales), which indicates the degree of concentration of the runoff and so allows the CTI 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. Please note that the units used in the original CTI study by Thorne *et al.* (1986) were in feet.

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 contain ephemeral gullies, while a gully 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 the locations with conditions known to be critical to gully formation – that is around gully heads where erosion is initiated. In consultation with the farmer, a grid point was located close to the gully head in each swale in an average year and the CTI value for that point found. The CTIs averaged across a number of gullyheads were then considered to provide a robust estimate of the critical CTI value for the site in question (Thorne *et al.,* 1986). Tests of these critical CTI values on an experimental field-site by Thorne *et al*. (1986) showed that actual and predicted locations of ephemeral gullies agreed almost exactly. Thorne and Zevenbergen (1990) describe how the strength of this method is that the particular value for a field will always be representative, because it is calibrated on the basis of the actual level of specific streampower necessary to overcome soil erosion resistance and initiate a gully head under conditions specific to each field in question.

Modern advances in topographic analysis.

The parameters needed to predict ephemeral gully locations can be obtained by various methods. For instance, Montgomery and Dietrich (1988) measured the maximum slope gradient where gully head formation started in the field using an optical clinometer, whilst Patton and Schumm (1975) measured the gradient on topographic maps. More recently, studies have used digital elevation models (DEMs) by digitizing the contour lines from large-scale topographic maps to obtain topographically-derived attributes. After converting this vector information into raster format, several algorithms are available to calculate slope and upslope drainage area.

Lacroix *et al.* (2002) describe how the more traditional techniques for deriving topographic information are tedious, costly, time consuming and subject to considerable operator variance. In recent years, geographic information system (GIS) technology has increasingly been employed to assist hydrologists with the task of model parameterization (Spence *et al.,* 1995).

A digital terrain analysis tool used for topographic evaluation, amongst other things, is TOPAZ (TOpographic PArameteriZation) which was developed by Garbrecht and Martz (1999). In brief, TOPAZ uses raster, digital elevation models to identify and measure topographic features and define surface drainage in order to assist topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis. Specifically, a collection of TOPAZ modules, referred to as TOPAGNPS, has been used to provide topographic analysis outputs for the USDA AnnAGNPS (ANNualized AGricultural NonPoint Source) hydrologic routing and pollution prediction modeling component.

There are a number of potential advantages to using the type of automated digital terrain analysis techniques included within TOPAZ/TOPAGNPS to derive parameters and variables for distributed hydrologic models (Lacroix *et al.,* 2002). In summary, these methods offer the advantages of speed, precision, reproducibility and the generation of digital output data that are readily incorporated into geographical information systems (Tribe, 1992). They are especially useful for larger watersheds where the manual measurement of network and basin properties is a time-consuming and error-prone activity (Martz and Garbrecht, 1998).

Considering the importance of digital elevation model grid resolution and value errors in topographic analyses.

One important consideration when performing topographic analysis on raster digital elevation models is the impact of the grid resolution on the resulting parameters (Holmes *et al*., 2000). The resolution of an elevation grid is the lateral distance separating neighbouring grid nodes. When a land surface is analysed using two different grid mesh distances, the statistical properties of the topographic indices are likely to change drastically (Zevenbergen, 1989). This has led some researchers to suggest that two land surfaces cannot be compared directly if the grid resolutions differ. Zevenbergen (1989) concluded that whether or not land surfaces are to be compared, a choice of grid size is still extremely important in any topographic analysis.

Whilst a grid resolution can be too large, resulting in the exclusion of significant slopes and land features, grid meshes can also be too fine, since with too fine a resolution micro-relief and elevation measurement errors become significant (Gerrard and Robinson, 1971). Zevenbergen (1989) describes how, when grid mesh distances are too large, real values between grid nodes will deviate excessively from the values represented by the grid; this is termed truncation error. Conversely, when grid mesh distances are too small, errors in elevation measurements have an excessive impact on the grid and cause excessive errors between real and calculated grid values.

A further concern when carrying out topographic analysis on digital elevation models is that DEMs, like any other datasets, can contain erroneous data. This is made more important by the fact that too often DEMs are created, distributed, and used without any reference to the magnitude of the error contained in the data (Walker and Willgoose, 1999). Therefore, when performing the topographic analysis which this report describes it is important to consider the influence of both error and grid resolution on the output parameter values.

The need for an automated method for mapping the potential locations of ephemeral gully channels.

This review has highlighted the importance of modelling ephemeral gully erosion in addition to sheet and rill erosion when predicting soil loss from agricultural fields. This pressing need for a procedure capable of predicting erosion along well-defined concentrated water flow courses on cropland drove the development of several procedures for predicting ephemeral gully erosion by researchers for the USDA (Woodward,1999). One of the results was a model and computer program called Ephemeral Gully Erosion Estimator (EGEE, later developed into EGEM), developed by Dr. John M. Laflen of the USDA Agricultural Research Service. This system estimated the quantity of soil eroded from a single ephemeral gully based on modelled watershed hydrology and erosion calculations. However, whilst the outputs from programs like EGEM are in no doubt valuable, in order to be useful within the AnnAGNPS framework it is necessary for the *locations* of the mouths of potential ephemeral gullies to be known.

It is this need, along with the availability of automated topographic analysis software and the existing theory on ephemeral gully initiation by Thorne *et al.* (1986), that led Bingner *et al*. (2006) to identify the fact that an automated method for mapping the potential locations for ephemeral gullies within a GIS environment would add value to the USDA–ARS AnnAGNPS watershed model. On this basis, a program of preliminary research into the area was deemed necessary.

STUDY AIMS AND OBJECTIVES

Based on the review of some relevant literature presented above it has become apparent that there is an opportunity to apply the CTI method (Thorne *et al.* 1986) for the prediction of potential ephemeral gully location within a GIS environment. It is also obvious that there is a demand for an automated means of locating potential ephemeral gullies, especially the mouth of the gully, in order to assist watershed sediment yield prediction programs such as the USDA-ARS's AnnAGNPS system. These and other issues raised in the literature review have led to the development of a study aim and the objectives that are encompassed within that aim.

<u>*Overall aim:*</u>

TO CREATE A GIS-BASED AUTOMATED TOPOGRAPHIC ANALYSIS, WHICH SUCCESSFULLY IDENTIFIES THE POTENTIAL LOCATIONS OF EPHEMERAL GULLY CHANNELS, AND TO RUN PRELIMINARY TESTING ON THE CREATED ANALYSIS METHOD ON ONE OR MORE FIELD-SCALE AREAS.

<u>*Study objectives:*</u>

Objective 1. *To generate a methodology for the identification of areas prone to ephemeral gullying and to investigate the ability of different techniques for locating the start and end points of ephemeral gullies based on identification of suitable critical CTI values.*

Objective 2. *To evaluate this methodology at a range of elevation grid resolutions and sources.*

Objective 3. *To investigate the sensitivity of this methodology to errors in elevation grid data.*

Various field sites have been made available for this study. As a minimum requirement each of the sites required: i) some form of elevation data that could be converted into a digital elevation model; and ii) the known locations of ephemeral gullies within the field site. The 10 sites included within this study are described in Appendix A. Using these study sites each of the project objectives outlined above was considered in turn in order to fulfil the goals of the project. Work carried out on Sites 1, 2 and 6 formed the basis for completing the majority of the above objectives with the remaining sites used solely in assisting the identification of suitable critical CTI values.

Objective 1: Generating a methodology for the identification of areas prone to ephemeral gullying, and investigating the ability of different techniques for locating the start and end points of ephemeral gullies based on identification of suitable critical CTI values.

Methodology

To develop a means to generate the original CTI as defined by Thorne and Zevenbergen (1984):

$$CTI = A \, . \, S \, . \, PLANC$$

it was first necessary to find ways of generating the three components of the CTI (slope, upstream area and planform curvature). To produce the first two of these parameters the TopAGNPS module was run within an ArcView 3.3 interface on a DEM that produced the output grids 'terrain slope' and 'upstream area'. The final parameter, planform curvature, was obtained through running an extension to the ArcView 3.3 interface in the form of the 'DEMAT' (Digital Elevation Model Analysis Tool) ArcView 3.x extension by Thorsten Behrens (http://arcscripts.esri.com/details.asp?dbid=10222). The values produced using this extension were validated against values manually computed in Excel using Zevenbergen's (1989) original formula.
Once the means of generating the three components of the CTI had been determined, preliminary testing was performed through application to Ellis Site A (Site 2) from the original CTI studies so that the results could be compared with the original findings by Zevenbergen (1989). Also, 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.

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 it is first necessary to determine the 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 data base of critical values, unfortunately this collection of data is unavailable and, therefore, it is necessary to compile new critical threshold data.

Three methods for finding the threshold CTI value for each of the sites were attempted and tested on each of the sites made available for this study. These methods were:

1. A GIS based adaptation of the technique originally suggested by Thorne and Zevenbergen (1990). This involved finding the calculated CTI values for grid cells at the start and end points of each gully in a field and then averaging the values for that field.
2. Finding the CTI values for every pixel on a grid that contained the known location of a gully. Then plotting these CTI values in order to find a base value that would result in the formation of a gully.
3. Adjusting the CTI threshold until a value is found which best distinguishes between a gully being present or not and then setting this as the critical CTI.

Results and Analysis

Figure 4 below shows the values of the compound topographic index that were calculated for Site 2 (Ellis Site A) compared with the actual gully locations and 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 digital elevation model successfully recreates the results that were originally generated using field measurements and manual calculations.

When comparing the results of the CTI output grid and an alternative index which includes upstream area and slope but not planform curvature [Figure 5], the predicted patterns of potential gully locations seem to be very similar. This is considered to be due to the strong influence of slope and upstream area over both indices, and the certain amount of correlation that occurs between upstream area and planform curvature. However upon closer examination of the results of the two indices important differences were observed. Figure 6 demonstrates how the index without planform curvature included overextends its prediction of the location of the ephemeral gully compared with the CTI. The reason for this is shown by the grid of planform curvature values which can be seen to drop significantly at the end of the gully location, demonstrating the importance of planform curvature in influencing the presence of ephemeral gullies. A second example of this importance can be seen in Figure 7, taken from Site 6. This again demonstrates how the absence of planform curvature in the alternative index means that it predicts gullies where there are none because planform curvature is low, and also fails to predict gullies where they are present because of high values of planform curvature. The CTI, because of the inclusion of planform curvature, is able to pick up the location of the gully whilst managing to recognise that gullies are not present in other areas even though upstream area and slope are high.

Figure 4: Results of GIS-based CTI process on Site 2 (Ellis Farm Site A) compared with actual gully locations and original predictions provided by Zevenbergen's thesis. Green shows cells where the CTI is greater than a chosen threshold value, the blue polyline represents the known gully locations and the purple polyline represents where Zevenbergen's original CTI results predict gullies to be located.

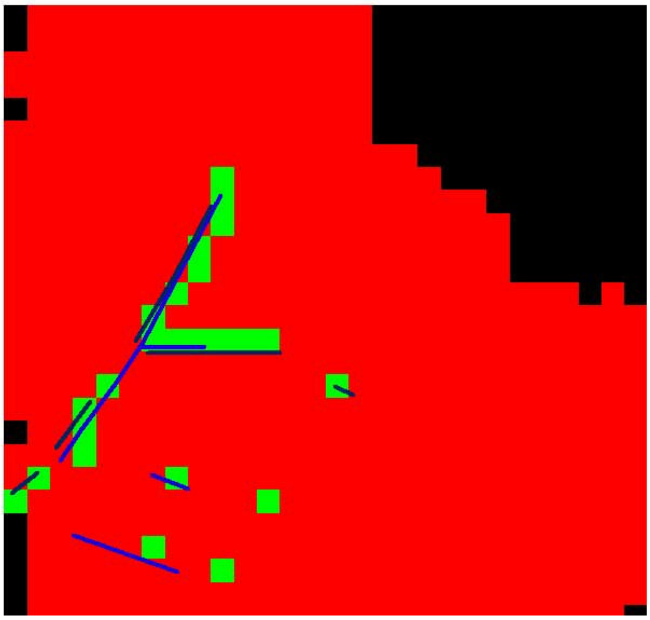


Figure 5: Results of GIS-based CTI process (left) on Site 2 (Ellis Farm Site A) compared with index composed of solely drainage area and slope (right). The highlighted cells represent index values above the threshold for this site. The blue polyline represents the known gully locations.

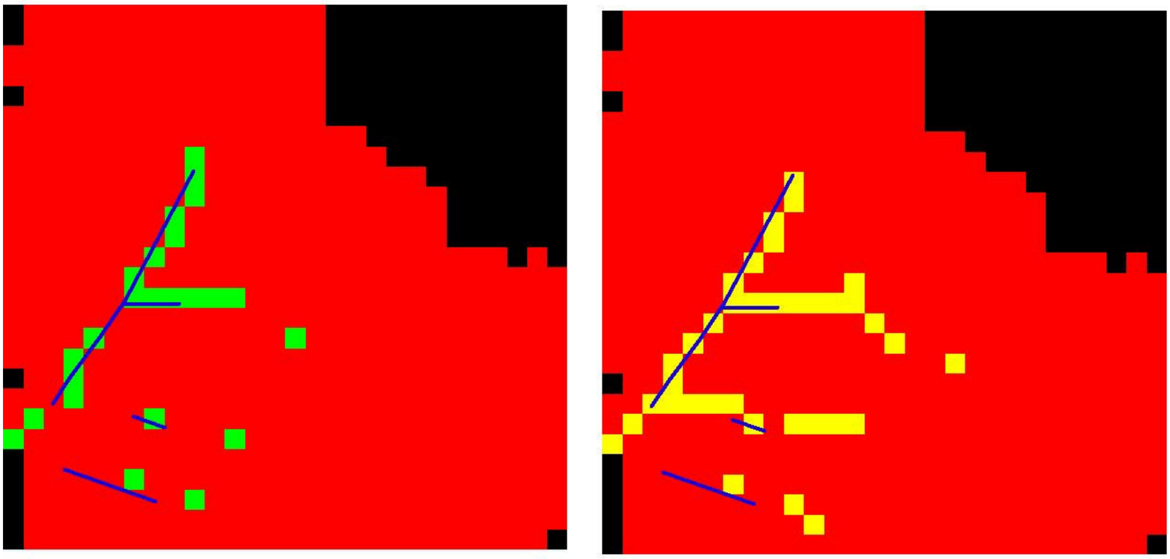


Figure 6: Close examination of the differences between the results of the CTI index (centre) and the alternative upstream area and slope index (right) for Site 2 (Ellis Site A).The left image shows an indication of the planform curvature values (with darker red cells having a higher / more concave curvature), which also form a backdrop to the centre and right images.

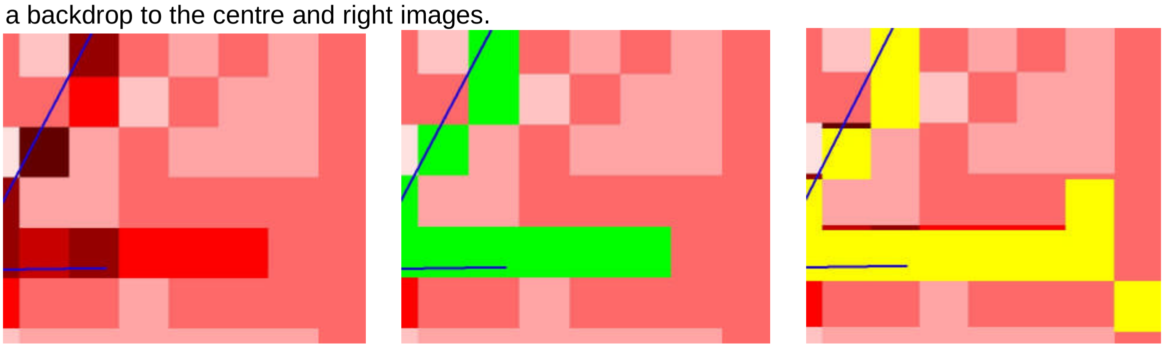
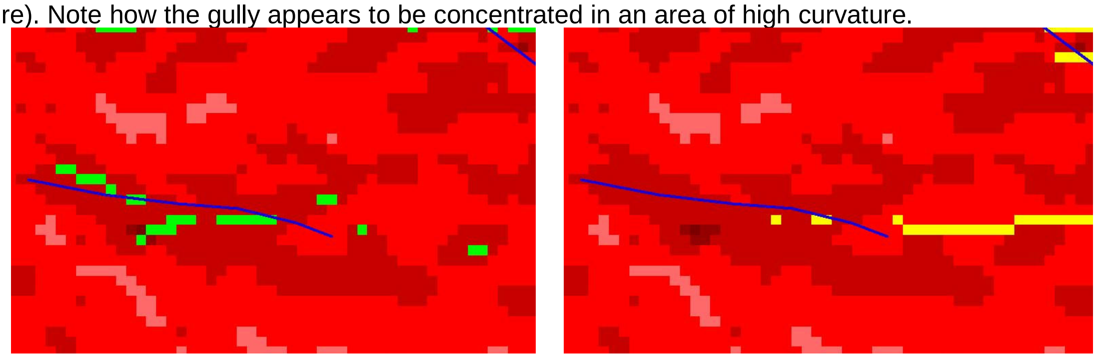
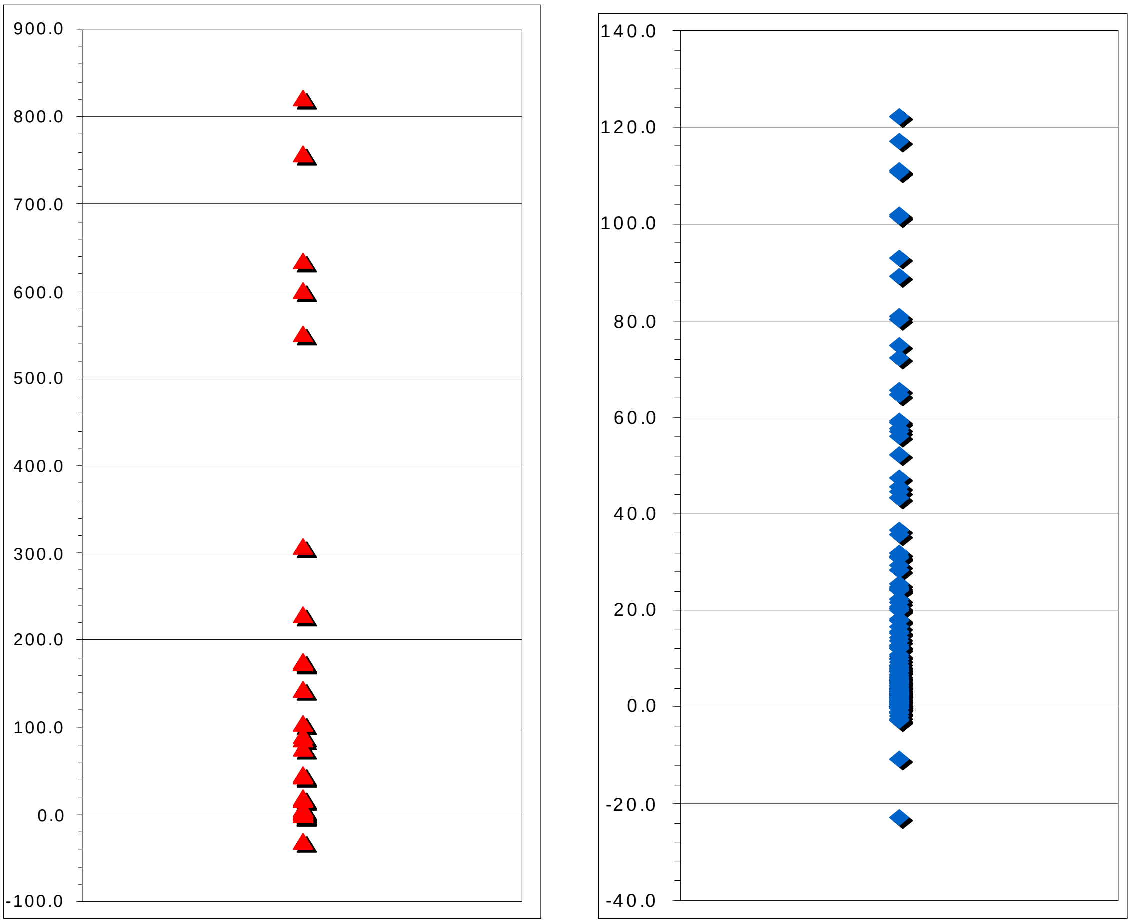


Figure 7: Close examination of the differences between the results of the CTI index (left) and the alternative upstream area and slope index (right) for a section of Site 6 (New Hampshire Site). The background to each of the images shows an indication of planform curvature (with darker cells having a higher / more concave curvature). Note how the gully appears to be concentrated in an area of high curvature.



Of the three methods of finding threshold CTI values that were tested on the sites in this study both the first and second were found to be impractical. This was due to the local scale variation in pixel CTI values. For the first of the proposed methodologies this meant that it was impossible to get a representative value for the start and end points of each of the gullies in the field. For the second, it meant that when the CTI values along the known course of the gully were plotted, the distribution of CTI values was so wide that no clear break point could be defined as a threshold value [Figure 8].

Figure 8: The distribution of CTI values (Y-axis) for pixels known to be on ephemeral gullies for Site 2 (left) and for Site 6 (right). Note that negative CTI values indicate the presence of negative (convex) planform curvature rather than a positive (concave) planform curvature.



The third method, which involved iteratively adjusting the threshold value until one was found that best represented where gullies were and were not present, is demonstrated for Site 2 in Figure 9. This figure shows how, as the threshold for the CTI value increases, the areas predicted to be potential ephemeral gully sites reduce in size. Based on a large number of iterations, the threshold value was found for which those areas predicted to be potential gully sites (in green) best matched the actual known gully locations (in blue). In the case of Site 2 (Figure 9) this critical CTI value was found to be 62.

This technique was repeated for all 10 of the study sites (see Appendix A) and the results are displayed in Table 2 along with available information on land use and soil type. Whilst there is a wide range of critical CTI values from 5 to 62, unfortunately there does not appear to be an obvious pattern between critical CTI values and the information that is available for each of the sites.

Figure 9: CTI values above a range of different thresholds (green) compared against known gully locations (blue) on Site 2 (Ellis Site A).

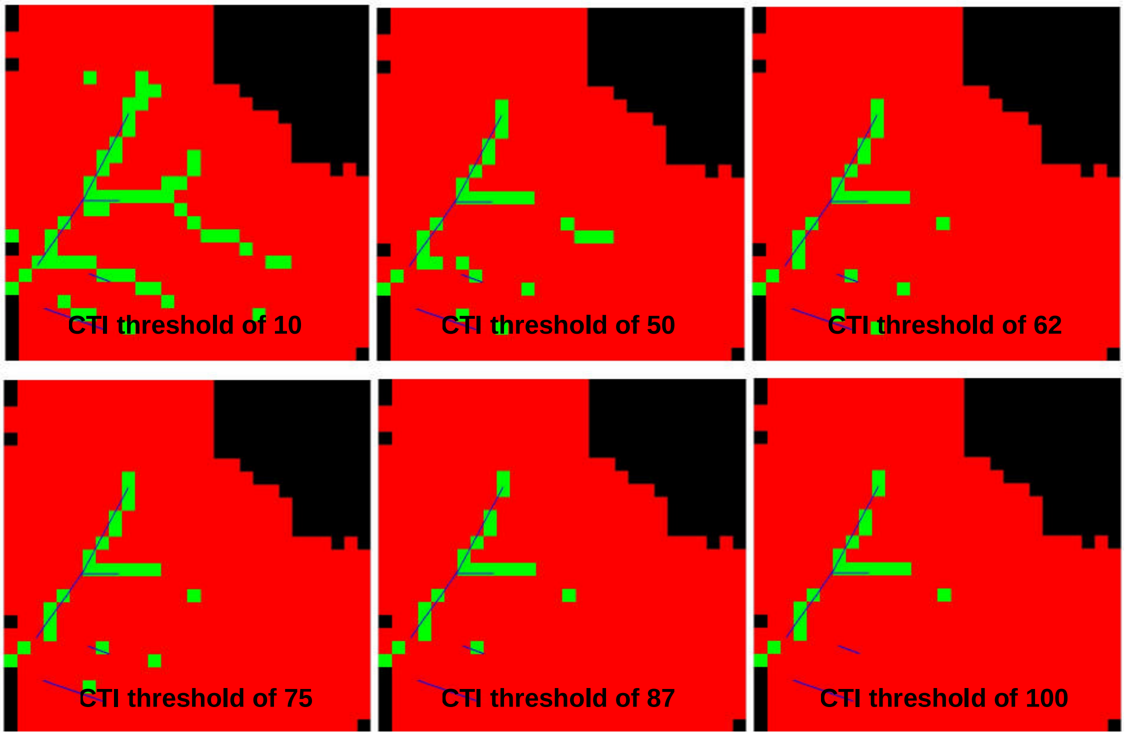


Table 2: Critical CTI vales found for each of the sites in the study along with any information on crop and soil type that is available.

Site	*Land Use*	*Soil Type*	*Critical CTI value*
1. Melton Farm	-	Alligator – Sharkey - Dundee	36
2. Ellis Site A	Broadcast Soybeans	Loring	62
3. Ellis 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
9. Bobbie Mellon	Corn	Loring	5
10. James Goodlow	Soybeans	Providence	30

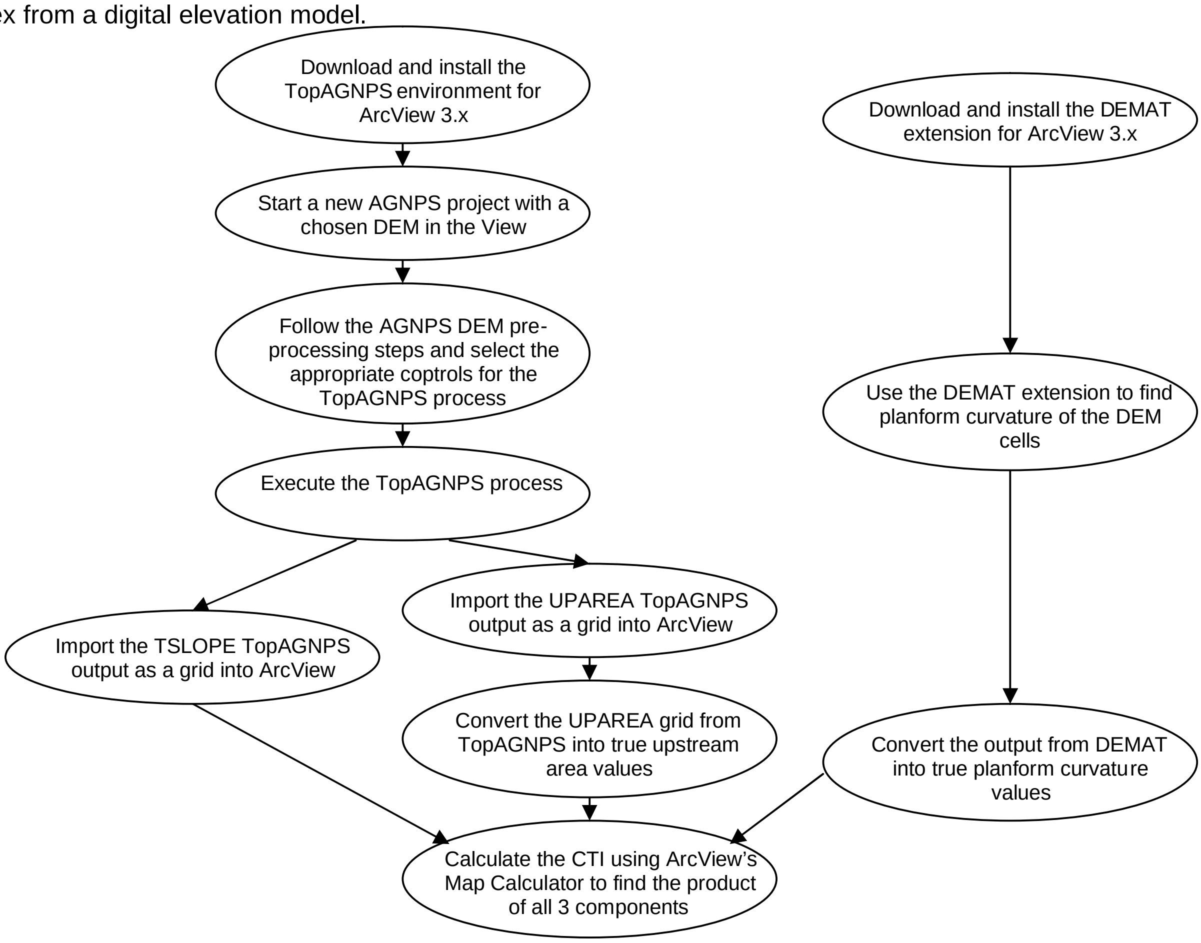
Discussion

Figure 4 demonstrates that the main objective of the project, to develop 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 (Garbrecht and Martz, 1999), 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 the ARS AnnAGNPS system, which currently lack the ability to automatically locate potential ephemeral gullies and instead relies 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 Zevenbergen (1989) appreciated that upstream area and planform convergence are not independent of each other, the present study demonstrates that 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 representing the degree of convergence and concentration of surface runoff, and this is demonstrated in the above analysis.

The steps necessary to generate the compound topographic index from a digital elevation model are summarised in the flow diagram in Figure 10. A more detailed description of these steps can be found in Appendix B.

Figure 10: Flow diagram representing the steps that are necessary to generate the compound topographic index from a digital elevation model.

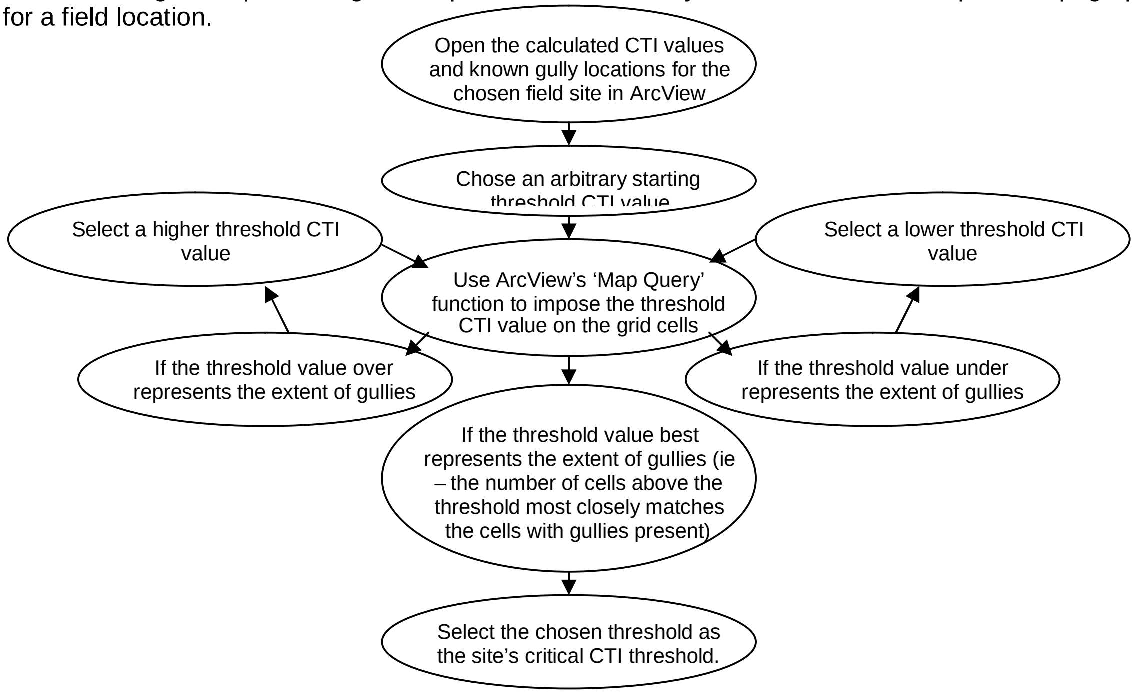


A technique for establishing critical CTI values for different sites was established as part of this objective as described by Figure 11 (again, more detailed instructions for carrying out this technique are given in Appendix B). The critical CTI values found using this procedure on the 10 study sites ranged from 5 to 62, 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 characteristics. This is probably because many other factors, aside from soil type and land use, impact a site's threshold value, for example climate, conservation practices and land management (Thorne *et al.,* 1986).

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. In fact, interestingly the critical CTI value found using the above methodology for Site 2 (Ellis site A) is strikingly similar (62m versus 250feet) to the value found by Zevenbergen (1989) in his thesis, despite his usage of a completely different methodology.

Finally, although the range in values found in this study may seem large, it may in fact be feasible to use a fixed threshold value as a critical CTI for all sites. This is because Figure 9 shows that whilst the CTI threshold was varied between 10 and 100, the general pattern of gullies predicted did not change, merely the extent of those gullies that were predicted. Therefore a chosen global critical CTI value could still be used to highlight areas of potential ephemeral gulling, so long as the user understands that the extent of the predicted gully network may not be accurate. Nevertheless, it is recommended that further work investigates the possibility of developing a means of automating the procedure in Figure 11 with an algorithm to find the threshold CTI value at which the location of 'above-threshold' is most closely correlated with the location of gullied cells.

Figure 11: Flow diagram representing the steps that are necessary to find the critical compound topographic index for a field location.



Objective 2: Evaluating the automated CTI technique at a range of elevation grid resolutions and sources.

Methodology

To complete this objective it was necessary to investigate two topics. Firstly, how the grid resolution of a digital elevation model affects the ability of the CTI to identify areas of potential ephemeral gully initiation and, secondly, how different elevation data sources impact on the performance of the CTI.

To investigate how the grid resolution alone impacted the predictive ability of the CTI, a range of grid resolutions from 1m to 20m were interpolated from the contour map of Site 6 (New Hampshire site) [Figure A.7, Appendix A]. The CTI process [as described in Appendix B] was then run on each of these elevation grids and the output grids inspected, to assess how the performance of the CTI responded to a decrease in the resolution of the elevation grid.

To investigate the performance of the CTI methodology using the 1m LiDAR, 1m AutoTopo, 10m USGS and 30m USGS elevation data sources, the process described in Appendix B was carried out on each of the relevant digital elevation models for Site 1 (Melton Farm field site). The output grids were then assessed for differences in performance. To ensure fair testing between data sources, further CTI values were then generated on digital elevation models from each of the four data sources after they had all been resampled to a 10m grid resolution. This was done to compare how the CTI process performed using different data sources but without the influence of grid resolution.

Similar testing was also performed on the Site 2 (Ellis Site A) data to compare the performance of the CTI on a 6.1m elevation grid obtained from field survey data to that for 10m USGS elevation data. On this occasion CTI outputs from each elevation source were compared at both elevation grid resolutions (i.e. at both 6.1m and 10m grid resolutions).

Results and Analysis

The resultant series of output grids from the first area of investigation within this objective is shown in Figure 12. For demonstration purposes only, a threshold CTI value of 10 has been imposed to highlight areas (in green) where the compound topographic index gives relatively high values. The actual, known locations of ephemeral gullies are also shown (in blue). As can be seen by examining the grids, the predictive ability of the CTI gradually degrades as resolution decreases and becomes extremely poor at a grid size of around 10m.

From the comparison of the various elevation data sources at the Melton Farm site at their original grid resolutions, a series of CTI output grids were produced [Figure 13]. The results demonstrate that whilst the LIDAR and AutoTopo elevation data effectively predict the known location of an ephemeral gully, the CTIs that were produced using the 10m and 30m USGS DEMs do not. Further, even when all four datasets were resampled to a 10m grid resolution the LiDAR elevation data [Figure 14] and the AutoTopo elevation data still managed to correctly highlight the area likely to feature an ephemeral gully, whilst the two USGS elevation datasets again failed to do so.

The results of tests carried out at Site 2 are shown in Figure 15. As is shown in the grids, whilst the CTI output from the surveyed 6.1m elevation data successfully predicted the location of the ephemeral gully to some extent at both the 6.1m and 10m grid resolutions, the CTI output from the USGS 10m elevation data failed to correctly identify the gullied areas at both of these resolutions.

The reason for this poor performance is clarified when the difference grid between the USGS and survey based DEMs for Site 2 is examined [Figure 16]. This figure shows that there is a fairly strong correlation between the location of the ephemeral gullies and the area of greatest positive difference between the USGS DEM and the Zevenbergen survey DEM. This is important as it reveals that the reason for the poor performance of the CTI on the USGS DEM is that the elevation data fails to properly represent the topographic depressions (swales) that are actually responsible for the concentrated overland flow that is necessary to form ephemeral gullies.

Figure 12: CTI values above 10 (green) compared against known gully locations (blue) for various levels of elevation grid resolution for Site 6 (the New Hampshire site).

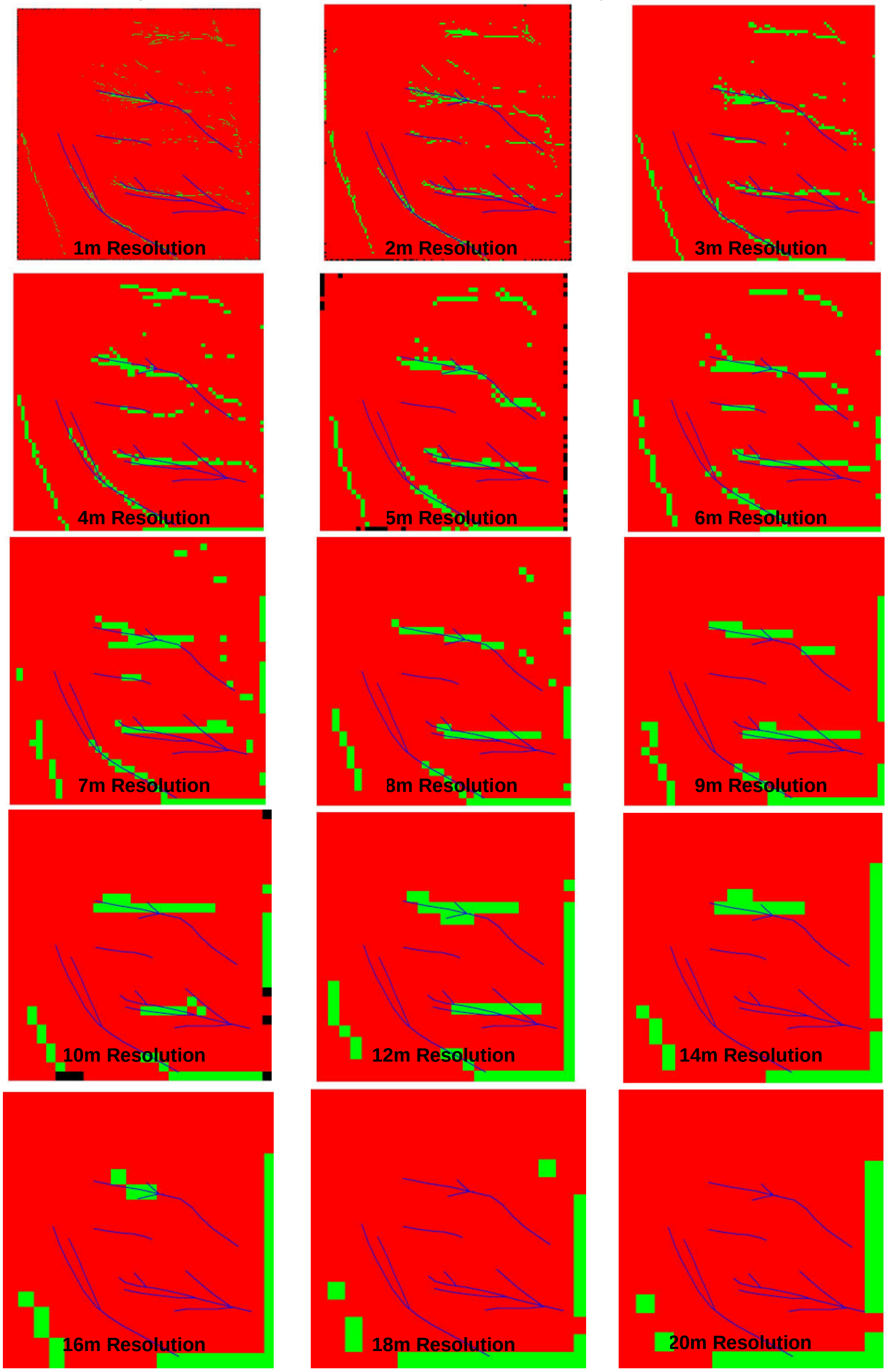


Figure 13: CTI values above 10 (green) compared against known gully locations (blue) for various elevation data sources for Site 1 (Melton Farm).

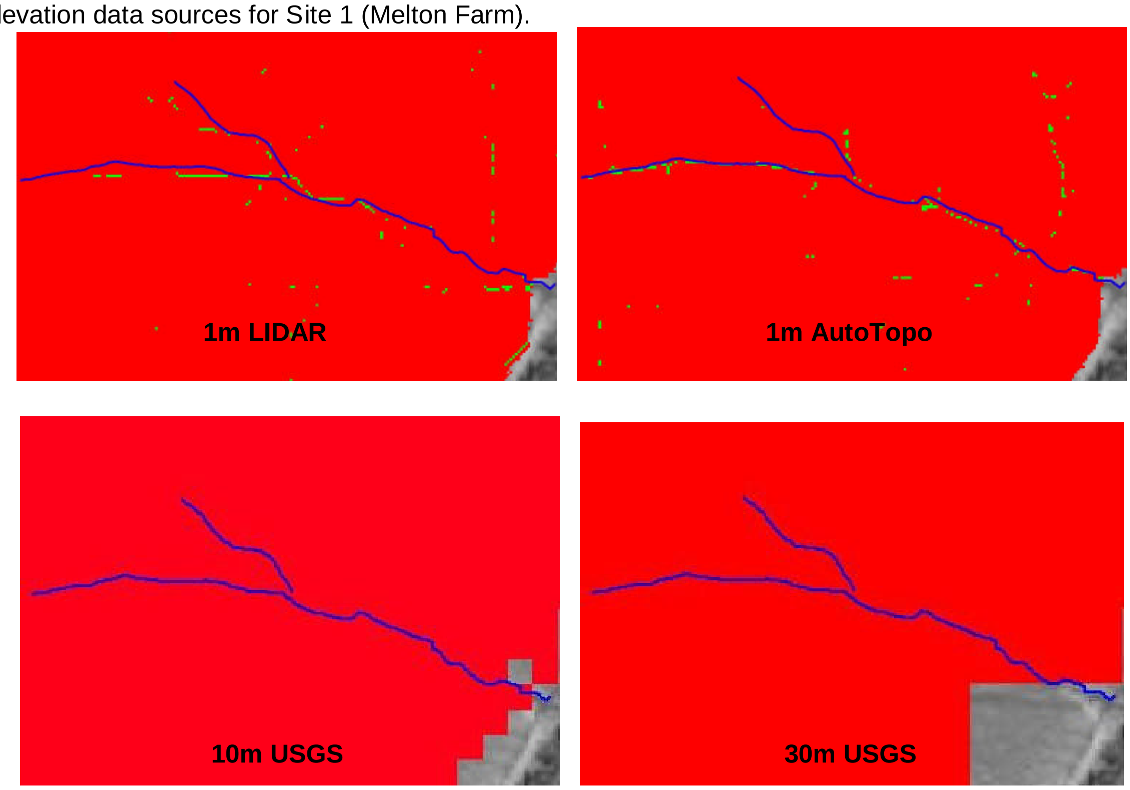


Figure 14: CTI values above 10 (green) compared against known gully locations (blue) for the 1m LIDAR data of Site 1 (Melton Farm) after it has been resampled to a 10m elevation grid.

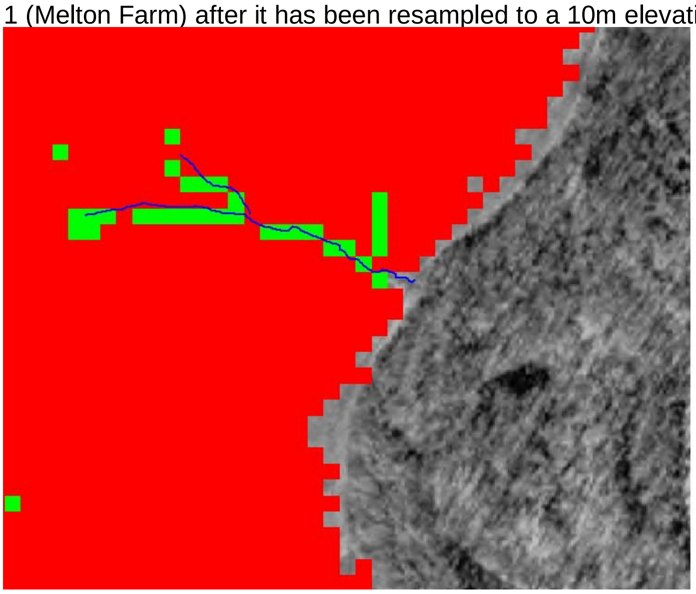


Figure 15: CTI values above 10 (green) compared against known gully locations (blue) for field surveyed elevation data grids and 10m USGS elevation data at both 6.1m and 10m grid resolutions at Site 2 (Ellis Site A).

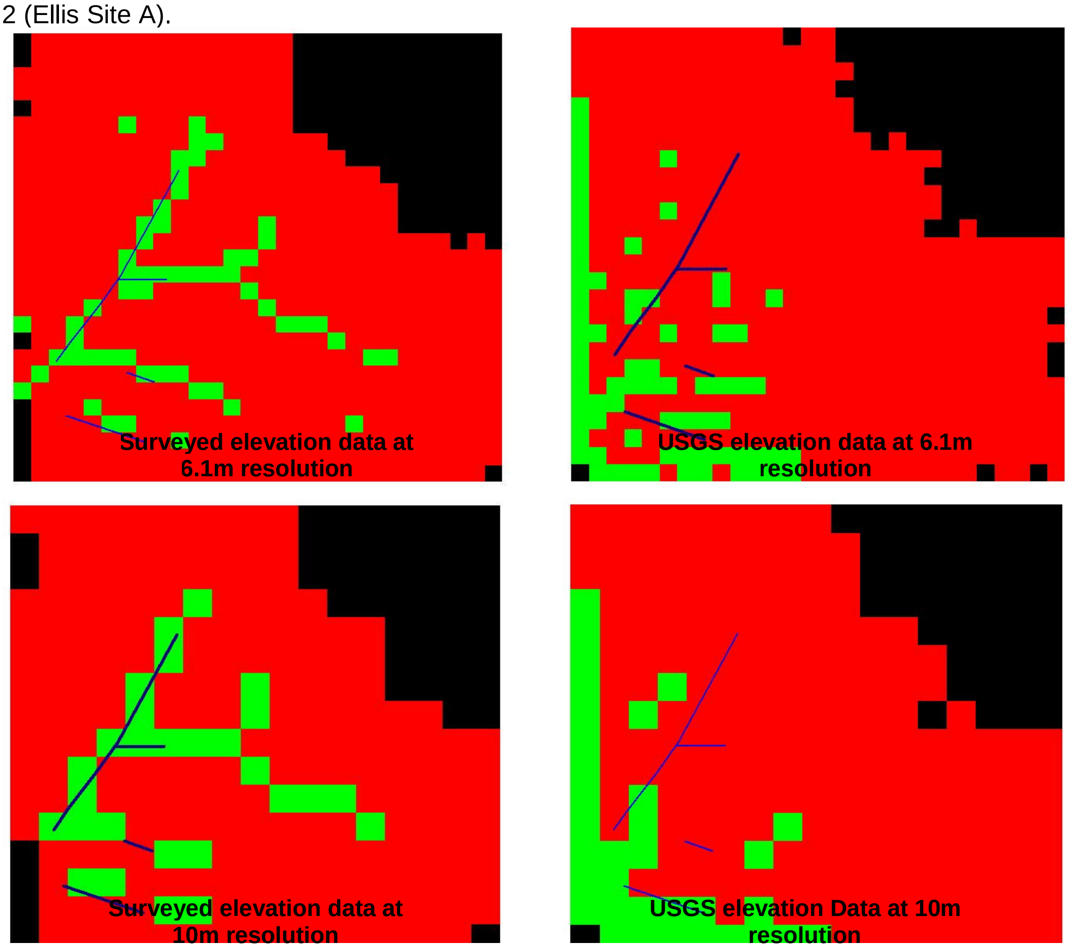
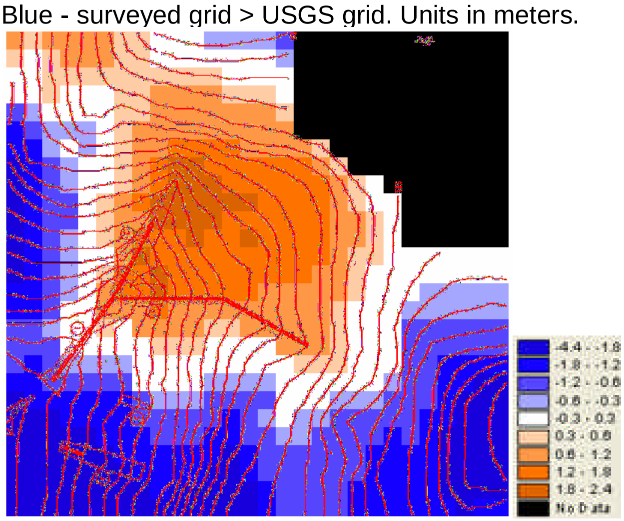


Figure 16: Difference in height values between Zevenbergen's surveyed elevation grid and the USGS 10m elevation grid FOR Site 2 (Ellis Site A). Orange cells represent cells where the surveyed grid elevations< USGS grid. Blue - surveyed grid > USGS grid. Units in meters.



Discussion

Figure 12 demonstrated graphically the principle of truncation error as described by Zevenbergen (1989). As the grid spacing increased above 10m the grid mesh became too large and the values represented by the grid in between nodes deviated excessively from the real values. In an analysis of the effect of DEM resolution on terrain attributes, Thompson *et al.* (2001) found that decreasing the horizontal resolution of a DEM 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 failed to identify gullied areas correctly. Therefore, whilst Walker and Willgoose (1999) found that the grid spacing of a DEM had no significant effect on the ability of that DEM to identify various hydrologic parameters provided the same base data was used for gridding, this study has shown that this is only the case to a certain extent, beyond which the ability of the CTI to perform breaks down.

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 this objective emphasize the importance of grid source in influencing the results of the CTI analysis. While Figures 13 to 15 shows that LiDAR, AutoTopo and traditional survey based DEMs can be successfully used to identify the locations of ephemeral gullies, the CTI analyses performed on the USGS-sourced 10m and 30m DEMs were not as good in comparison, even when performed at the same resolution. This supports Thompson *et al*.'s findings that showed differences between DEMs generated from different data sources are more significant than those from similar sources but different resolutions. In fact, they too found that a USGS DEM gave a significantly less accurate representation of depressions and drainage pathways compared to a field survey DEM.

While the reasons for failure of the USGS DEM to properly represent the swales present at Site 2 [Figure 16] are unknown, it is thought that inaccuracies may stem from the USGS data originally being derived from contour maps. This could have introduced inaccuracy in several ways, including the influence of the map scale used to produce the cartometric DEM, a factor which has been recognized by Wolock and Price (1994). A further error source is thought to derive from interpolation from contour lines to a continuous surface (McCullagh, 1998). Finally, an additional potential reason for the inadequacy of the USGS DEMs for this particular purpose is due to projection issues due to the situation of Site 2 at the far western edge of UTM zone 16. Whatever the cause, the presence of errors within USGS digital elevation models is well supported in the literature. For example, an analysis of a USGS dataset by Holmes *et al.* (2000) revealed that, whilst the average error was small, local errors were often large and spatially correlated. In addition, other studies have shown how systematic errors within the DEM are often compounded in terrain attributes such as the slope, curvature and upstream area used within the CTI analysis (Bolstad and Stowe, 1994; McKenzie *et al*., 2000).

The results of this part of the study have clearly demonstrated that, whilst the CTI technique performs extremely well using LIDAR, AutoTopo and traditional survey elevation data of a suitable resolution, it is unable to perform on the USGS elevation datasets. This is important because it is USGS datasets that are available across large geographic areas while the other data sources are currently available only for research plots and catchments. 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 data is from LiDAR or some another source.

Objective 3: Investigating the sensitivity of the automated CTI methodology to errors in the elevation grid data.

Methodology

In order to understand the influence that errors within a DEM may have on CTI-based analyses. To do so, two basic error analyses were performed. The first involved applying a random grid to the Site 6 1m DEM so a digital elevation grid with random errors ranging from +0.1m to -0.1m of the original elevation value was produced. This was intended to illustrate the effect that a random error of up to ±0.1m within a DEM could have on the resultant CTI values, with further tests for different error band widths exploring what level of error the technique was able to cope with.

The second error analysis involved performing the CTI analysis outlined in Appendix B on several DEMs of the Site 6 that had errors deliberately introduced into them by randomly changing the original contour height values that were the basis for their interpolation. In this test, errors in the contour heights were randomly introduced at ± 1/10, 1/5, 1/2 and a whole of the contour interval, which equates to artificially introduced contour height errors of ± 0.1ft, 0.2ft, 0.5ft and 1ft. Further, an additional CTI was produced based on a DEM that had been interpolated from a series of contours that included two deliberate contour height errors that were intended to simulate the result of incorrectly entered height values.

Results and Analysis

The results from the first form of error analysis were unfortunately not useful in the way that had been expected for reasons which are discussed below, but are nevertheless still useful in highlighting key characteristics of the CTI analysis. As Figure 17 shows, the distribution of CTI values above the chosen threshold value seems to be randomly distributed, failing to highlight areas of potential ephemeral gully development.

Consideration of how the compound topographic index is formed revealed the reasons for this. Slope and planform curvature are sensitive to the erratic changes in the model surface that were introduced by the random introduction of errors. Planform curvature is especially sensitive as demonstrated by Figure 18 which shows how the introduction of random errors causes a high level of local variation which masks the general patterns present in the topography. This is due to small scale changes in curvature and slope being introduced by the increases and decreases in elevation – which were artificially localised. The result is that there are many false increases in slope and large positive and negative planform curvature values, which in turn gives a much larger and more erratic range of CTI values.

Whilst this makes any further work on this particular form of error analysis difficult, it does highlight the fact that, when performing a CTI analysis, it is important to avoid DEMs that contain significant local errors in measured elevations. This because these local variations may hide the general pattern of topography that is important to the generation of concentrated surface runoff and the formation of ephemeral gullies.

The contour errors introduced into the Site 6 data did not have a significant impact on the results of the CTI analysis up to and including the introduced errors of ±0.5 feet (half a contour interval) as shown by Figure 19. However, once the introduced errors were increased beyond half a contour interval, it caused the predictive capability of the CTI to break down. Further, the CTI analysis that was performed on the DEM with 2 incorrectly entered contour height values performed particularly badly (Figure 19). This has implications which are discussed below.

Figure 17: Top: CTI values above 10 (green) compared against known gully locations (blue) for the DEM with artificially introduced random errors of ±0.1m for Site 6 (New Hampshire site).
Bottom Left: Detailed view of the patterning of high CTI values around a known gully location.
Bottom Right: Detailed view of the same area without introduced errors.

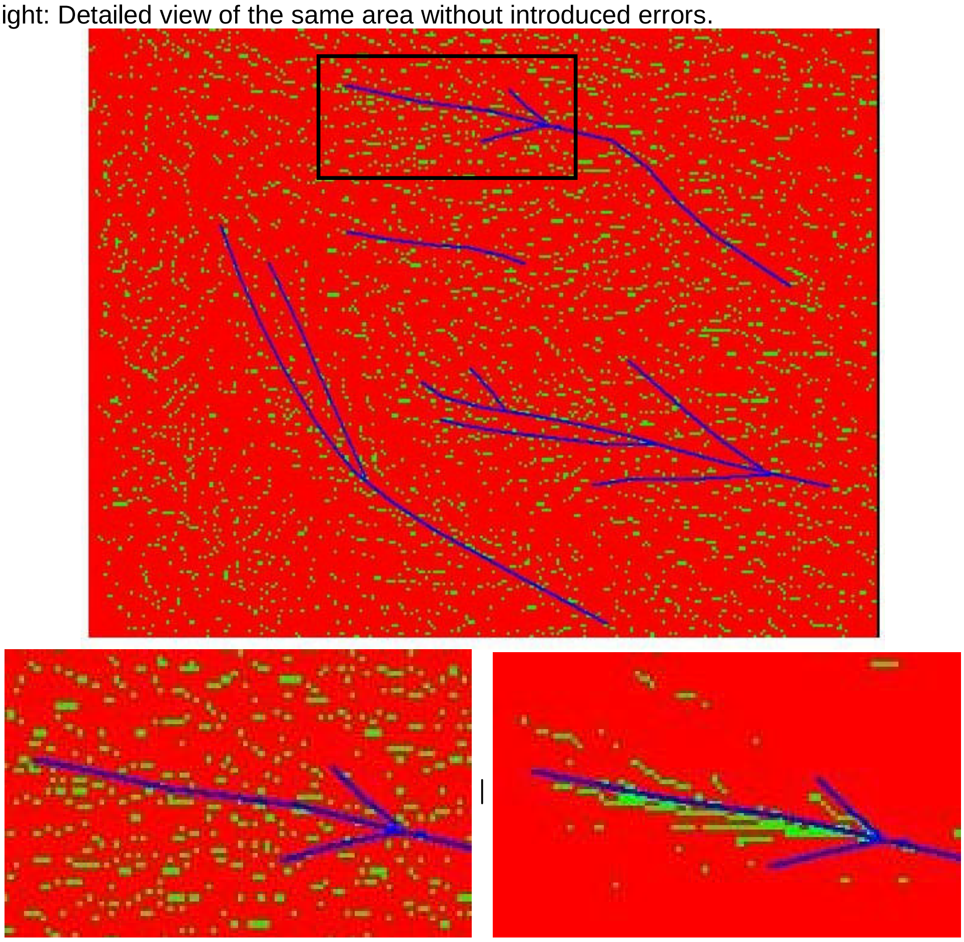


Figure 18: Planform Curvature (blue = positive, red = negative) produced before (left), and after (right) artificially introduced random errors of ±0.1m were added to the New Hampshire site DEM.

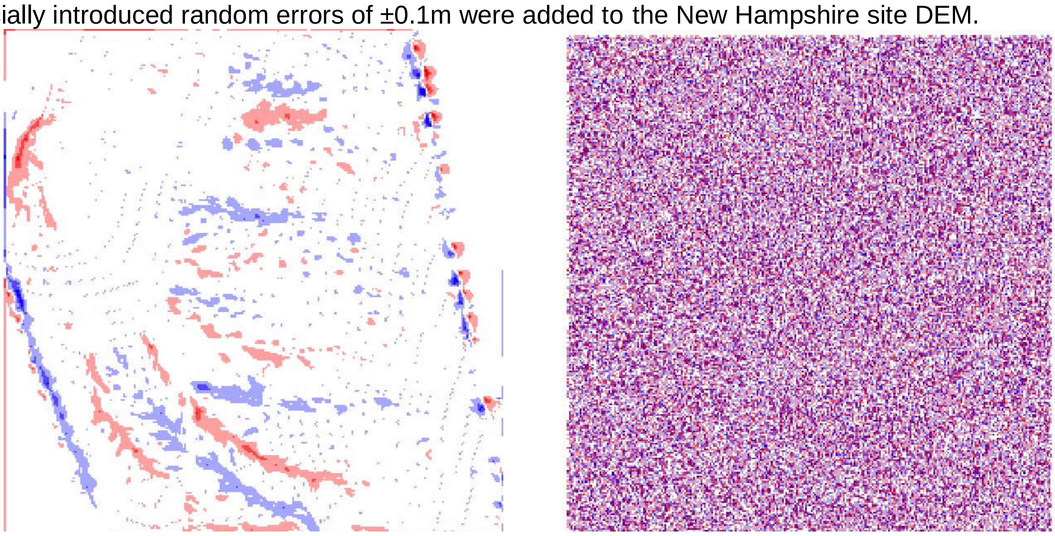
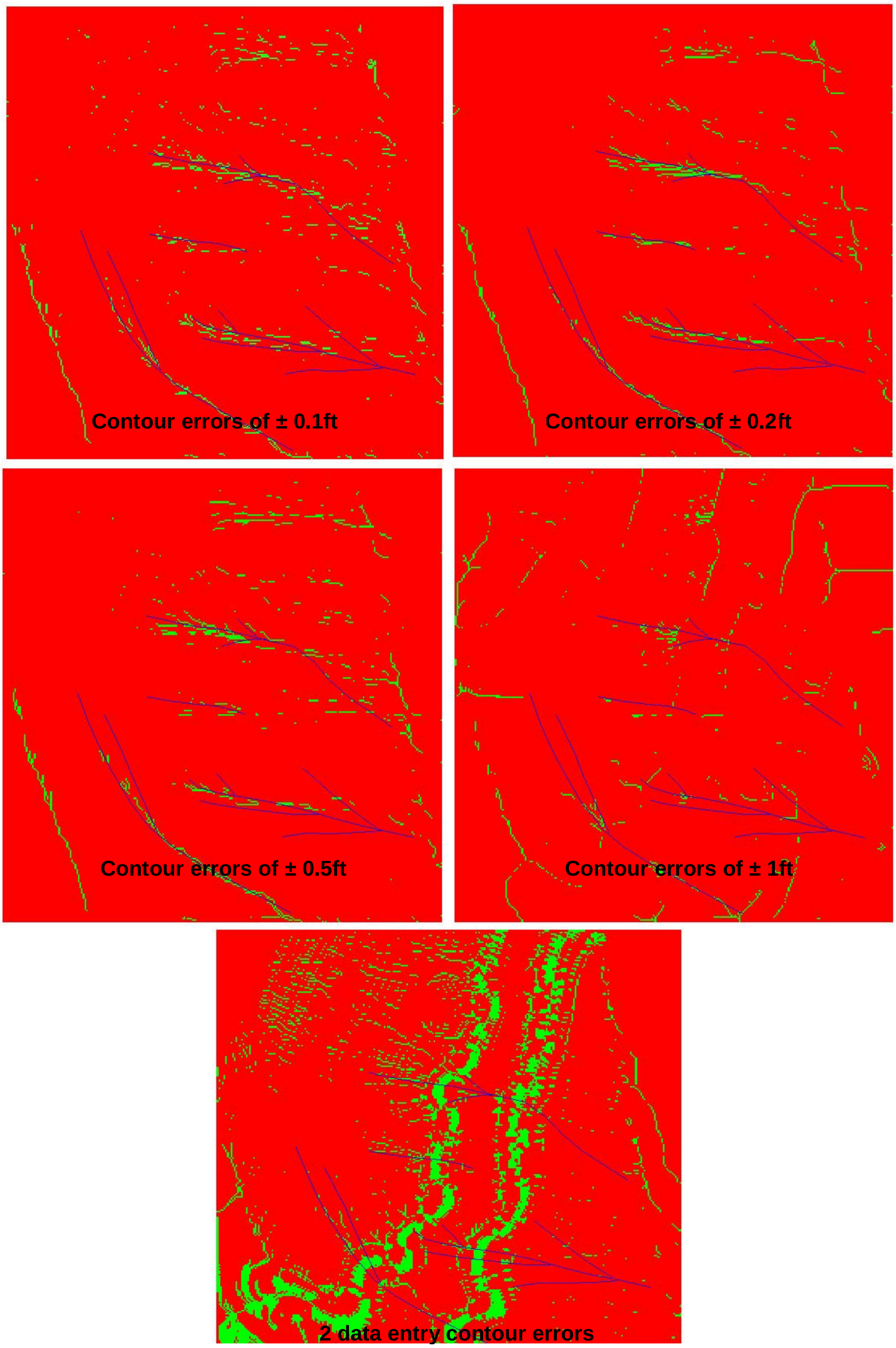


Figure 19: CTI values above 10 (green) compared against known gully locations (blue) for each of the DEMs with errors introduced through changing the contour height values of Site 6 (New Hampshire site).



Discussion

As mentioned above, the results from the first form of error analysis were unfortunately not useful in the way that had originally been expected. This is mainly due to the fact that the application of random error does not realistically represent the type of error that is generally found in the real world. Real world errors in DEMs tend towards being systematic rather than random, as was demonstrated above in Objective 2 where Figure 16 shows how the difference in height values between the USGS sourced DEM and the surveyed elevation values is spatially distributed around the gully locations. Further, it is necessary to recognise that the elevation data source into which errors were added already contains 'real' random inaccuracies and so the further errors applied essentially doubled the frequency of the error. Nevertheless, the key point to draw from the results of the first part of Objective 3 is that local level error can mask the general pattern of topography that controls the CTI and so result in poor predictions. As identified above, the reason for this is the sensitivity of slope and curvature to erratic surfaces on a fine scale mesh, a phenomenon also identified by Zevenbergen (1989). Wise (1998) also notes this, and claims that the Zevenbergen and Thorne methods for deriving slope and planform curvature are particularly sensitive to errors in elevation values on a fine grid since they are based solely on measurements relating to a grid point's direct orthogonal neighbours. This relates particularly to work by Gerrard and Robinson (1971) who describe how it is possible that, when using a fine elevation grid, for micro-relief and elevation measurement errors to become significant. This is an important issue since it suggests that rather than using the finest resolution data source available it may be preferable to resample elevation grids to a coarser resolution in order to avoid the impact of fine scale variations. Figure 12 demonstrates that running the CTI process using LiDAR data provides satisfactory results even when resampled to a grid resolution of up to 10m, showing that resampling need not have a detrimental effect on the results of the CTI analysis.

The second area of Objective 3 demonstrated the impact that errors in contour data can have on a digital elevation model, and the resultant CTI analysis. The general literature indicates that being correct to within half a contour interval is the minimum level of accuracy that can be expected from contour data (Baudot, 1991; Felus and Csatho, 2000; Van Niel *et al.,* 2004; Cogley and Jung-Rothenhäusler, 2004). Since the results of Objective 3 showed that issues only arose with the CTI process once the introduced errors rose above half a contour level interval this type of error does not seem to be an important issue in this case. Therefore, as long as the standard level of accuracy or better for contour maps is maintained, errors should not influence the CTI analysis results unduly. However, it is important to consider that the topographic maps used in this study contained relatively fine contour intervals of 1 foot, with the maximum error of half a contour interval being 0.5 ft. If a topographic map with contour intervals of 10 ft were used then obviously this maximum error of half a contour interval would jump to 5 ft, which is far more likely to cause issues in the resultant CTI calculations. Whilst obviously the distance between 1 ft and 10 ft contours is likely to differ significantly and thus reduce the effect, it is important that the impact of this is investigated further.

McCullagh (1998) describes how incorrect heighting is a particular problem that often occurs when digitising contours for elevation grids. This is difficult to spot until the finished result is viewable and can often result in the formation of characteristic "Roman ramp and ditch fortification" structures within the DEM (McCullagh, 1998). As Figure 19 demonstrates, this can have a significant impact on topographic and hydrologic parameters derived from the DEM. Consequently, it is vital to avoid this type of data entry error and requires a thorough check of all digital elevation models for heighting problems before they are used in the CTI analysis process.

Whilst this study has focused, to an extent, on the influences that errors in digital elevation models can have on the devised CTI methodology, it is clear that more work needs to be done in this area. This is because DEMs, as with all data sources, contain errors and it is important that the impact of these errors on the analysis of DEMs be fully understood by the user (Wise, 1998).

CONCLUSIONS AND RECOMMENDATIONS

The results of this study offer enough evidence for several tentative conclusions to be drawn. The most important of these is that the main aim of the study, to create a GIS-based topographic analysis which successfully identifies the potential locations of ephemeral gully channels, has been achieved. The utility of this type of analysis has also been demonstrated and it is apparent that the technique developed here could be integrated into the USDA-ARS TOPAGNPS system.

However, the CTI analysis is not a finished product by any means and although this study has attempted to find the optimum combination of parameters to form the index, further work is necessary to ensure that the methodology described in Appendix B is the best possible technique, perhaps using an extended collection of known ephemeral gully locations at the Melton Farm site (Site 1). Also, for the technique to be made fully operational, further testing and subsequent decision making is necessary regarding the correct use of critical CTI values. The results of this study suggest that the threshold CTI value can vary greatly between sites due to the large number of factors that influence the initiation of ephemeral gully channels. Nevertheless the study also shows that it may in fact be possible to use a single critical CTI value for all sites, provided that the user appreciates the limitations in accuracy that this will bring.

While the CTI process has been shown to be successful when using appropriate data, this study has also shown that the quality of the digital elevation model used has a large influence over how effectively the analysis can predict areas of potential ephemeral gully development. In this respect elevation grid resolution, elevation data source and errors were found to have significant effects. Perhaps most importantly, the current source of elevation data widely available for topographic parameterisation (USGS DEMs), is of insufficient quality for CTI analysis.

In closing, this report shows 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 developed in this investigation can then help in the understanding and quantification of ephemeral gullying, and thus assist the USDA in its attempts to conserve agricultural resources in the United States.

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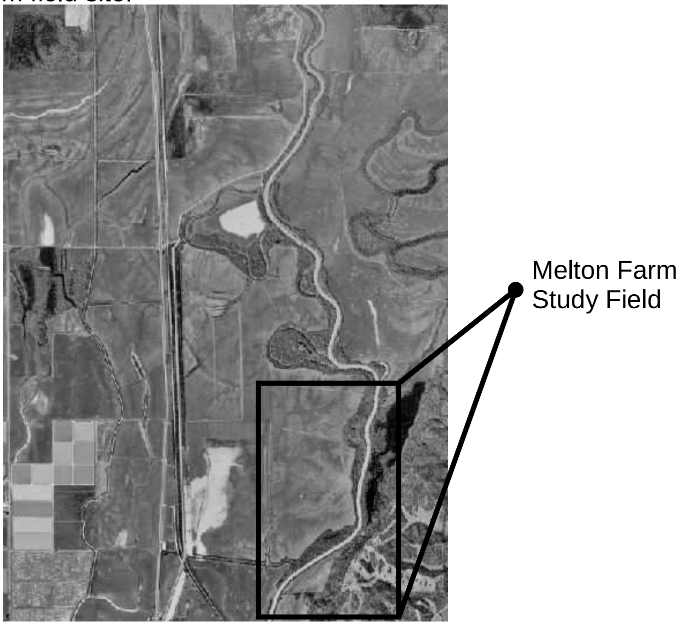
Appendix A: Study field site details.

Site 1: The initial site to be identified for use in this study is a field on *Melton Farm* [Figure A.1]. Alligator Sharkey Dundee soil. This site was considered suitable because gridded elevation data is available for this site at a variety of scales including an Auto-topo survey DEM with a grid resolution of 1m, a LiDAR survey DEM with a grid resolution of 1m, USGS DEM grid at a resolution of 10m and USGS DEM grid at a resolution of 30m.

Figure A.1: Site 1 – Melton Farm field site.

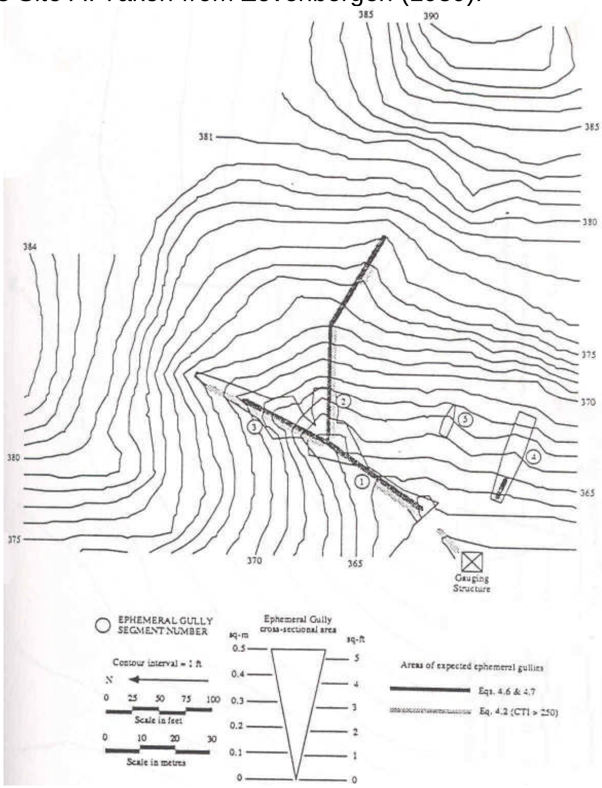


The thesis by Zevenbergen (1989) that underpins this study utilised data collected at four sites in or near the Goodwin Creek Experimental Watershed, Panola County, Mississippi. Zevenbergen included in his thesis 1ft elevation contour and gully location topographic maps for each of the sites [Figures A.3 to A.6], as well as the cell values for a Digital Elevation Model (DEM) of Ellis Site A. These sites are:

Site 2: *Ellis Site A* (within Goodwin Creek Experimental Watershed). Panola County, Mississippi: Loring soil. Land-use broadcast soybeans [Figure A.2]

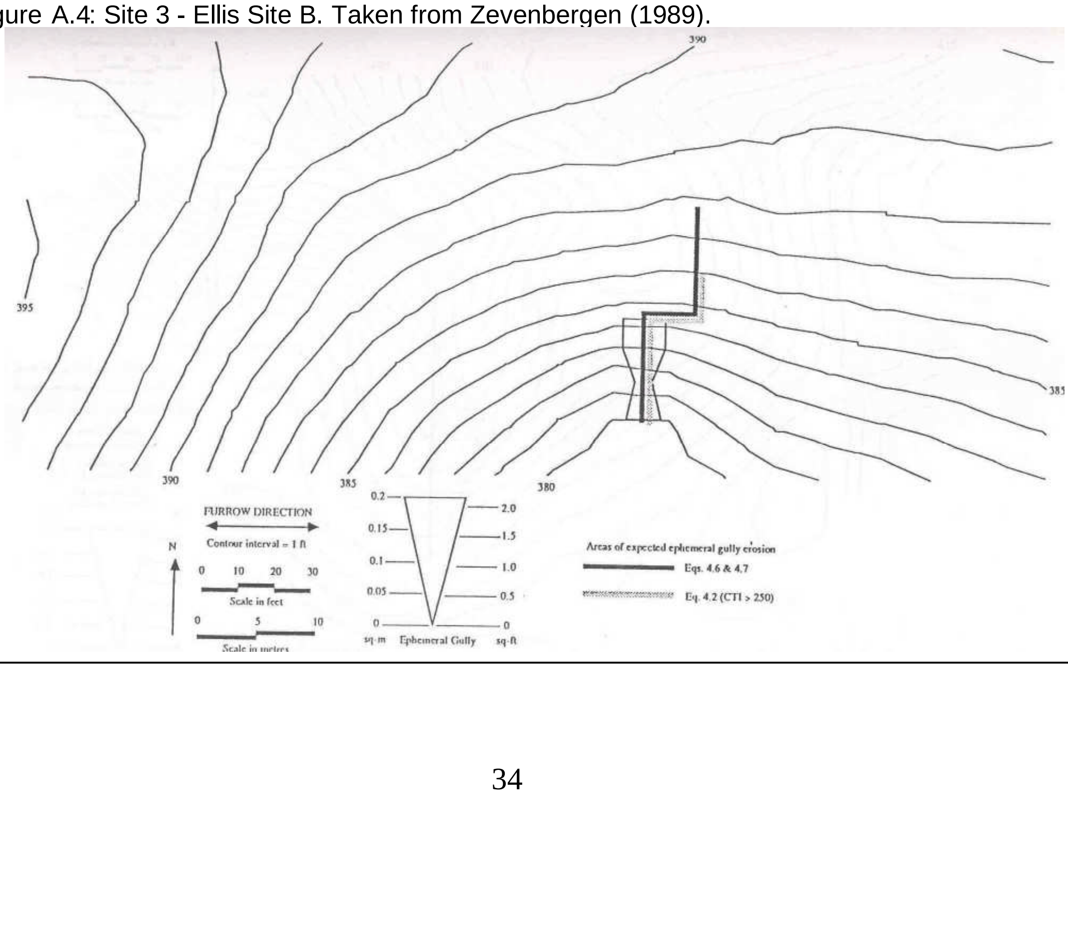
Figure A.2: Site 2 – Ellis Farm Site A. View looking South South-West.

Figure A.3: Site 2 - Ellis Site A. Taken from Zevenbergen (1989).



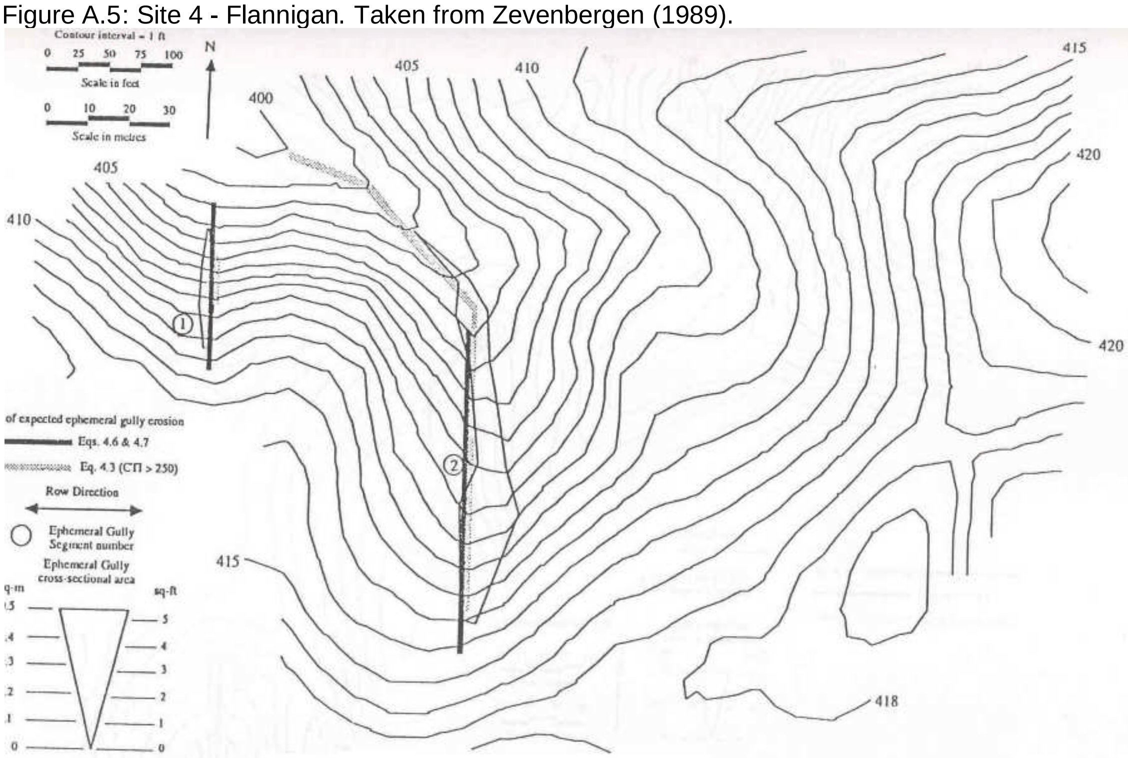
Site 3: *Ellis Site B* (within Goodwin Creek Experimental Watershed). Panola County, Mississippi: Loring soil. Landuse corn.

Figure A.4: Site 3 - Ellis Site B. Taken from Zevenbergen (1989).



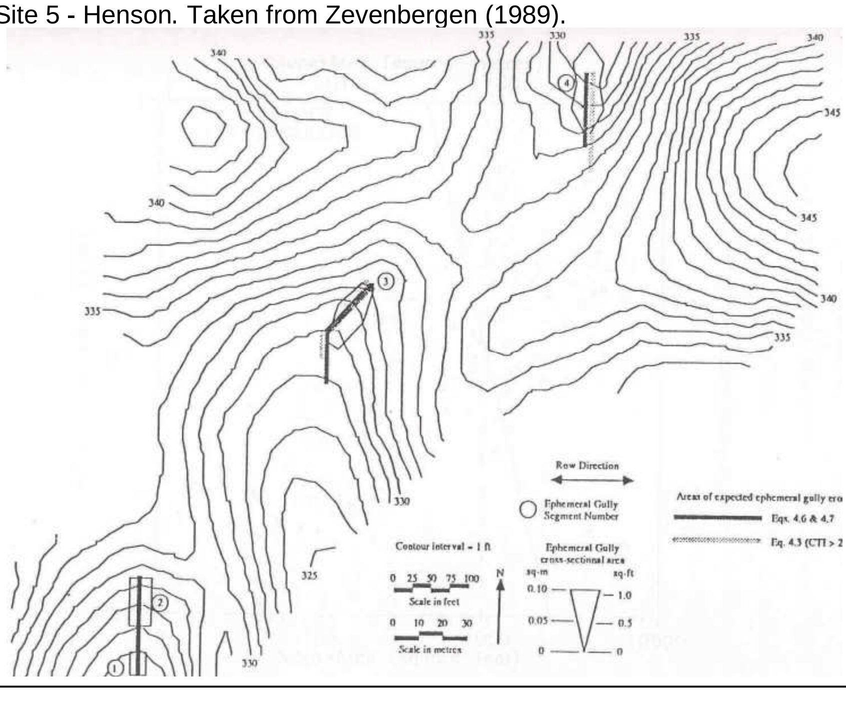
Site 4: *Flannigan Site* (within Goodwin Creek Experimental Watershed). Panola County, Mississippi: Loring soil. Landuse milo.

Figure A.5: Site 4 - Flannigan. Taken from Zevenbergen (1989).



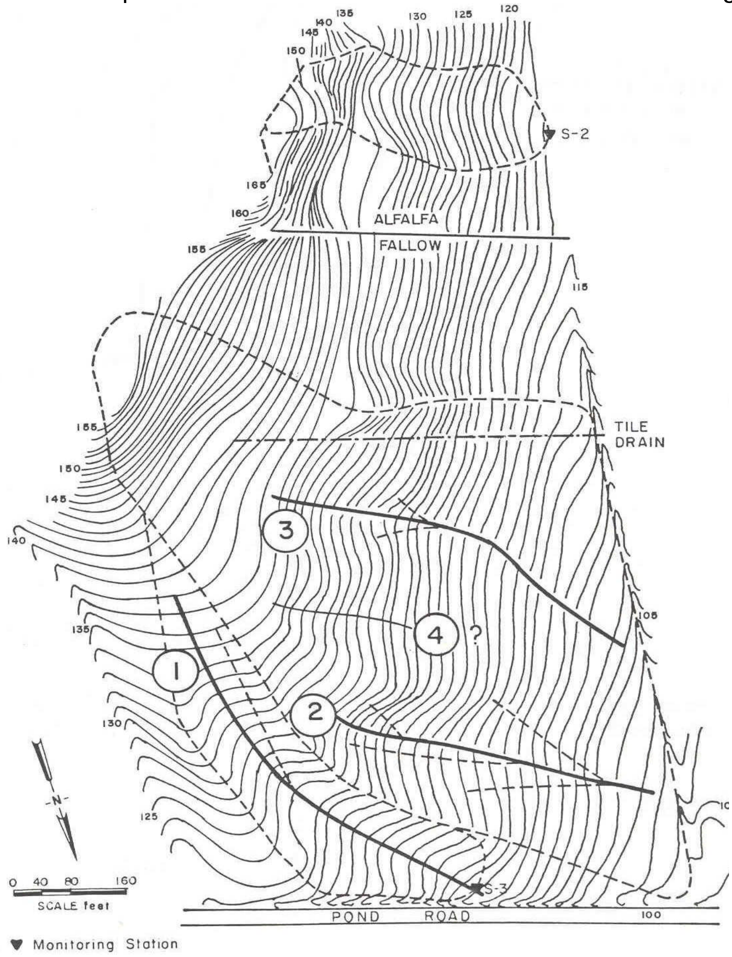
Site 5: *Henson Site*, Panola County, Mississippi: Loring soil. Landuse corn.

Figure A.6: Site 5 - Henson. Taken from Zevenbergen (1989).



Site 6: *New Hampshire site*. Data for this site was extracted from a paper by Thorne and Zevenbergen (1984). Within their report the authors credit Tom Iivari, SCS, Chester, Pa with the data, which included a 1ft elevation contour and gully location topographic map [Figure A.7]. Whilst this map provided all the data needed for this study, no further information was available for the site.

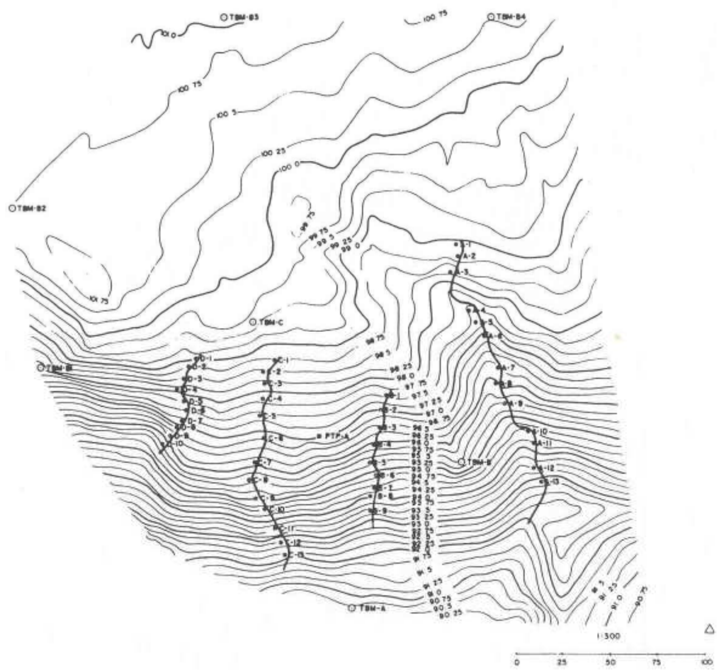
Figure A.7: Site 6 – New Hampshire watershed. Taken from Thorne and Zevenbergen (1984).



Finally, an additional 4 sites were taken from a study of ephemeral gullies in Mississippi by the late Lawson Smith, formerly of the US Army Corps of Engineers, Waterways Experiment Station. Each of the sites was surveyed using electronic distance measuring equipment and data points were obtained at sufficient proximity to complete topographic maps of the site, which have contour intervals of 0.25ft and 0.33ft [Figures A.8 to A.11]. Continuing from above these sites are:

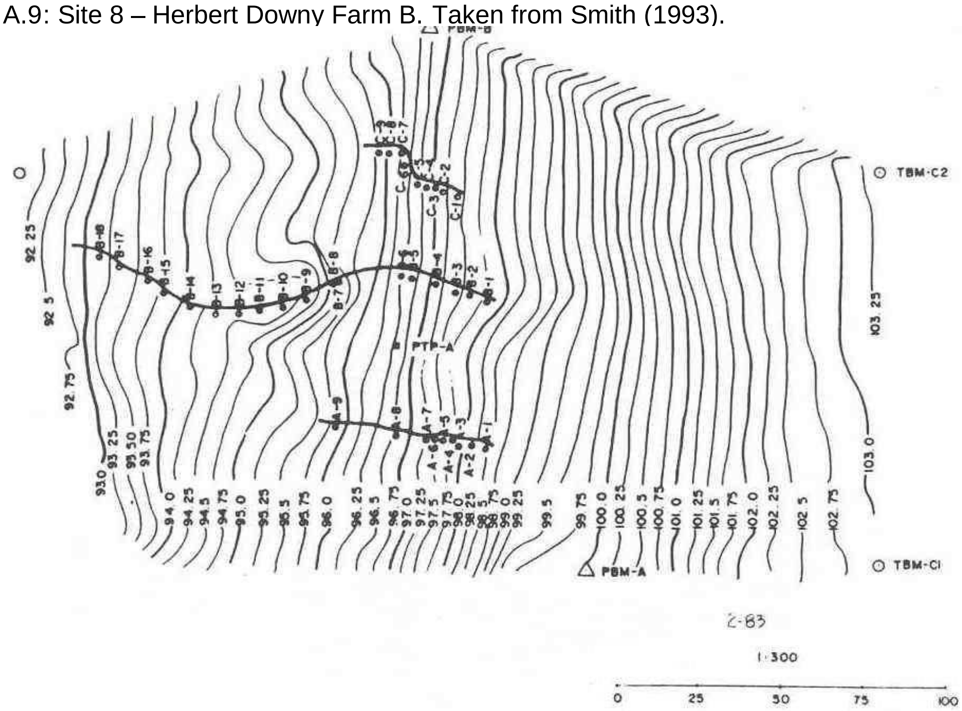
Site 7: Herbert Downey Farm A, Warren County, Mississippi: Memphis soil. Landuse soybeans.

Figure A.8: Site 7 – Herbert Downy Farm A. Taken from Smith (1993).



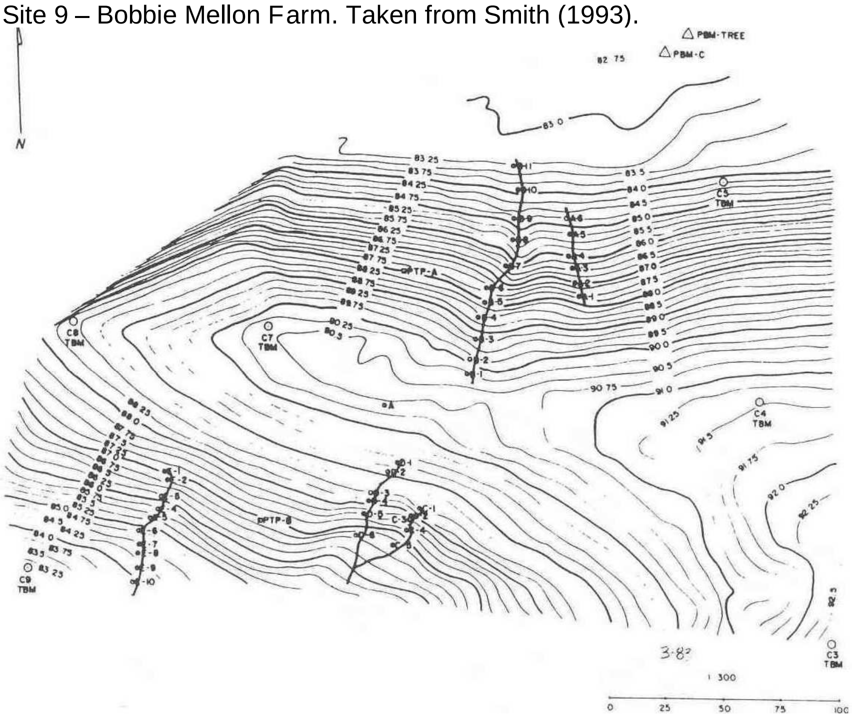
Site 8: Herbert Downey Farm B, Warren County, Mississippi: Memphis soil. Landuse soybeans.

Figure A.9: Site 8 – Herbert Downy Farm B. Taken from Smith (1993).



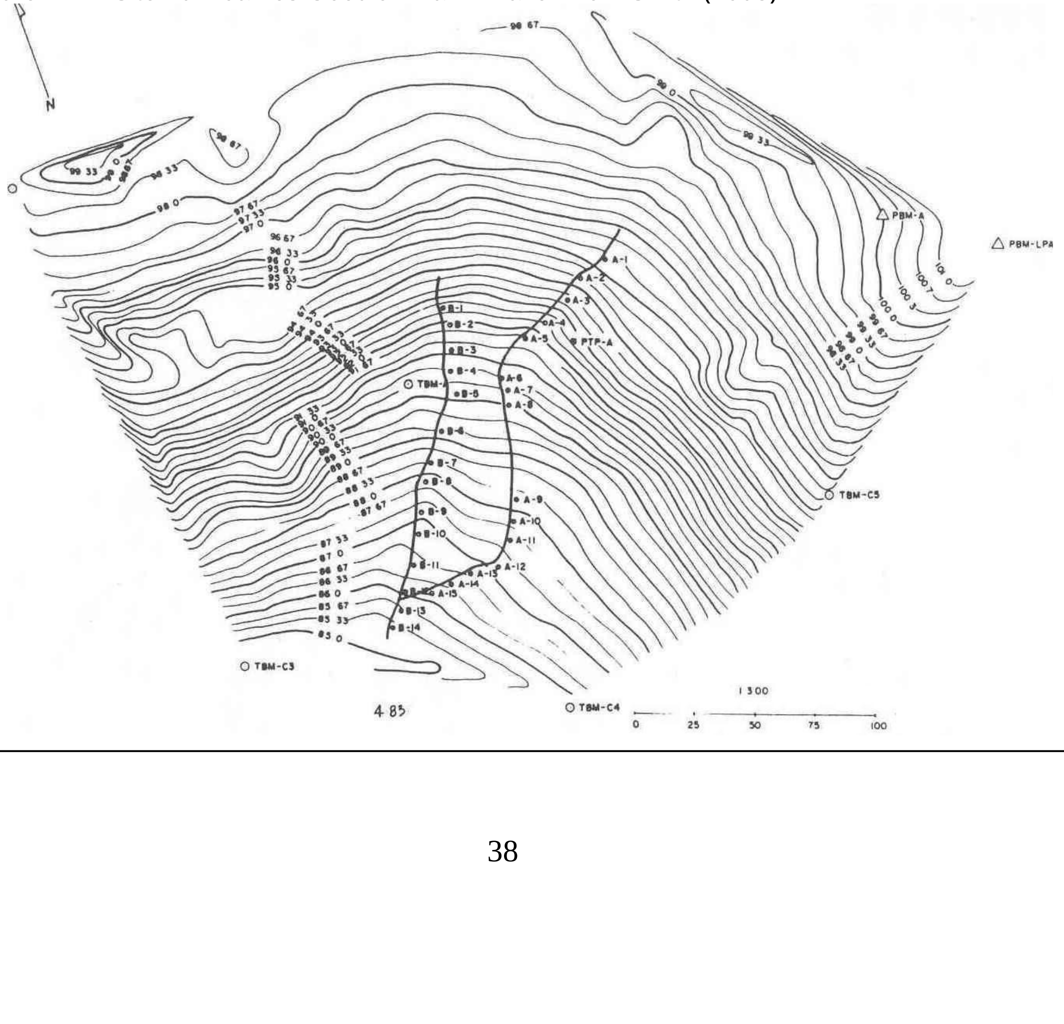
Site 9: Bobbie Mellon Farm, Hinds County, Mississippi: Loring soil. Landuse corn.

Figure A.10: Site 9 – Bobbie Mellon Farm. Taken from Smith (1993).



Site 10: James Goodlow Farm, Madison County, Mississippi: Providence soil. Landuse soybeans.

Figure A.11: Site 10 – James Goodlow Farm. Taken from Smith (1993).



Appendix B: CTI Analysis Methodology

These descriptions assume that the user has an understanding of the standard operations within an ArcView3.x system and has some experience with the TopAGNPS system. It is also assumed that the 'ArcView_Rasfor.inp' file has been adapted so that 'TSLOPE.OUT' is produced during the AGNPS process.

Remember that three components are required to calculate the CTI: slope, upstream area (as a proxy for runoff discharge), and planform curvature. Slope and upstream area are calculated within the TopAGNPS environment. Planform curvature is calculated within the DEMAT extension created for ArcView3.x by Behrens (2005).

To access the TopAGNPS environment:

TopAGNPS is incorporated into the AGNPS model, which can be accessed at http://www.ars.usda.gov/Research/docs.htm?docid=7000

Download and run the executable ZIP file.

Initiate the AGNPS ArcView environment by navigating to C:\AGNPS\Utility\AGNPS_Arcview_Interface

Run the executable ZIP file 'AGNPS_Arcview_Interface.exe'.

This will create a new directory: C:\AGNPS_Watershed_Studies\AGNPS_Arcview_Interface.

Change the generic name of 'AGNPS_ArcView_Interface to something distinct to your project.

To access the DEMAT extension:

DEMAT is available at no charge from the ESRI support center web site, http://support.esri.com. Search for 'ascr10222', 'DEMAT', or 'Zevenbergen', or access it directly at http://arcscripts.esri.com/details.asp?dbid=10222

Download and unZIP the file.

Put the .avx extension file into the ArcView extensions directory, C:\ESRI\AV_GIS30\ARCVIEW\EXT32

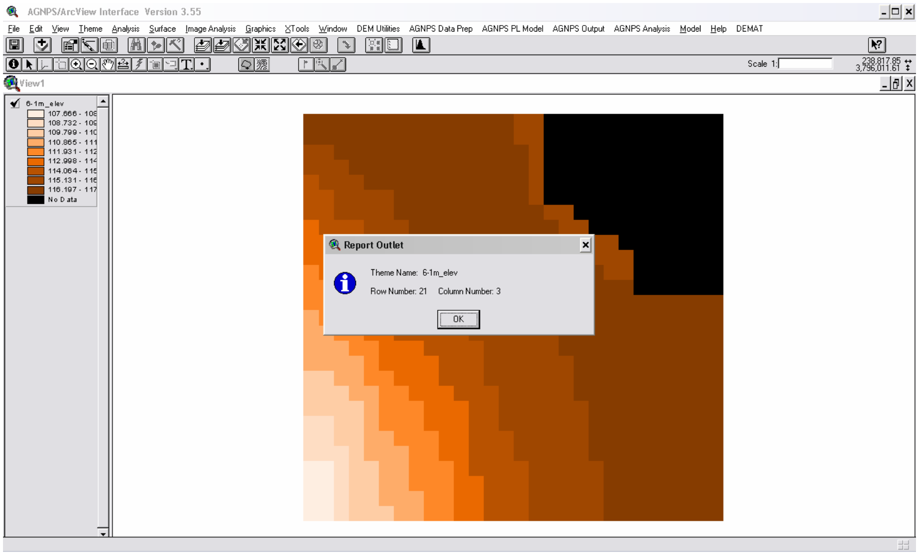
Start the AGNPS ArcView project:

Navigate to the renamed directory indicated above. Open the folder called '4_ArcView_Datasets. Inside is an ArcView project file, AGNPS.apr. Double-click on it to start the ArcView project. Agree in the two information pop-ups. Immediately save the project with a different name: File > Save Project As….

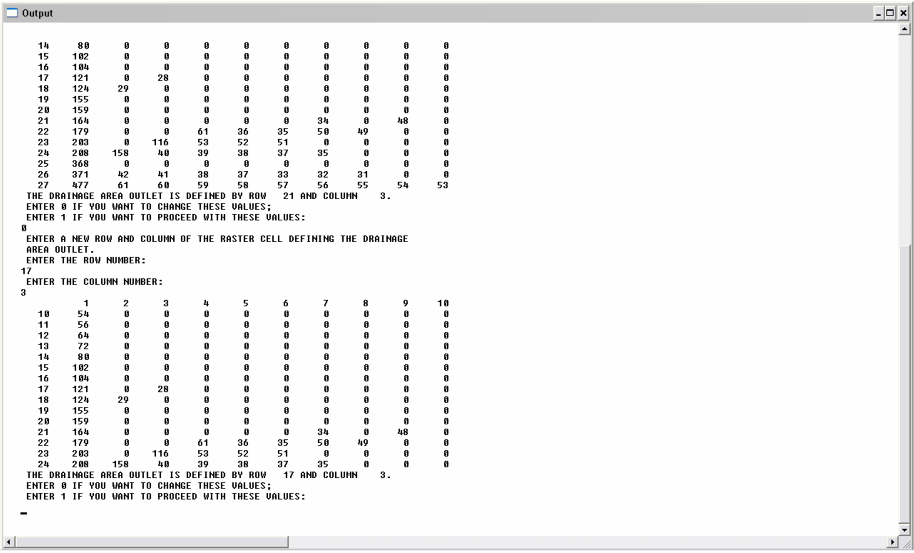
Activate the DEMAT extension. File > Extensions…. > scroll through the list and check the box next for 'DEMAT' > click OK. This will add the menu called DEMAT to the View GUI.

Now follow these steps:

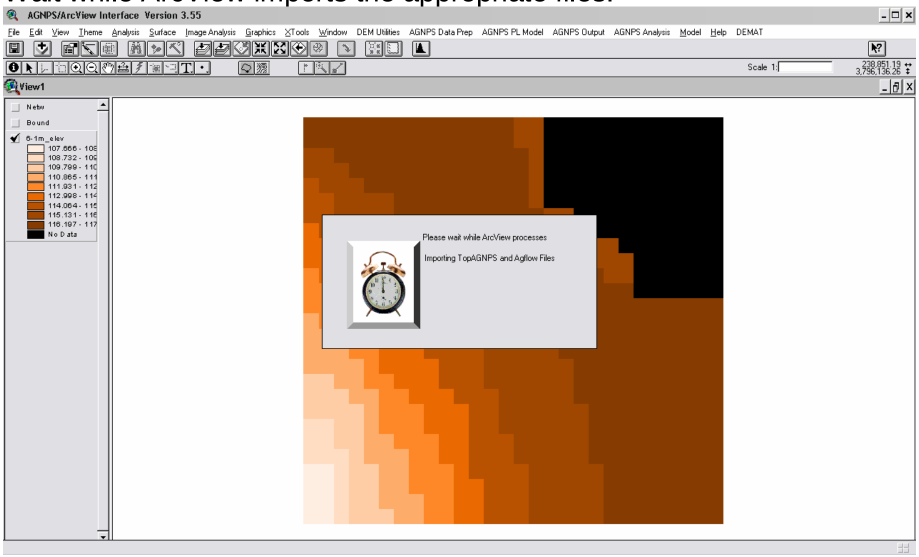
1. Open a new View and add the chosen digital elevation grid to the View.
2. Assign the chosen elevation grid as the AGNPS DEM theme. ['AGNPS Data Prep' → 'Assign Themes'].
3. Select a grid cell to be a watershed's outlet point for the analysis. ['AGNPS Data Prep' → 'Step 2 Select Watershed Outlet' → 'Interactively Select Outlet'. Then click on an appropriate grid cell that is likely to have a significant level of flow routed through it.] Note that this cell cannot be along the edge of the grid, nor can it be at the junction of two distinct flows.



4. Create the input files that control the TopAGNPS process. ['AGNPS Data Prep' → 'Step 3 Create TopAGNPS Input Files' → Choose the type of TopAGNPS run – 'Full' → Choose whether you would like to use variable CSA and MSCL values – 'No' → Choose whether you would like to input the CSA and MSCL values – 'Yes' → Enter appropriate CSA and MSCL values (CSA = Critical Source Area – defines the number of contributing upstream cells needed to register a raster cell as containing a channel; MSCL= Minimum Source Channel Length – defines the minimum channel length before the concentrated flow path can be defined as a channel at the downstream point of a source subwatershed). For this small example grid values of CSA = 0.1ha, MSCL = 10 meters are suitable.
5. Execute the TopAGNPS process. ['AGNPS Data Prep' → 'Step 4 Execute TopAGNPS' → Observe the output text for the DEDNM phase and follow the instructions to make sure the drainage outlet is defined by a cell that has flow routing through it.]

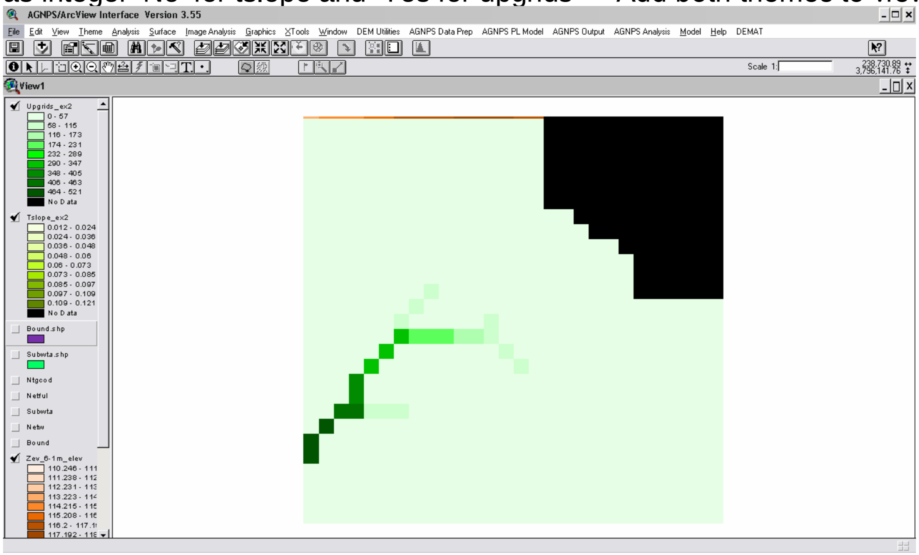


6. Once completed close the output window and report that the DEDNM phase executed correctly.
7. Observe the output window for the RASPRO phase and once completed close the window and report that it was executed correctly.
8. Observe the output window for the RASFOR phase and once completed close the window and report that it was executed correctly.
9. Observe the output window for the RASPRO ArcView output phase and once completed close the window and report that it was executed correctly.
10. Execute ‘AgFlow’. [‘AGNPS Data Prep’ → ‘Step 5 Execute Agflow’ → Observe output text and report that it executed correctly].
11. Import the TopAGNPS .arc files. [‘AGNPS Data Prep’ → Step 6 Import TopAGNPS *.arc Files → Enter an appropriate name for the grids to be filed in – For this example ‘Example’].
12. Wait while ArcView imports the appropriate files.

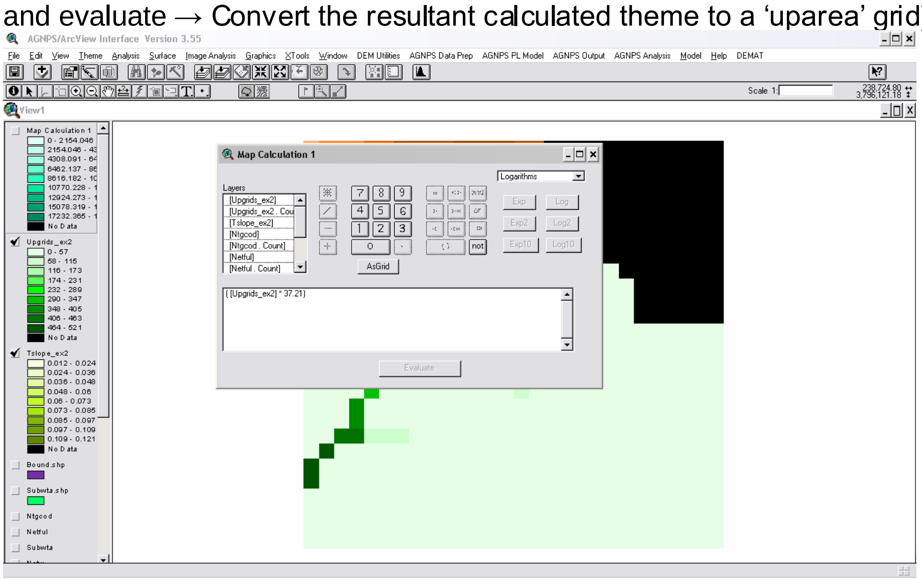


13. Move the TSLOPE.ARC file into the correct directory (as currently not automatically put in chosen output folder by TopAGNPS). [Move ‘TSLOPE.ARC’ from ‘1_TOPAGNPS_Datasets’ to ‘4_ArcView_Datasets’/’Example’.]

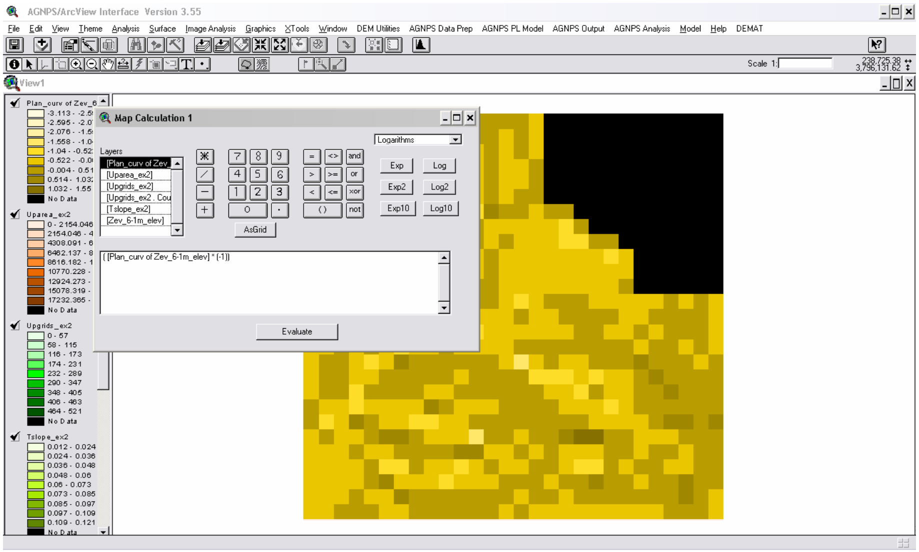
14. Import the TSLOPE and UPAREA .arc files as grids. [‘File’ → ‘Import Data Source’ → Select ‘ASCII Raster’ as import file type → List files of type ‘All’ → Choose ‘tslope.arc’ and ‘uparea.arc’ as the import files → Choose appropriate output grid names for each grid, for example ‘tslope_ex’ and upgrids_ex’ (upgrids rather than uparea as TopAGNPS gives the number of contributing grid cells rather than their area) → Choose cell values as integer ‘No’ for tslope and ‘Yes for upgrids → Add both themes to view.



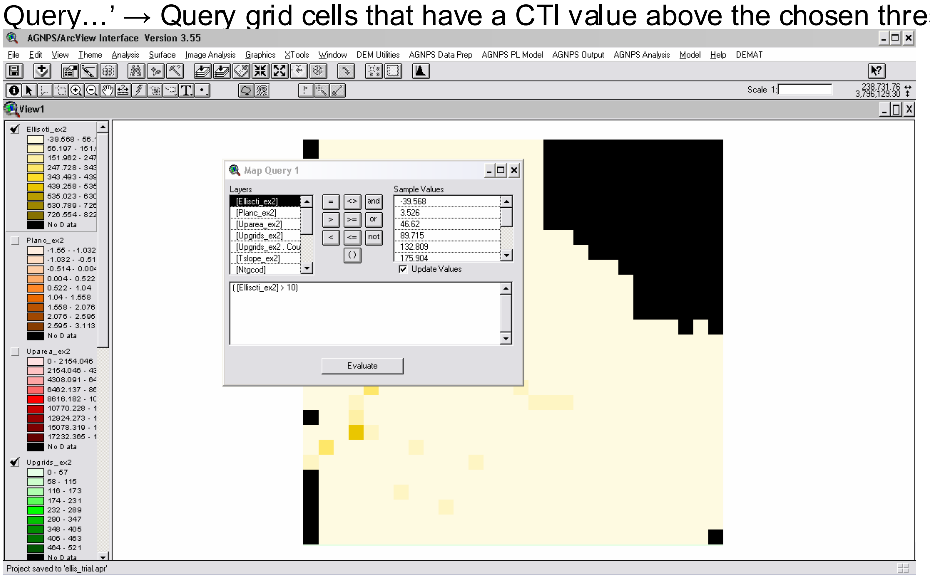
15. Convert ‘upgrids’ to ‘uparea’ using Map Calculator. The ‘uparea’ units should always be in meters. [‘Analysis’ → ‘Map Calculator…’ → multiply ‘upgrids’ by the area of a grid cell and evaluate → Convert the resultant calculated theme to a ‘uparea’ grid].



16. Use the DEMAT extension to generate a grid representing planform curvature. [Select the elevation grid theme → ‘DEMAT’ → ‘Plan Curvature’].
17. Convert the DEMAT plan curvature to usable CTI plan curvature by multiplying by negative 1 in Map Calculator [‘Analysis’ → ‘Map Calculator…’ → multiply ‘Plan_curv of Zev_6-1m_elev’ by (-1) → convert the resultant calculated theme to a ‘planc’ grid.]

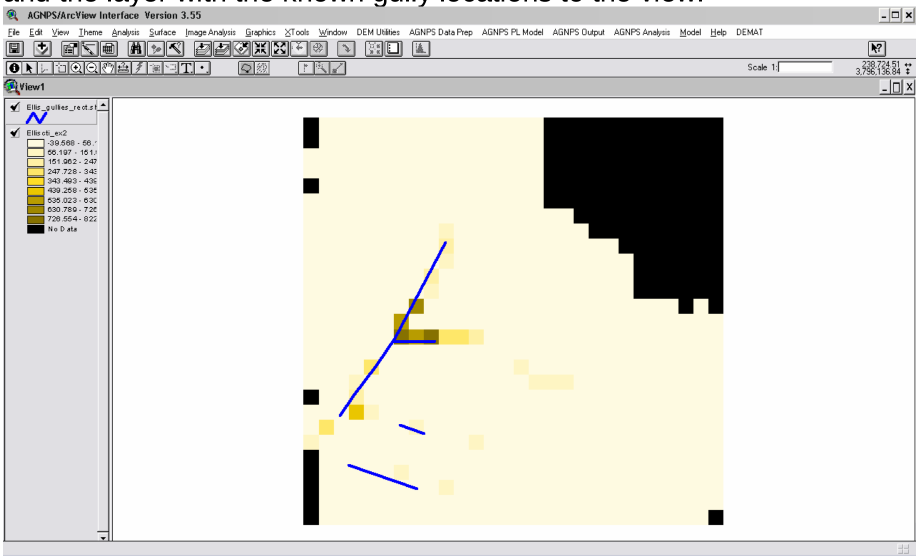


18. Calculate the CTI value using map calculator. [‘Analysis’ → ‘Map Calculator…’ → multiply ‘planc’ by ‘uparea’ by ‘tslope’ → convert the resultant calculation theme to a ‘CTI’ grid.]
19. Find which grid cells are above a certain threshold using map query. [‘Analysis’ → ‘Map Query…’ → Query grid cells that have a CTI value above the chosen threshold.]

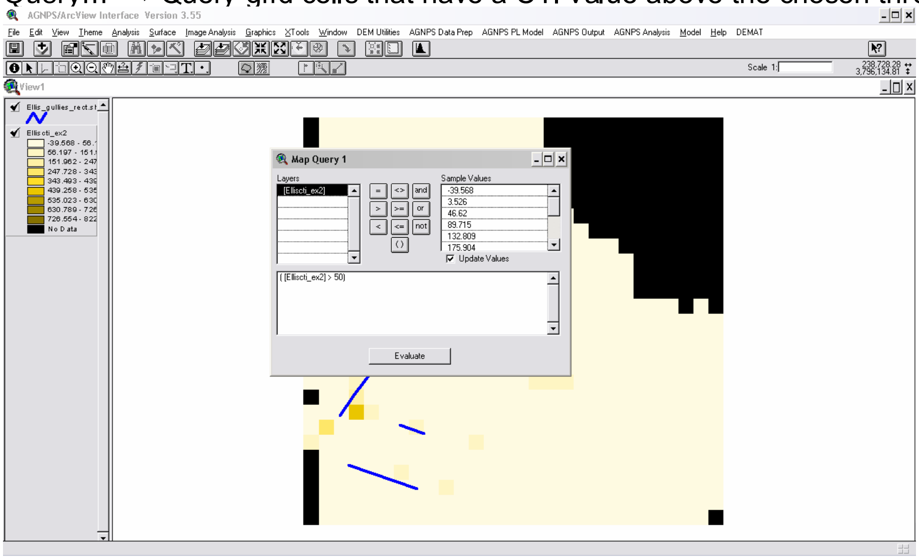


(ii) How to find the critical CTI value for a specific field site.

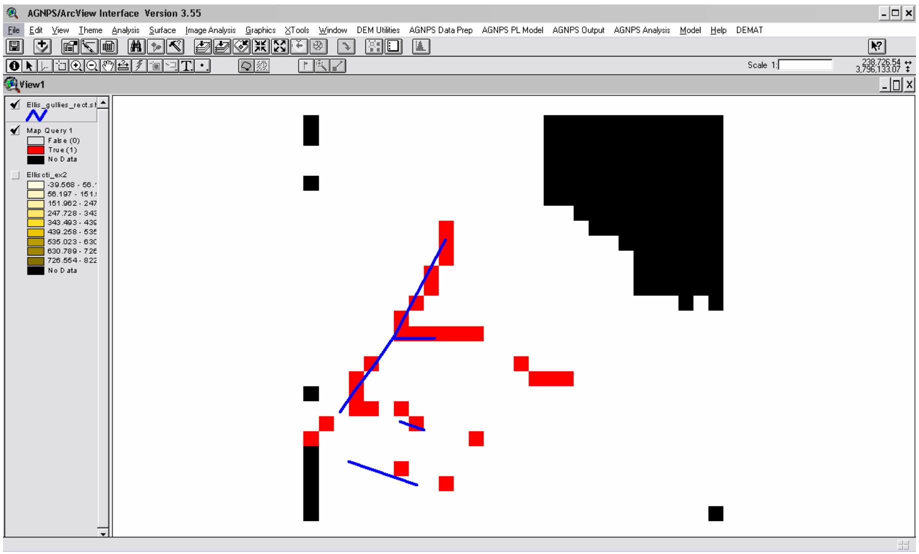
1. Open a new view in the AGNPS / ArcView interface and add the chosen CTI value grid and the layer with the known gully locations to the view.



2. Use map query to impose a threshold CTI value on the grid cells. [‘Analysis’ → ‘Map Query…’ → Query grid cells that have a CTI value above the chosen threshold.]



3. Compare the grid cells with values above that threshold and those below the threshold and decide whether that threshold value over or under represented the extent of gullies at the site.



4. If the chosen threshold value over represented the extent of gullies then use map query to find all grid cells with CTI values above a higher threshold. If the threshold value under represented the extent of gullies then select a new lower threshold.
5. Repeat for this second threshold and keep repeating until the best threshold for representing the extent of gullies at the selected field site has been found.