Integrating GIScience and Environmental Models

for a GISystem-based Natural Resource Management Tool

by

Martin William Minkowski

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Abstract

Soil erosion can be a serious problem, resulting in the removal of valuable nutrients within agricultural fields, the reduction of land along streams and rivers, and disturbing of ecological systems. Many tools have been developed over the past half century to try to predict erosion amounts; two of these tools, the Water Erosion Prediction Project (WEPP) and the geospatial interface for WEPP (GeoWEPP), work together to provide the user with the necessary information and visualization to determine which area within a watershed are most susceptible to erosion.

The current version of GeoWEPP uses a topographical parameterization program, called TOPAZ, to analysis the digital elevation model to determine the flow network of the DEM. When TOPAZ creates the subcatchments, the flow directions of all cells within the watershed are examined and the subcatchments are created based on which cells within the watershed flow into which side of the channel – left bank, right bank, or source. When the subcatchment information is passed to WEPP, a representative profile of the subcatchment is created; this profile is a generalization of the slope and length of each possible flowpath within a subcatchment. This results in a loss of the nuisances within the watershed.

The goal of this research is to create a better representation of the watershed approach within GeoWEPP. To this end, a Visual Basic program, called VBFlow, was created to subdivide the large subcatchments into smaller ones based on how the watershed flows into each channel raster cell. The focus of this research is how well the new subcatchments created represent the real world; there are three aspects that need to be validated to demonstrate the accuracy of the new modifications. First, the topography of the simulated study area needs to be correlated with the observed topography. Once this has been confirmed, the simulated hydrology and the observed hydrology need to be compared to demonstrate the accuracy of the hydrologic component of the model. The final aspect looks at the geomorphology of the study site; the simulated erosion and sediment yields need to be compared to observed values. The simplest way to validate the new subcatchments is to hold all other parameters as constants, except for the subcatchment creation. This is done using data for the Lucky Hills nested watershed outside of Tombstone, Arizona.

Three separate scenarios were created to test VBFlow: short-term assessment, long-term assessment, and onsite assessment; the purpose of these scenarios is to determine how well both subcatchment creation methods, GeoWEPP/TOPAZ and VBFlow, perform when compared to observed results. The short-term assessment used two storm series: the 1982 and 1984 storm seasons. The hydrology and geomorphology for the large watershed showed that both creation methods performed very well compared to the observed values. For the smaller watershed, it appears that VBFlow performs slightly better in regards to the runoff compared to the observed values, but the remaining variables – peak runoff and sediment yield – can not be compared at this time due to a lack in observed values. Once these data gaps are filled, a complete analysis of the performance of both methods within the smaller watershed can be completed.

The long-term assessment consisted of a 50 year simulation; the same input parameters used in the short-term assessment were used in this scenario, except different climate files were used. This scenario lacked observed data, so only a comparison between the simulated results was made at this time. An unforeseen issue occur when the VBFlow simulations were ran: reported extreme sediment transport values within the channels and extreme sediment yield values at the outlet point. Since these extreme values occur after a certain point, the 50 year simulation was divided into 10 five year simulations; each five year simulations would use a different five years of climate data. The end result showed that VBFlow and GeoWEPP provide very similar results. Therefore, the problem exists between how the subcatchment information is being passed into WEPP and back.

In the final scenario, the simulated soil loss/gain for the large nested watershed over 50 years was compared to observed sample sites. Unfortunately, no correlation was observed between the observed and predicted values. Many factors contribute to this lack of correlation; experimentation with input parameters and new sample sites could improve the correlation between the sample sites and the simulated results, but the accuracy of the watershed method should not be sacrificed.

The research present in this work shows that VBFlow has the potential to improve upon GeoWEPP, but more testing is needed before this can be confirmed. The scenarios created for VBFlow validation need to be completed before the validation can continue. Once this series of scenarios had been completed and it has been determined that the new subcatchment creation method could be a benefit, more scenarios will be tests by varying soil and landuse data. From that point, more testing is other watersheds will also be necessary to determine the flexibility of the improved GeoWEPP.

1 Introduction

Soil erosion can be a serious problem, resulting in the removal of valuable nutrients within agricultural fields, the reduction of land along streams and rivers, and disturbing ecological systems. The results can be devastating to the environment with the introduction of more sediment within the channel network and lakes. If a storm or series of storms are strong enough, mudslides can also occur, resulting in major upheaval of ecosystems, damage to man-made structures, and the loss of life. Many tools have been developed over the past half century to try to predict erosion amounts; two of these tools, the Water Erosion Prediction Project (WEPP) and the geospatial interface for WEPP (GeoWEPP), work together to provide the user with the necessary information and visualization to determine which area within a watershed are most susceptible to erosion.

In 1910, a deadly fire rage across the Rocky Mountains, burning over 5 million acres of woodland and killing 79 fire fighters. The media soon dubbed wildfires as natural disasters and the public pressured local and federal governments to prevent deadly fires from occurring. The growth of the population and the migration west had moved innocent people into regions that were susceptible to natural (and man-made) fires (Davis 2001).

From these pressures grew the policy of "Total Suppression", a policy that would not change for many years and has caused some major (and deadly) effects on the environment. This policy prevented all fires, including natural ones, from spreading. The end result is the growth of the understory, the brush and smaller plants on the forests floor that would normally be cleared by natural fires. The introduction of this new growth had several effects on the forest landscape. First, the increase in plant material increased the amount of canopy within the forest; this reduced the amount of rainfall that can directly reach the forest floor and also reduce the speed of incoming raindrops resulting in a reduction in splash erosion. The new plant material also changed the way water flowed across the landscape. The presence of these plants altered the flow patterns within the forest, changing where soil is eroded and deposited. These plants also reduced the amount of erosion possible by binding the soil with their roots; prevent the soil from being eroded away by fluvial processes.

The increase in understory growth not only reduced the amount of erosion possible with the forest, it also increased the fuel load by providing more standing vegetation and dead vegetation for the fires to consume. When a fire does occur in this type of forest landscape, the fire burned more intense and spreads faster. The end result is the sudden remove of the understory – the "natural" erosion barriers within the forest. These same fires would also change the mineral properties to a more hydrophobic one, thus reducing the amount of water that can infiltrate into the landscape. The combination of these two factors results in conditions ripe for mass erosion and mudflows (Wade and Lunsford 1988).

The prevention of these major events is the main goal the US Forest Service Burned Area Emergency Response (BAER) Teams; these teams attempt to rehabilitate areas burned by wildfires. The goal is to implement erosion manage plans within the burned areas to prevent the mass erosion that would occur during and after the first rainstorms following the fire. These teams use many tools to aid in this recover and rehabilitation process, including WEPP and GeoWEPP. The main focus of this research is to improve on GeoWEPP's representation of watersheds, so that a more accurate simulation of erosion processes can be created. Thus, by improving the tools the BAER teams use, the better the management plans can be developed; this could lead to better and faster implementation.

Before any model can be created or improved upon, it is best to have an understanding of what is being modeled and to review previous attempts made to model it. The next several sections discuss the erosion process and some of the previous models that have been created to in an attempt to understand and predict the effects of the erosion process.

1.1 The Water Erosion Process

Erosion is the removal of material from one location by an outside mechanism, while deposition is the placement of material at another location by an outside mechanism; much of the literature concentrates on fluvial erosion. The outside mechanism for fluvial erosion is water and can be broken down into three forms: precipitation, overland flow and stream flow. The initial stages of erosion begin with rainfall and splash erosion, when a raindrop strikes unprotected soil. When the rain drop impacts the soil, it creates an impact crater, blasting particles of soil upward and outward from its original position; when this occurs on slopes, the particles tend to move down hill. Overland flow – rill, interrill, and sheet flow – is the focus of most erosion studies.

Erosion on Hillslopes

Much of the rainfall during the beginning of a storm will strike the ground and infiltrate into the soil, so there is little or no water movement on the surface. Soil particles are moved by splash erosion, but this is only small distances. But there is a point during the storm when the rainfall rate of the storm exceeds the infiltration rate of the soil, resulting in the accumulation of water on the surface. Gravity, along with surface tension, will cause the water collecting on the surface to travel down slope, forming overland flow. Initially, this flow forms a thin sheet over the surface called sheet flow. As the sheet flow travels along the surface, it begins to pick up the splash eroded soil particles, causing rill and interrill erosion.

Rill Erosion

As the sheet flow travels down slope, it picks up speed and its water volume increase. With this increase in speed and volume, more soil particles can be transported. Eventually, turbulence begins to break up the sheet flow into multiple tiny channels called rills. This concentrated flow can now erode more soil particles; the increase in speed and volume increases the flows carrying capacity; it also begins to loosen and erode soils through hydraulic power. The result is called rill erosion.

Gully Erosion

If this process continues, the rills will begin to converge forming larger rills, called gullies, causing gully erosion. As these gullies begin to get larger, they become part of the drainage system within the landscape. This is the transition from overland flow to stream flow. This more concentrated flow increase the erosion ability of water by producing a flow that has more volume which increases the amount of sediment the flow can carry; this allows for more soil to be eroded. The flow speed also has an effect on the carrying capacity of the flow; faster moving water can carry more sediment than slower moving flows. The combination of speed and volume results in more erosive power than that seen in overland or rill flows.

Channel Erosion

Finally, gullies eventually flow into channels. Once water has entered the channel, its ability to erode soils is greatly increased. Through a combination of hydraulic power, abrasive sediment, and chemical reactions, channeled water can erode channel bottoms to bedrock, while meandering streams can erode away channel banks creating broader valley floors. In most case, channels contain continuous flows of water whose sources come from the above mentioned overland flows, subsurface flows, and sites of water storage (for example: aquifers and lakes). While overland, rill, and gully flows remove materials from the watershed’s surface, channeled water transports the sediment from these source to an outlet point – whether it be a flume, another watershed, lake, or ocean.

An understanding of the erosion process is the first step in developing models to mimic the processes. Scientists have been attempting to create models for more than a half century. The early attempts tried to simplify the erosion process. Later models tried to incorporate the dynamic nature of erosion. The next section discusses these early models, the improvements on these models and the introduction of newer models. Since of these newer models have been incorporated into Geographic Information Systems, a brief history of the development of GIS is also discussed.

1.2 Modeling Erosion

The study, modeling, and prediction of soil erosion is a relatively young field. The early study tried to determine the factors that contribute to the erodibility of soil by fluvial process. H. L. Cook identified three factors – the soil's susceptibility to erosion, the potential for erosion due to runoff and rainfall, and the protection plant cover provides soil – that contribute to increase or decrease in erosion (Cook 1936). Several years later, slope steepness and slope length were added (Zingg 1940).

Over the next decade, more factors were added. Factors for cropping systems, support practices, soil erodibility, and soil management were added; the introduction of a specific annual soil-loss limit and more extensive tables were created listing values for different soils, crop rotations, and slope lengths were also introduced. More emphasis began to be placed on slope: slope length limitations on different cropping systems with specific soils and recommended length limits for contour farming, and soil-loss ratios for contour farming, stripcropping, and terracing at different slopes were presented (Smith 1941; Browning, Parish et al. 1947; Smith and Whitt 1947).

1.2.1 Simulating Long Term Plot Scale Soil Erosion

In 1948, Smith and Whitt presented a new equation for estimating erosion at the plot scale (Eq 1). This erosion equation incorporates several factors that take into account the soil erodibility, slope length and steepness, cover and management practices. The equation was meant to be applied to the soils of Missouri and included many of the factors that have been discussed over the past, but it lacked a factor for rainfall into the systems (Smith and Whitt 1948).

$$A = R \times K \times L \times S \times C \times P \qquad \text{(Eq 1)}$$

where:

A – Average annual soil loss by water ($t \cdot ha^{-1} \cdot y^{-1}$)
R – Rainfall-runoff Erosivity Factor (hundreds of $m \cdot km \cdot kg \cdot s^{-2} \cdot mm \cdot ha^{-1} \cdot y^{-1}$)
K – Soil Erodibility Factor ($t \cdot ha \cdot h \cdot [\text{hundreds of } m^3 \cdot km \cdot kg \cdot s^{-2} \cdot mm]^{-1}$)
L – Slope Length (dimensionless)
S – Slope Steepness Factor (dimensionless)
C – Cover-management Factor (dimensionless)
P – Support Practice Factor (ex: contouring, stripcropping, terracing) (dimensionless)
(Renard, Foster et al. 1997)

Other regions in the US began to develop their own soil-loss equations for their localized conditions. The Musgrave equation built upon Smith and Whitt's equation and was developed for the US Corn Belt. Factors for rainfall, soil characteristics, vegetation cover, and runoff due to slope characteristics (length and steepness) were added to the equation (Musgrave 1947). An equation for soil loss in Illinois estimated soil loss using a number of factors, including a soil loss factor based on measurements from soil plots (Van Doren and Bartelli 1956). These and many other equations became so useful that it created a push for the creation of an equation that could be applied nation wide. This push resulted in the establishment of the National Runoff and Soil Loss Data Center in West Lafayette, Indiana, at Purdue University in 1954. From the research by and data collected at the Data Center, a new nationwide equation was created – the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1958).

It took time for the widespread acceptance of USLE. As USLE became more accepted, more research and experiments added to the improvement of USLE. Some of these improvements included a time-varying approach to simulate freeze-thaw and subfactors for the cover-management factor (C) for certain areas including rangelands and croplands. The equation was modified by combing the slope steepness and slope length into one factor (LS), which also includes the ratio of rill to interrill erosion (Renard, Foster et al. 1997). Modifications to the USLE equation were made to produce the Modified USLE (MUSLE), which estimates sediment yield for a single event. In MUSLE, the rainfall factor was replaced with a runoff energy factor. The estimated results obtained using MUSLE are reliable for small watersheds, less than 13 km^2. Eventually, users demanded more flexibility in erosion modeling, so revisions were made to USLE and imported into computer systems, creating the Revised USLE (RUSLE) (Renard, Foster et al. 1997). These revisions improved the USLE, but there are still limitations. RUSLE can predict long-term sheet and rill erosion, but its predictions are applied to the entire study site; there is no spatial distribution of erosion. RUSLE also does not account for deposition, gully erosion, channel bank erosion, or sediment yields(Renard, Foster et al. 1997).

The development of USLE and RUSLE lead to the development of other models, including AGNPS. The AGricultural NonPoint Source model (AGNPS) is an event-based model developed by the US Department of Agriculture – Agriculture Research Service (Aksoy and Kavvas Article in Press); the model was developed to predict the water quality of runoff from catchments that measure in size from a few hectares to as large as 20,000 hectares. AGNPS contains a mix of empirical (USLE, RUSLE) and physically based components. The input parameters for AGNPS include precipitation data, channel morphology, hill slope, hill length, soil texture, impoundment factor, fertilizer levels, Soil Conservation Service (SCS) curve numbers (a rainfall-runoff relation model number), Manning's roughness coefficient, and landuse variations (Merritt, Letcher et al. 2003). The model simulates runoff, sediment, and nutrient transport from agricultural watersheds; the watershed is subdivided into uniformly distributed square cells ranging from 0.4 to 16 hectares. Upland erosion is estimated by using the USLE. Model outputs include: runoff volume; peak runoff rate; sediment yield, concentration, particle size and distribution; upland erosion; amount/percent of deposition. Soluble Nitrogen (N) and Phosphorous (P), as well as sediment bounded N and P are also computed.

From these early models, scientists were able to create newer models that accounted for some of the aspects the empirical models could not incorporate. These new process based models were developed using newer computer technologies and the advances in Geographic Information

Systems. The next section discusses several of these newer models and concludes with a comparison on their capabilities by Nearing et al. (2005).

1.2.2 Event-based and Watershed Scale Process Modeling

The early erosion models lacked some of the variability found on the real world; new models were developed to incorporate the missing "natural" aspect of the erosion process. The early models lacked the dynamic weather conditions and did not approach the erosion process from a truly spatial point of view. Newer models began to represent the watershed as small catchments of different dimensions and shifted from the long-term approach to short-term or individual storm events assessments.

The introduction of computers aided in this shift. Before computers, maps were considered to be static; the information these maps held were considered to be valid for decades. The introduction and widespread use of computers changed this. Scientists were about to incorporate other sources of information, like aerial photographs and satellite images into Geographic Information Systems (GIS) to create more up to date and dynamic maps. Scientists were also able to obtained more detailed representations of areas that could not be derived from older topographic maps. This section provides a brief description of a few of these newer process-based models and concludes with a discussion on the sensitivity analysis Nearing, Jetten et al. (2005) performed on these models.

SWAT

The Soil and Water Assessment Tool (SWAT), developed by the USDA-ARS, is a watershed scale model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time; SWAT is a long-term yield, process based model that simulates the movement of water, nutrients, chemicals, and sediment within a watershed (Arnold, Srinivasan et al. 1999; Neitsch, Arnold et al. 2002). Even though SWAT is a process based model, it still contains some empirical methods. Swat uses the SCS Curve Number method to estimate runoff and MUSLE to estimate the sediment yield from the watershed. SWAT also assumes a triangular rainfall distribution during each simulation day; this causes a problem when specific storm results have a different distribution than that entered into the SWAT model (Nearing, Jetten et al. 2005).

KINEROS

KINEROS (KINematic EROsion Simulation) was developed for the USDA-ARS by Smith et al. (1995). KINEROS "is a distributed, event-oriented, deterministic and physically based model. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds" (Nearing, Jetten et al. 2005). KINEROS requires that the watershed be broken down into homogeneous catchments, which the developers call overland flow planes, and channel segments. KINEROS2 modifies this so that the overland flow planes equal the area of the contributing catchments. The channel segments receive water and sediments uniformly from the channel sides, upstream channels or from the overland flow plane. Rainfall on the channel is not considered. Erosion and deposition rates are the combination of splash erosion and hydraulic erosion and deposition rates (Aksoy and Kavvas Article in Press).

STREAM

STREAM (Spatial Tool for River basins, Environment and Analysis of Management) is "a grid-based spatial water balance model for estimating runoff amounts in river basins" (Aerts, Bouwer et al. 2005). STREAM – a non-dynamic, single event based model – is based upon what Aerts, Bouwer et al. (2005) call a 'multi-compartment' methodology; the hydrologic cycle within a watershed is considered a series of storage compartments and flows between compartments. STREAM calculates the water balance – the balance between precipitation (input) and runoff and evapotranspiration (outputs) – for each raster cell. STREAM takes into account soil surface characteristics to derive infiltration rates and soil erodibility {Nearing, 2005 #17}.

STREAM operates at both small and large scales. At the scale, or plot scale, seven factors are combined to define the infiltration capacity, soil water storage, and the potential sediment concentration of the flow: rainfall amount and duration, surface sealing, random and oriented roughness, vegetation cover, and an antecedent rainfall index. At the large scale, or watershed level, the flow network is based on the topography; it but also takes into account features, like furrows and ditches, which may influence flow directions within the watershed. Sediment is routed with the flow in each pixel, the size of which is dictated by the DEM resolution, as a function of inflow from upslope {Nearing, 2005 #17}.

LISEM

"Because of spatial and temporal variation in runoff and soil erosion processes, GIS has been a very useful tool to use in hydrological applications. The LImburg Soil Erosion Model (LISEM) (De Roo et al., 1996) is one of the first models that use GIS" (Aksoy and Kavvas Article in Press). LISEM mostly uses empirically derived equations and uses raster based information for the watershed. The raster information is loaded into the model using PCRaster, a raster based program. LISEM is able to simulate the hydrology and sediment transport within a small catchment (10 to 300 hectares) during and after a storm event. LISEM incorporated rainfall, interception, surface storage, infiltration, vertical movement of water within the soil, overland and channel flow, soil detachment due to rainfall, transport capacity, and detachment by overland flow. The latest developments include P, NO_3 and NH_4 loss, gully formation, and multiple sediment classes for erosion and deposition(DeRoo 1998).

MEFIDIS

MEFIDIS, short for Physically-based Distribution Erosion Model in Portuguese, simulates erosion for short-duration storm events at a scale where the erosive factors can be considered homogenous. Therefore, the variability mostly depends on rainfall and the characteristics of the watershed. MEFIDIS requires several raster maps as input: altimetry, landuse, soil type, rainfall, and soil moisture (Nunes, Vieira et al. 2001). The soil type parameters include hydraulic conductivity, soil suction, effective porosity, critical shear stress for cohesive sediments, and median soil particle diameter.

MEFIDIS uses a cellular automata approach to distribute the runoff and detach soil. First, the watershed is divided into homogenous square cells. The basic physical processes are simulated within each cell and the resulting runoff and detached soil are then distributed to each cell's neighbors (Nunes, Vieira et al. 2001). The runoff direction flows toward the cell with the steepest slope. Rainfall, infiltration, and surface storage are all taken into account by MEDFIDIS; the Green-Ampt equation is used for infiltration. Within MEDFIDIS, interrill soil detachment is assumed to be caused by splash erosion; vegetation and ground cover are assumed to protect soil from detachment (Nearing, Jetten et al. 2005).

WEPP

The Water Erosion Prediction Project (WEPP) is a processed based erosion model that incorporates hill slope, hill length, climate, management/vegetation information, and soil information to predict possible soil erosion. WEPP, developed by the US Department of Agriculture, "represents a new erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics" (Flanagan and Nearing 1995, p. 1.2). This type of process based software modeling allows for a more dynamic model that accounts for plant growth and seasonal change in a temporal format; thus, moves beyond the empirical formulas, like USLE. Like KINEROS2, the watershed's catchments are represented by rectangular objects that have the same area as the actual catchment. Channels are represented by line segments with the same length as the watershed's channel section. WEPP uses a representative hillslope profile for each catchment to calculate the amount of soil loss and deposition. One of the benefits of WEPP is that a single hill or the entire watershed can be modeled (Flanagan and Nearing 1995).

GeoWEPP

A watershed needs to be created within WEPP to run the watershed method; this construction method is time consuming and can introduce errors. To increase accuracy and decrease construction time, Dr. Renschler created GeoWEPP – the Geo-spatial interface for WEPP. GeoWEPP uses current GIS technology and commonly available data to import the watershed input parameters into WEPP. GeoWEPP uses a digital elevation model (DEM) to lay out the topography of the watershed and to delineate the channel network. GeoWEPP, which runs in ESRI's ArcView, also prepares the soil and management parameters using raster layers for each. From these inputs, WEPP is able to create a watershed. Once the model has completed its run, the resulting spatial erosion patterns and sediment yields are displayed within the GIS. GeoWEPP provides a more accurate spatial distribution than is practical in WEPP.

Nearing, Jetten et al. (2005) ran a sensitivity analysis on each of the above models based on variations of a few key input parameters. "Sensitivity of runoff amounts, peak runoff rates, gross erosion, and net sediment yield were assessed relative to changes in rainfall intensities and amounts and differences in canopy and ground cover" (Nearing, Jetten et al. 2005, p. 136). The models used vary in their ability to handle spatial and temporal components of soil erosion. Spatial and temporal distributions are import when trying to model and understand the processes taking place within a watershed. Spatial variations in soil parameters (e.g. hydroconductivity, permeability, and soil make-up) and vegetation (e.g. type, canopy cover, and amount), along with the topography (e.g. slope), influence the amount of erosion that will occur due to hydrologic processes. Temporal changes in climate, which increase and decrease the amount of precipitation, and vegetation (changes in type, density, live vs. dead biomass) also influence the amount of soil eroded over time.

RUSLE uses empirical formula and constant plant and rainfall parameters on a monthly series to determine erosion, so neither spatial nor temporal factors affect the outcome. STREAM is non-dynamic spatial model, but it lacks a temporal element. MEFIDIS, LISEM, and KINEROS are all event-based spatial models; the events are short duration storms, but they do not account for multiple events. SWAT and WEPP are the only models that contain a long term temporal aspect along with a spatial parameter. SWAT is used to model long term changes within a channel. WEPP changes the vegetation over time and simulated events over the entire multiple year simulations(Flanagan and Nearing 1995).

The results of the Flanagan and Nearing analysis show that all the models responded with increase erosion when there was an increase in rainfall intensity. All the models also showed a decrease in erosion when the soil cover and canopy where increased. These were the expect results since an increase erosion corresponds to an increase in rainfall intensity and a decrease in erosion is expected when the soil cover and canopy is increased. The only exception to this was RUSLE which had a higher sensitivity to soil cover than it did for rainfall intensity. This may be due to the nature of the equation (annual vs. event-based). In fact, RUSLE showed the least amount of fluctuation for all the scenarios. This is due to the empirical nature of the model, where only a few parameters may change from scenario to scenario. The end result was that RUSLE had a lesser sensitivity to rainfall changes and a greater sensitivity to soil cover than the process-based models (Nearing, Jetten et al. 2005).

Knowing what is being model and how it has been model are two important piece of information one needs to create or modify an erosion model. One final piece of information is needed to complete this task; why is it being model? The next section discusses one of reason why erosion needs to be model and this is the driver force behind the research present here.

1.3 Decision-support for Natural Resource Management

The US Department of Agriculture - US Forest Service has a major interest in being able to predict spatially distributed erosion patterns. Erosion is a common and potentially deadly occurrence in forested regions that have recently suffered a wildfire; the result of a long history of “Total Suppression”. The US Forest Service has created special teams, called Burned Area

Emergency Response (BAER) teams, whose soul purpose is to implement soil management plans within watersheds that have suffered from wildfires. Their goal is to create structures and managements that will reduce the potential for deadly and devastating mudflows from occurring. The team surveys the burned area once the fire has been extinguished to determine where the best locations will be to implement erosion prevention plans. These plans consist of either the planting of grasses, the distribution of ground cover material to prevent mass wasting, the moving of fallen tree trunks to act as erosion barriers or dams, and many other techniques.

Since the BAER team's goal is to develop a spatial management plan to prevent erosion, a spatially distributed prediction model would be a benefit. Realizing this, the US Forest Service Interagency Joint Fire Science program has invested in the further development of GeoWEPP – the geospatial interface to the Water Erosion Prediction Project (Renschler 2003). The BAER teams need tools that can predict and visualize both onsite erosion patterns, as well as offsite sediment yield predictions. An offsite assessment would provide the BAER team with a starting point by identifying which hillslopes within a burned watershed have the potential for large sediment yields. The onsite assessments provide a better reference to where on a particular hillslope the team should focus their erosion prevent plans. GeoWEPP provides both of these tools, but there are some limitations.

The goal of this research is to reduce or eliminate the limitations GeoWEPP has when simulating erosion events. One of the limitations GeoWEPP has is the way in which the watershed's subcatchments are created. These subcatchments and the information they provide to WEPP results in a generalization of the watershed; in other words, the nuisances present in the watershed are lost. The reduction in the generalization of the watershed is the prime motivations of this research.

1.4 Motivation

The purpose of any model is to represent real world phenomena as closely as necessary. The more accurate the representation within the model, the more like the real world the model becomes. The research presented in this document is an attempt to provide a better representation of the real world within a currently working model - GeoWEPP. GeoWEPP, the geospatial interface for WEPP, models the real world by using commonly available spatial data and then imports its representations into WEPP for erosion prediction. Unfortunately, there are currently several drawbacks with the way GeoWEPP represents this data.

The current version of GeoWEPP uses a topographical parameterization program, called TOPAZ, to analyze the digital elevation model to determine the flow network of the DEM. Each cell of the raster data is examined and assigned a flow direction based on how a flow exits that cell. TOPAZ creates a channel network based on these flow directions and by a default channel critical source area and a minimum stream channel length. The final result is an approximate estimation of the real network. This simulated network has two drawbacks. The first is that the DEM is smoothed, preventing pits and sinks; these modifications could result in the misrepresentation of channels in the study. The second drawback, common to most models, is that network flow can only converge; never diverge. Stream networks in nature both converge and diverge, thus the modeled network is not a true representation of the real world.

The hillslopes, or subcatchments, are derived in a similar fashion. A watershed is comprised of subcatchments and channels. When TOPAZ creates the subcatchments, the flow directions of all cells within the watershed are examined and the subcatchments are created based on which cells flow into which side of the channel – left bank, right bank, or source. Depending on the size of the channel and how much of the watershed flows into it, the bank subcatchments could be small (made up of only a few cells) or very large, consisting of hundreds of cell. The drawback with this method is that the larger the subcatchment, the more generalized in become.

When the subcatchment information is passed to WEPP, a representative profile of the subcatchment is created; this profile is an abstraction of the slope and length that represent the flowpaths within a subcatchment. The result is a loss in the nuisances of the watershed.

GeoWEPP uses data in raster format to represent the needed input parameters for WEPP; soil maps, landuse/vegetation files, and DEMs are used to create the region to be studied. The issue is not the scale or detail of the data, but how GeoWEPP sends this information to WEPP. GeoWEPP can present the user with a detailed soil and landuse raster map that can result in a larger number of soil/landuse combinations for each cell, but this is not the way WEPP models the watershed. Each subcatchment is defined by the dominant soil and dominant landuse. In other words, the most occurring soil values and the most occurring landuse/vegetation values found on a hillslope are assigned as the soil/landuse values for the entire subcatchment. This is repeated for each subcatchment within the watershed. Thus, the erosion prediction is based on only one type of soil and one type of landuse/vegetation, no matter how many different types actually occur on the subcatchment. The use of dominant soil and vegetation, along with the abstraction of the subcatchments, could result in simulated hillslopes that may not reflect the reality of the watershed.

The goal of this research is to create a better representation of the watershed approach within GeoWEPP by reducing or eliminating the effects of the above described drawbacks. The three main problem areas are the network structure (converging, but no diverging channels), generalized subcatchments resulting in loss of landscape nuisances, and the use of dominant soils and dominate vegetations reducing the diversity of the watershed. The research presented in this work concentrates on only one issue – the subcatchments. Each subcatchment created within GeoWEPP is based on how a portion of the watershed flows into a channel; the result may be large subcatchments that "hide" the variety of the soils and landuses, as stated above. The hypothesis is that, if the large subcatchments can be better divided, then the diversity of the landscape can be better represented. To this end, a Visual Basic program was created to subdivide the large subcatchments into smaller ones based on how the watershed flows into each channel raster cell. By creating these smaller subcatchments, more diverse profiles can be imported into WEPP; thus, creating a better representation of the real watershed. If the new program does provide a better representation of the real world, they there should be a more accurate prediction of the sediment yield and hydrology of the digital study area and thus a closer measured versus predicted relationship. At the very least, the new program should work as well as the original GeoWEPP.

The focus of this research is how well the new subcatchments created represent the real world. There are three aspects that need to be validated to demonstrate the accuracy of the new modifications. First, the topography of the simulated study area needs to be correlated with the observed topography. Once this has been confirmed, the simulated hydrology and the observed hydrology need to be calibrated to demonstrate the accuracy of the hydrologic component of the model. The final aspect looks at the geomorphology of the study site; the simulated erosion and sediment yields need to be compared to observed values. The simplest way to validate the new subcatchments is to hold all other parameters as constants. In other words, only change the method used to create the subcatchments, nothing else. This is done using data for the Lucky Hills nested watershed outside of Tombstone, Arizona. The parameters and study site are discussed in the next section.

2 Materials and Methods

2.1 Linking Topographical Parameterization and Erosion Modeling

Model creation involves three main phases: recognizing the real world phenomena to model, creating the model, validating the model with the real world observations or measurements. The real world phenomena, in this case, are the fluvial erosion processes that take place within rills and interrill areas. The goal is not to create a new model for fluvial erosion, but to build upon and improve currently existing models. To do this, several programs have been selected that predict and spatial visualize erosion. The Water Erosion Prediction Project (WEPP) model is used for predicting erosion, while GeoWEPP is used to spatially represent the study region from commonly available data. The channel network is created within GeoWEPP using a topographical parameterization software called TOPAZ. These three elements work together to predict erosion spatially and temporally. The research presented is an attempt to improve the interaction between these elements to better represent the real world within a computer system. The final stage is to validate any new approaches. To this end, a study site has been selected as a test area. Lucky Hills, Arizona, provides historical flume and rain gauge data, as well as, sample site data. This section describes the three programs mentioned above and describes the Lucky Hills study site and the methods used to collect the sample site data.

2.1.1 Topographical Parameterization Software (TOPAZ)

GeoWEPP is essentially a data visualization tool that allows the user to see the spatial nature of the input data and the WEPP predicted output data. GeoWEPP gives the appearance of delineating the channel network and the subcatchments within the watershed, but this is actually accomplished using another tool. Inputs to and outputs from this tool are handled through and visualized by GeoWEPP. Several of these output files are used as input parameters within the WEPP model.

The channel networks and the subcatchments in GeoWEPP are created using a TOpographical PArameteriZation tool called TOPAZ; a software package containing a number of different programs created by Jurgen Garbrecht and Lawrence Martz of the Agricultural Research Service (ARS) (Garbrecht and Martz 2000 p.52). The main objective of TOPAZ is to provide a comprehensive analysis of a given topography to determine the drainage network within that landscape. The result is a predicted channel network within a given digital elevation model (DEM) based on several parameters, the smoothing of the DEM to remove ambiguous points, and the physics underlying energy and water flux processes on surfaces.

GeoWEPP uses only three programs from the TOPAZ package: DEDNM, RASFOR and RASPRO. DEDNM does most of the work, while RASFOR and RASPRO converts the resulting data from DEDNM into a form GeoWEPP and The Translator can use. The Digital Elevation Drainage Network Model (DEDNM) performs the major tasks needed to determine the overall drainage network of a DEM. DEDNM analyzes the DEM and modifies the elevation data to remove any pits or flat surface area, providing an unambiguous definition of downslope drainage. The program also defines the watershed boundary based on the flow directions of each raster cell within the DEM., creates the subcatchments within the watershed, creates the channel network based on various input parameters, and creates the subcatchment and network tables.

Many of the output files that DEDNM creates are used within GeoWEPP and the Translator, but they are not in a format the ArcVIEW is able to recognize. The Raster Formatting program, RASFOR, converts these output files into a format that GeoWEPP and the Translator will be able to read; the process converts any file with the extension *.OUT to an ESRI ARC file.

The final program used within TOPAZ is the Raster Properties program, called RASPRO, which aids DEDNM in the subcatchment creation process. RASPRO performs alternative slope and aspect computations, calculates flow travel distance within the channels and to the outlet point, and the aggregation of all subcatchments draining into a channel creating the contributing are for that channel within the watershed (Garbrecht and Martz 2000 p.52).

2.1.1.1 Channel Network

The channel network is calculated using Critical Source Area (csa) and Minimum Stream Channel Length (mscl) as input parameters for the entire DEM. Each channel is the derived based on how each raster cell flows within the DEM. Any convergent flows that have a minimum source area that equals the csa and would have a channel length greater than or equal to the mscl will be classified as a channel. GeoWEPP loads the channel network (as a raster file converted from TOPAZ output file) as the topmost layer within the view. The result is the computed channel network is displayed for the entire DEM allowing the user to select an outlet point from the channel network to begin the process of erosion analysis on a particular watershed.

2.1.1.2 Subcatchments

Subcatchments are the contributing area within the watershed to a channel. TOPAZ creates these subcatchments based on which direction they drain into the channel: left, right, or source. Can have any combination of the three, but only first order channels can have a source area. TOPAZ determines the subcatchments based on how each raster cell within the DEM will flow. TOPAZ uses this information, along with the channel network, to determine which portions of the watershed becomes a subcatchment for a channel. The subcatchment output file contains the subcatchment indices, a value assigned to each raster cell to designate which subcatchment the cell belongs to. Each channel is assigned a Node Number (NODN) and each raster cell within the watershed is assigned a value based on its relationship to the channel. Equations 3 through 6 show how the values are calculated.

Source Node Subcatchments = (NODN * 10) + 1 **(Eq 2)**
Right Bank Subcatchments = (NODN * 10) + 2 **(Eq 3)**
Left Bank Subcatchments = (NODN * 10) + 3 **(Eq 4)**
Channel Network Cells = (NODN * 10) + 4 **(Eq 5)**

For example, it is was determined that a flow from a certain raster cell would eventually drain into the left side of the channel with the node number of 5 would be assigned the value of 53, a cell from the source area draining into the same channel would have the value of 51.

The resulting subcatchment output file is loaded into GeoWEPP as a raster theme called "subcatchments". The user will be able to see the overall watershed they selected as well as the individual subcatchments (if there are only a small number of subcatchments) or a color ramp presentation of the watershed. This file is also use by the Translator to identify the hills WEPP will be applied to; each subcatchment created by TOPAZ becomes a WEPP hill. A WEPP hill is comprised of three parts: slope, soil layer, and management layer. The slope is calculated using a particular algorithm based on the slope of all the flow paths within a subcatchment. The management and soils are based on the dominant management and soils of the subcatchment based on the landuse and soilsmap layers from GeoWEPP. The final result is a hill that contains the dominant soil, dominant management, and a derived slope; this is the representative profile.

2.1.1.3 Network and Subcatchment Tables

TOPAZ creates two important tables that are used as input parameters for the Translator that contain important information about the spatial distribution of the subcatchments and the channels within the watershed. The network table, NETW.TAB, contains the coordinates for the start and end of each channel, the channels linkage topology, channel lengths, upstream drainage area, the elevation of upstream and downstream ends of the channel. This information is necessary for WEPP to create the channels within the watershed method of erosion prediction.

The second table, SBCT.TAB, contains information describing the subcatchment drainage areas and their relationship to the channels. Each channel has up to three subcatchments that drain into it; they are the left and right drainage area and, for first order channels only, the source area. The table lists each channel, its length in number of raster cells, and the size of each subcatchment, listed as a number of rater cells, that drains into it. WEPP uses the information in this table to aid construction of the hillslopes.

2.2 Key Tables Linking TOPAZ to WEPP

TOPAZ generates two important tables that WEPP uses to define the subcatchment and channel setup for its watershed approach. This section describes the information that is found within the tables. A diagram flowing two descriptions provides a visual representation of the data sources for both tables.

2.2.1 Subcatchment Table

The subcatchment table, SBCT.TAB, has 8 columns and a number of rows equal to the number of channels in the watershed stream network plus one row for the outlet point. Table 1 shows an example of a subcatchment table for a small watershed containing 15 channels.

Table 1 – Subcatchment Table: SBCT.TAB

CHAN. CNTR.	CHAN. ORDER	CHAN. INDEX	SUBCATCHMENT AREA IN NUMBER OF CELLS SOURCE	LEFT	RIGHT	CHANNEL	TOTAL
1	1	16	40	93	46	17	196
2	1	15	36	50	25	10	121
3	1	14	35	30	14	6	85
4	1	11	38	45	16	8	107
5	1	10	33	9	2	6	50
6	1	5	50	23	92	12	177
7	1	8	35	24	11	9	79
8	1	7	40	12	29	6	87
9	2	13	-1	29	19	8	56
10	2	12	-1	0	2	3	5
11	2	9	-1	67	101	20	188
12	2	6	-1	97	48	15	160
13	2	4	-1	34	71	16	121
14	3	3	-1	2	0	1	3
15	3	2	-1	8	8	2	18
16	3	1	-1	-1	-1	-1	-1
-1							

Column 1 – Channel Counter

The first column is the channel counter and listed in ascending order. This numbering system is based on several factors: stream order, channel starting point, and TOPAZ numbering scheme. The first order channels are listed first, then the second order, and then the third and so on. The last line is always the outlet point. Within the first order streams, the channels are listed based on their starting point. The channel that has the northern most starting point is first. The remaining rows are following the same principles; the next northern starting point is next and so on. It has not been determined what happens when two channels with the same north position (or same row number in the grid) are found. This has only happened once during the testing phase and the result is either the order is based on left to right (western most) or from farthest to closest from the outlet point. Both cases are accurate for the one occurrence found. This aspect is not important for the program since the order created by TOPAZ is kept during the recreation process of this table. Once the first order channels have been put into the table, the remaining channels are enter in descending order based on the index number created by TOPAZ (see column 3).

Column 2 – Channel Order

The next column holds the order number of the channel, which is the stream order of the channel. Channels that have a source area are first order streams. When two first order streams merge, they form a second order stream. When two streams with the same number merge, the order number is increase for the new stream portion. If two streams with different orders merge, the higher (larger) order number is kept for the new stream portion. In TOPAZ, whenever two channels converge on a point, it is the start of a new channel. As stated above, first order streams are listed first, then second order, and so on.

Column 3 – Channel Index

The third column holds the Channel Index number created by TOPAZ. This is the number used to create the index numbers in the subcatchment output file and follows the structure of Index Number * 10 + cell type (Left, right, source, or channel). For example, if the index for the channel is 5, all the source cells would have an index of 51, all the channel cells would be 54, all the left side cells would be 52, and all the right side cells would be 53. The numbers are assigned to the channels as TOPAZ travels up the network from the outlet point. The outlet point is assigned an index of 1; the channel that flows into the outlet point has an index of 2. These indices are assigned are TOPAZ travels up the network assigning the channels of one side of the "main" channel first, and then traveling back down the channel and assigning the remaining channels as it progresses down the "main" channel. The channel indices created by TOPAZ are rewritten by the new subcatchment creation program, so the actual ordering procedures for this column or the network are not vital since the order created by TOPAZ will be kept.

Column 4 – Subcatchment Source Area

The remaining columns are for the cells counts for the subcatchments and the channel. Each column holds a value that indicates the number of grid cells for the type in question. The first of these columns, subcatchment source, records the number of grid cells that make up the source area for the channel in question; this column will either contain a positive value or a -1. The -1 is meant for channels that do not have a source area, like second order or higher channels.

Column 5 and 6 – Left and Right Subcatchment Areas

The next two columns are for the left and right subcatchments, respectively and contain the cell count for each subcatchment. A zero value means that the channel does not have a subcatchment draining into it from that side.

Columns 7 and 8 – Channel Area and Total Area

Column 7 is for the number of channel cells within the channel. This value is always at least one for a channel and is the total number of cells that make up the channel. The final column is the total of the four previous columns, with one exception: the source subcatchment column is only added if the value is not -1.

Outlet Point

The row for the outlet point does not follow the format above. It has a -1 in each of the five remaining columns, is always the last line in the table, has the same order number has the highest order channel, has a channel index of 1, and has the highest channel counter.

An example of the subcatchment table of a simple network appears in the appendix.

2.2.2 Detailed Description of the Network Table

The network table, NETW.TAB, contains 24 columns and a number of rows equal to the number of channels in the network plus one row for the outlet point, which is the same number of rows found in the subcatchment table. Below (tables 2 and 3) is an example NETW.TAB, followed by the description of each of the columns. The table has been broken up into two sections: the first section contains columns 1 through 16, which are the columns that need to be changed within the new program, and the second section contains columns 17 to 24, which contains the same data for each row.

Table 2 - Column 1 through 16 (out of 24 columns) of Network Table NETW.TAB

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	251	280	253	279	254	279	3.41	2171.8	2158.4	26	41	154	16	8
2	1	255	292	254	280	254	279	14.24	2207.7	2158.4	24	108	154	85	9
3	1	256	271	257	271	258	270	2.41	2123.4	2107.4	27	48	325	22	4
4	1	259	276	258	275	258	274	2.41	2151.1	2132.5	23	25	263	3	11
5	1	260	283	257	277	257	276	8.24	2185.9	2144.5	28	53	218	26	10
6	1	262	273	260	269	259	268	6.24	2145.2	2099.0	26	51	411	26	12
7	2	254	279	256	277	257	276	4.24	2158.4	2144.5	154	160	218	10	7
8	2	257	276	257	275	258	274	2.41	2144.5	2132.5	218	232	263	18	6
9	2	258	274	258	271	258	270	4.00	2132.5	2107.4	263	273	325	15	5
10	2	258	270	258	269	259	268	2.41	2107.4	2099.0	325	335	411	13	3
11	2	259	268	259	267	258	266	3.41	2099.0	2094.3	411	429	429	42	2
12	2	258	266	258	266	258	266	0.00	2094.3	2094.3	429	429	429	0	1
-1															

Columns 1 and 2 – Channel Counter and Channel Order

Columns 1 and 2 are the same as columns 1 and 2 of the subcatchment table. Column 1 contains the Channel Counter, while column 2 holds the Channel Order values.

Columns 3 through 8 – Upstream and Downstream Coordinates

The next set of columns are grouped together, Columns 3 through 8 hold the coordinates - the row and column number of the network grid - of a cell at certain points in the network. The odd columns hold the row number while the even columns hold the column number. This group is broken down into three parts: Upstream, Downstream Previous, and Downstream Last. The Upstream is the location of the first cell in the channel; the Downstream Previous is the location of the last cell of the channel; the Downstream Last is the location of the cell in which the Downstream Last cell flows into (the upstream cell of the next channel in the network). The origin of the network grid is located in the upper left-hand corner of the grid; the first grid cell has a location of 1, 1.

Since the outlet point is a single point, all three pairs of coordinates are the same and represent the location of the outlet point (and the location of the last cell of the channel that flows into the outlet point).

Column 9 – Channel Length

Column nine has the length of the channel. This is the flow distance, measured in number of cells, as the flow travels from the first cell to the last cell of the channel. If a flow that passes through a cell has a flow direction parallel to the cell side, then the distance traveled is 1. If the flow passes through a cell by entering from one corner and flowing out through the opposite corner, then the distance it has traveled is 1.4142. Is a flow enters a cell from a corner and leaves through the midpoint of one of the sides (or vice versa), the distance is 1.21. Once the distance traveled through each cell is determined, they are summed and rounded to two decimal paces, then entered in column nine for the channel.

How are these distances determined? It is assumed that the only exit and entrance points for a flow are located either at the four corners or at the midpoints of the four sides. It is also assumed that the flow passes through the center of the cell. Since the final value is in cell length, the length of a side of a cell is 1. Therefore, any flow that passes from one midpoint to the midpoint of the opposite side has traveled the same distance as one of the sides of the cell, i.e. 1. To determine the length from corner to corner, the Pythagorean Theorem is used; the cell is a square and the distance from one corner to the opposite corner forms the hypotenuse of a right triangle. The result is the square root of 2, which is about 1.41. The flow that passes from a side to a corner (or vice versa) must pass through the center of the grid, therefore it travels half the distance of each of the previous examples or (0.5 + 0.707 = 1.207 ~ 1.21). The only remaining paths are from any corner to any corner or from any midpoint to any midpoint. In these cases, the distance is 1.41 or 1, respectively.

Columns 10 and 11 – Elevation Data

The next two columns contain elevation data. These values are taken from a file created by TOPAZ called INELEV.ARC. This file contains the elevation of every cell within the DEM, modified to smooth out sinks and holes. Column 10 has the elevation of the upstream cell (the cell with the coordinates found in columns 3 and 4). The other column holds the elevation of the cell in which the channel flows into (the cell with the coordinates found in columns 7 and 8). For both columns, the location from the coordinate columns is found within INELEV.ARC and the value found in that cell is recorded in the table.

Columns 12, 13, and 14 – Accumulates Upstream Drainage Area

The next three columns all deal with the Upstream Area flowing into a particular node. This is the number of cells that flows into the particular cell. In this case, the cells in question are the cells with the coordinates found in column 3 through 8. To determine the value in each of the columns, a new file is use: UPAREA.ARC. Each cell of this file has a value in it that represents the number of cells that the flow passing through the cell has already passed through; this includes any flows that have merge with the current flow. For example, the value found at the source of a first order channel should be the number of cells found in the source area for that channel.

To determine the number that should be entered into the columns, the location of the cell is found in UPAREA.ARC and that value is entered in the column. Column 12 is the uparea for the first cell of the channel. Column 13 is the uparea for the last cell of the channel, while column 14 is the uparea for the cell in which the channel flows into.

Column 15 – Direct Drainage Area

The Direct Drainage Area (column 15) is the summation the left and right subcatchments and the number of channel cells found in the subcatchment table (columns 5, 6, and 7). The value in this column is the number of cells that make up the left and right subcatchments of the channel, as well as the number of channel cells. Another way of looking at this value is that it equals the total found in column 8 of SBCT.TAB, minus the source area (column 4) if the channel is a first order channel.

Column 16 – Node Index

Column 16 is the first of seven columns for the Node Index. The other six columns are discussed below. This column holds the channel index of the channel. This is the same value that can be found in the Channel Index column (column 2) of the subcatchment table.

Columns 17 through 24 – Node Index and Slope

The remaining eight columns all contain the same values for each row. The Node Index (columns 17 through 22) contains all zeros. The Slope columns (column 23 and 24) have -1.000 entered for each column and row. These columns are not important for GeoWEPP, WEPP, or the new subcatchment program.

Outlet Point

Unlike the SBCT.TAB, the outlet point follows the format described above, except where noted. The only difference is that it is a single cell that does not have a channel length or a drainage area.

An example of the network table for a simple watershed appears in the appendix. This is the same watershed that the subcatchment table in the appendix was derived from.

Table 3 - Columns 17 to 24 of Network Table NETW.TAB

17	18	19	20	21	22	23	24
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000
0	0	0	0	0	0	-1.000	-1.000

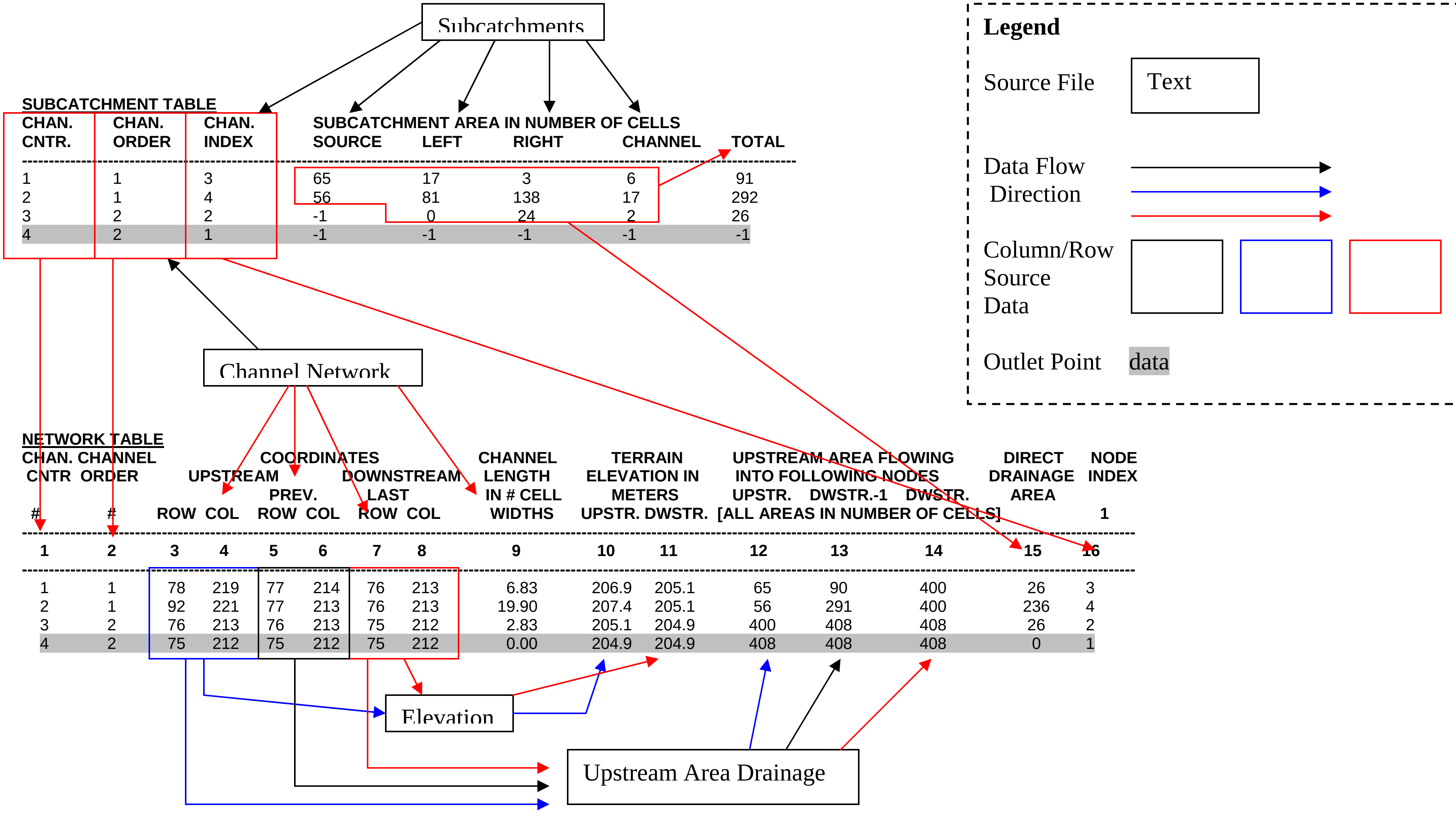


Figure 1 – Data flow between SBCT.TAB, NETW.TAB, and the TOPAZ output files.

2.3 Study Site - Lucky Hills, Arizona

The study site used to validate the smaller subcatchment creation program is the Lucky Hills watershed, located within the United States Department of Agriculture - Agriculture Research Service (USDA-ARS) Walnut Gulch Experimental Watershed in southeast Arizona near the town of Tombstone (see figure 2 and 3). The Lucky Hills has been a study site for the USDA since the early 1960s. Researchers at that time identified two watersheds that drained into stock ponds; one of these watersheds was Lucky Hills – a 115 acre watershed dominated by shrubs. Early into monitoring stages, researchers had difficulty developing a rainfall to runoff relationship (Kincaid, Gardner et al. 1964).

Two smaller watersheds were used within Lucky Hills as “unit-source” watersheds. Unit-source watersheds are natural drainage areas that have essentially uniform soil, vegetation and precipitation. Runoff measuring weirs, rain gauges and soil moisture blocks were installed in there smaller watersheds. Since the Lucky Hills has adjacent watersheds with similar soil and vegetation characteristic, a nested watershed had be instrumented by 1963. This nested watershed consisted of Lucky Hills Watershed 103 (9.1 acres, 3.7 ha.) which contained the Lucky Hills Watershed 101 (3.2 acres, 1.3 ha) (Canfield and Goodrich 2003). This nested watershed is the study site used for the validation of the new subcatchment creation program. The Lucky Hills watershed is classified as rangeland, but there hasn’t been any grazing by domestic livestock since the watershed has been fenced off since 1963. Smaller herbivores, like rabbits, may still grave within the watershed.

“Since the instrumentation was installed in the early 1960s, rainfall and runoff data have been collected with only short interruptions for upgrading equipment, which generally occurred during the winter (Canfield and Goodrich 2003, p. 445).” Rain gauge 83, installed in 1963, is within the nested watershed of the study area and is the main source of precipitation data used for validation.

There have been several attempts to characterize the topography of the watersheds since research had begun in Lucky Hills. A five-foot contour map, from field survey, was used in the first papers describing research at the watershed, a topographic map was prepared from a 1975 areal survey which resulted in a 1 foot contour map of the watershed, and a 2.5 m x 2.5 m DEM was prepared based on field survey (Canfield and Goodrich 2003, p. 445).

The most recent characterization of the Lucky Hills topography was a new DEM used in this study. This data was collected during the first few weeks on March, 2005, using a Light Detection and Ranging (LIDAR) device, which uses laser rangefinding, Global Positioning System (GPS), and inertial altitude technology to create a Digital Elevation Model (DEM). During the weeks prior to the scheduled flyby, cardboard makers were placed through the Lucky Hills as guide points for the airplane and the resulting data. These makers were placed at specific locations using a GPS device. All points were reconfirmed prior to the scheduled flyby. The LIDAR sensor data resulted in the 1m DEM used as an input parameter for GeoWEPP, TOPAZ and the new subcatchment creation program.

2.3.1 Landscape and Climate

The benefit of the Lucky Hills watershed, as stated above, is the almost uniform soil, vegetation, and precipitation within the study site. The study site covers about 8.3 acres (3.36 ha), with an elevations ranging from 1363 meters to 1375 meters. The soils within the study area are mapped as Luckyhills-McNeal Sandy Loam (Ustochreptic Calciorthids) (Breckenfeld, Svetik et al. 1995), with approximately 25% rock fragments and a surface layer composed of approximately 60% sand, 25% silt, and 15% clay (Nearing, Jetten et al. 2005). The vegetation is shrub dominate consisting mainly of Acacia [Acacia constricta Benth.], Tarbush [Floursensia cernua DC], and Creosote [Larrea divaricata Cav.] and covering about 26% of the watershed. The average height of the shrubs is approximately 0.6 meters, with a clump leaf index of 1.15 to 1.54

and a Leaf Area Index of about 0.3 – 0.4. The small coverage and area tends not to catch much of the moving soil (Ritchie, Nearing et al. 2005).

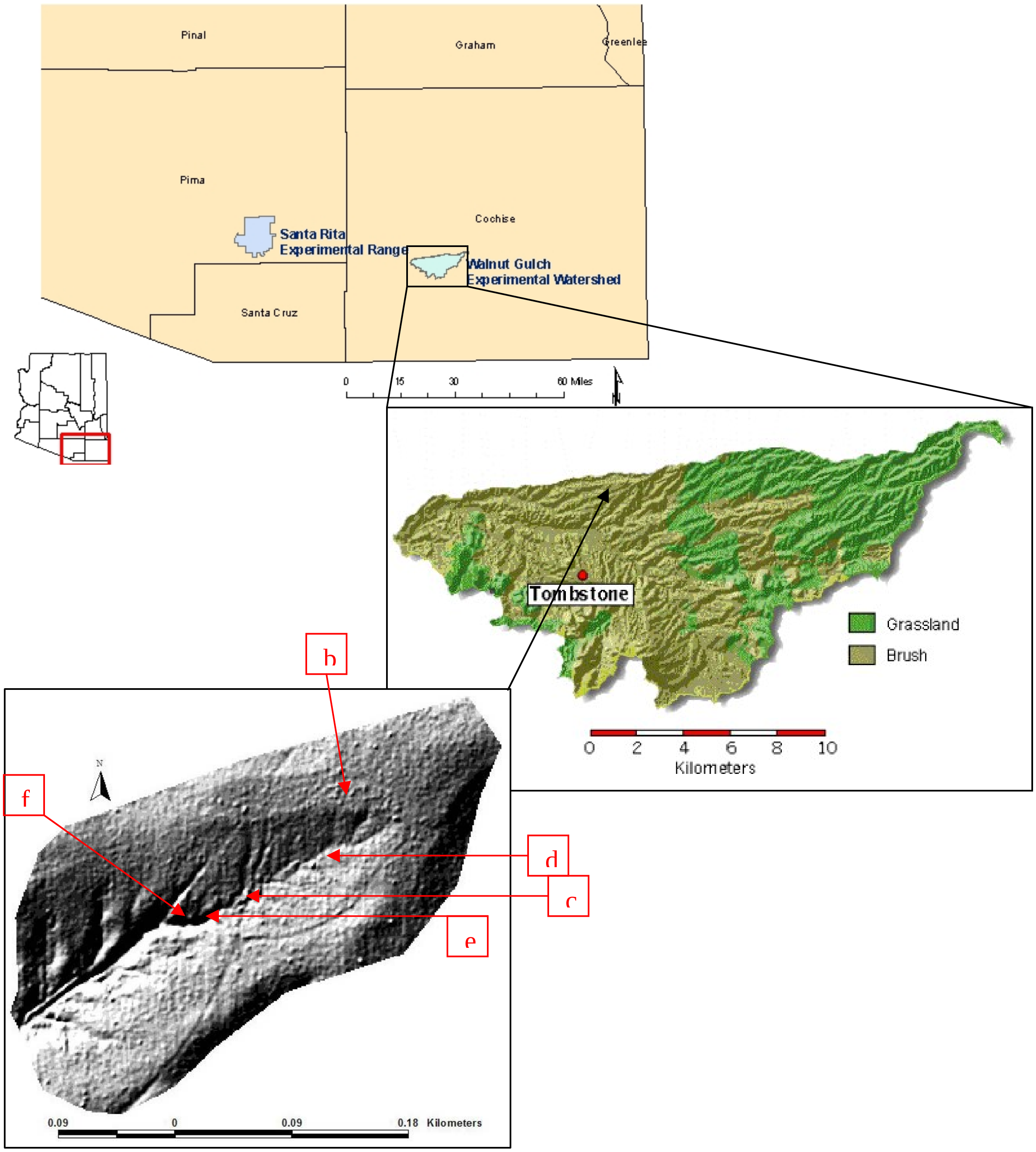


Figure 2 – The location of the Lucky Hills nested watershed relative to Arizona. Lucky Hills is located within the Walnut Gulch Experimental Watershed. Letter b through f correspond to the pictures in figure 3 with the arrows pointing to the shots location. (Arizona and Walnut Gulch images from USDA-ARS Southwestern Watershed Research Center website – http://www.tucson.ars.ag.gov/)

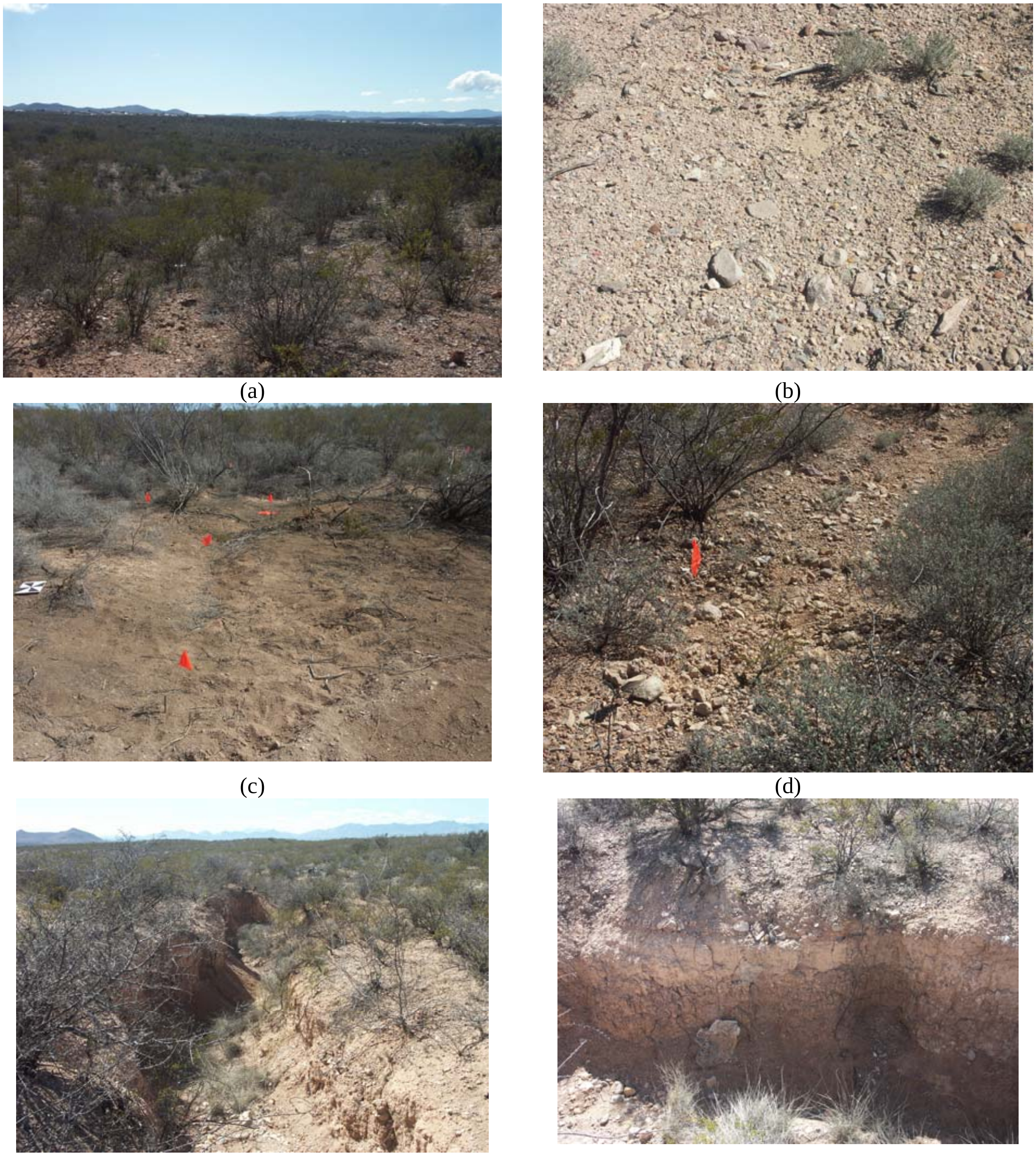


Figure 3 – Selected images of Lucky Hills, Arizona. (a) Most of the landscape of Lucky Hills consists of scattered shrubs, resulting in regions that have no protection from rainfall. (b) The soil consists os mainly sand with rock fragments. (c) In the upper watershed, channels as mainly small and shallow. This image shows two such channels (upper portion of photo) converging into one channel. Flags denote the sample site locations. (d) On of the upper watershed channels, mainly consisting of rock fragments on the surface and shrubs along the channel banks. (e) The start of the main channel leading from the smaller upper watershed. This photo was taken from the former location of a weir (flume 101). Downstream from the image (e), this portion of the main channel (f) is approximate 2 meters deep.

The Lucky hills watershed receives an average of 356mm of precipitation a year; two-thirds of which occurs during the July to August monsoon season (Canfield and Goodrich 2003). By comparison, the regional precipitation ranges from 250 mm to 500mm per year. The mean annual temperature for Lucky Hills is 17ºC, with a temperature range from 1ºC in January to 35ºC in June (Ritchie, Nearing et al. 2005). Frost does not play a role in the erosion process within the nested watersheds.

2.3.2 Methodology and Other Data

The main purpose of this new subcatchment creation program is to improve GeoWEPP's ability to represent reality. The first step is to insure that the subcatchments created by the new program represent the watershed. In other words, the newly derived watershed's boundary should match with the GeoWEPP derived watershed's boundary, the new subcatchments should flow into the channels, and now portion of the watershed is left out. This visual interpretation and validation does not validate the performance of the new program, it's just a step in which the visualization aspect is checked for any bugs.

The validation of the new subcatchment creation program is handled in two stages. The first is a comparison of its predicted results with the predict results from the original GeoWEPP program. This stage is described in the validation section. The other stage is to compare the predicted results with the observed measurements from the study area. This process is still continuing as more observe measurements are being collected, but some preliminary analysis can begin using a series of samples taken from the Lucky Hills study site (Nearing, Jetten et al. 2005).

The 74 soil samples taken at Lucky Hills were collected on a 25 meter grid layout. Each sample was taken from the 0-25cm layer; a differential GPS device was used to record coordinates and elevation and cover conditions were recorded (Ritchie, Nearing et al. 2005). The samples were dried at 80 ºC and sieved through a 2mm screen. The soil that passed through the screen were weighed and sealed within beakers for ^{137}Cs analyses. The remaining material, rock fragments larger than 2mm, was only weighed. Of the 74 samples, sixteen were used as references site at were assumed to represent the ^{137}Cs input into the watershed; these sites showed little evidence of physical disturbance (Nearing, Jetten et al. 2005).

The data collected from the sample sites within Lucky Hills showed that the erosion and deposition rates ranged from 9.8 t ha^{-1} yr^{-1} (metric tons per hectare per year) of soil loss to 7.0 t ha^{-1} yr^{-1} of soil deposition; with a total average loss over the watershed of -3.8∀4.5 t ha^{-1} $year^{-1}$ (Ritchie, Nearing et al. 2005, p. 127). A total of 54 sample sites, which accounts for about 73% of the sites, recorded a net soil loss. This soil loss tended to occur on the higher elevation within the study area. Vegetation within the study site did not have a major effect on the soil redistribution; even though soil loss was found to be greater under or near shrubs, the difference was not significant when compared to sample sites found between shrubs (Ritchie, Nearing et al. 2005).

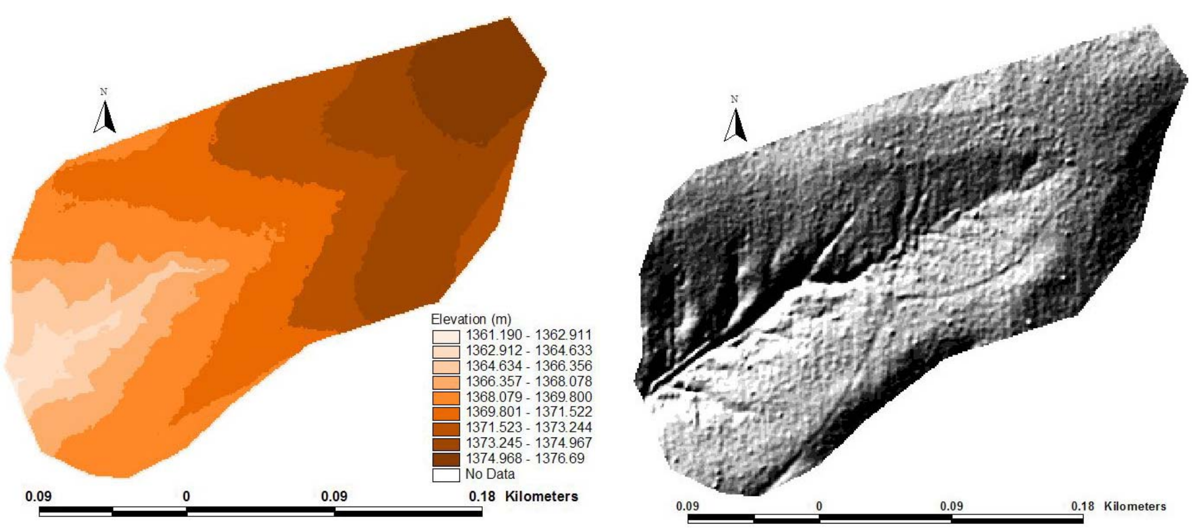
The remaining 20 sample site recorded a net soil gain. These sites where located near or under shrubs, near large or medium rocks, or on rocky soil. None of these site where located near or in channels. These factors contribute to the deposition of material because they tend to either disrupt the flow of water along the surface or by only allowing heavy water flow to reach these sites (Ritchie, Nearing et al. 2005).

2.4 Input Parameters

GeoWEPP and WEPP require four input parameters: elevation, soil, management or vegetation, and climate data. For the validation runs, all the same parameters were used for each run – except for the storm season analysis. The LIDAR DEM of Lucky Hills (figure 4a), provided by Dr. Mark Nearing and Dr. Mary Nichols of the USDA – Agricultural Research Service, is used as the elevation input parameter. The DEM was converted to an ASCII file format, which is the only input type allowed within GeoWEPP. Each of the subcatchment's hill slope and hill length will be calculated from the DEM. The WEPP parameter file, Creosote and Whitethorn for

Tombstone AZ.rot, is used as the vegetation input parameter. This parameter file, created by Dr. Chris Renschler – Department of Geography, the State University of New York at Buffalo – and Dr. Bill Elliot – US Forest Service – will be used as a global vegetation input for the entire Lucky Hills study site. Since this parameter is global, a separate ASCII raster file was not needed as a GeoWEPP landuse input file. A similar process was used for the soil input parameter. The WEPP soil parameter file, called SoilsMcNeal-AZ0400 hc375.sol, was used as the soil input parameter for the study site. This parameter was also treated as a global parameter; therefore an ASCII raster file was not needed. The final input parameter, climate, was created Dr. Renschler and Dr. John Laflen – Adjunct Professor, Agricultural and Biological Engineering, Purdue University, and WEPP Project Leader, 1989-1999. The WEPP climate parameter file, LH TOMBSTONE AZ.cli, was used to generate for the 50 year run.

The three WEPP parameter files – climate, soil, and vegetation – were initially prepared for an investigation of the response of different erosion models to a few climate changes within two watersheds (Nearing, Jetten et al. 2005); one of which was the Lucky Hills watershed. No modifications were made to these parameters for this study.



(a) (b)

Figure 4 – Elevation input parameter for WEPP. The left image (a) is the 1m LIDAR DEM of the Lucky Hills, Arizona study site. The hillshade of the DEM (b) clearly depicts the deep cut of the main channel within the study site.

2.5 CLIGEN – The Climate Generator

CLIGEN is a stand alone program that can generate climate data for a single event or for a long duration. CLIGEN uses the data gathered from approximately 1200 weather stations across the United States. These stations contain 25 years worth of precipitation and maximum and minimum temperature data in daily, hourly, and 15-minute intervals (Flanagan and Nearing 1995). From this data, climate files where created for many stations across the US.

Once the initial database has been created, CLIGEN is able to create event data over a specified course of time; this process begins with determining if an event occurs. A two-state Markov chain is used to determine if a wet day (an event) occurs or not. This is done by creating two probabilities: the probability that a wet day will follow a dry day (α) and the probability that a dry day will follow a wet day (β). From these probabilities, the probability of a dry day following a dry day ($1-\alpha$) and the probability that a wet day follows a wet day ($1-\beta$) can be determined. Finally, twelve monthly values are determined from these probabilities is determined. Random sampling of the monthly data is used to determine the wet and dry day occurrences (Flanagan and Nearing 1995).

2.5.1 Determining Precipitation Amount, Storm Duration, and Peak Intensity

The next step is to determine the amount of rainfall for each event using equation 6, where u, s, and g are the mean, standard deviation, and skew coefficient of the average monthly values determined above. A raw value, X, is derived from the monthly distribution. Finally, the precipitation amount, x (mm), is calculated (Flanagan and Nearing 1995). The type of precipitation modeled is based on the maximum and minimum temperatures; in the case of Lucky Hills, the minimum temperature rarely goes below 0 C, so the precipitation is classified as rainfall.

$$x = \frac{6}{g}\left\{ \frac{\left[\frac{g}{2}\left(\frac{X-u}{s} \right) + 1 \right]^{1}}{3} - 1 \right\} + \frac{g}{6}$$

(Eq 6)
(Flanagan and Nearing 1995)

The storm duration is determined using the SWRRB model (Arnold, Williams et al. 1990). The storm duration is calculated using equation 7, where D is the storm duration in hours and *rl* (dimensionless) is the parameter for the gamma distribution of the half-hour monthly average (Flanagan and Nearing 1995).

$D = \frac{9.210}{-2\ \ln(1 - rl)}$	**(Eq 7)** (Flanagan and Nearing 1995)

The peak intensity is calculated using equation 8 purposed by Arnold and Williams (1989). The peak intensity, r_p, in recorded in $mm \cdot h^{-1}$ is based on the total storm precipitation amount (P) calculated above and on *rl* (discusses above).

$r_p = -2\ P\ \ln(1 - rl)$	**(Eq 8)** (Arnold and Williams 1989)

2.5.2 The Climate Parameter File

The climate parameter file created for WEPP contains the observed monthly averages based on the weather station used in CLIGEN, along with the event information calculated by CLIGEN. The storm duration, precipitation amount, and peak intensity were described above. The remaining data is calculated using the mean and standard deviation of the observed monthly average and a standard normal deviate to statically derive the event data. Finally, all the data it tabulated and added to the file. Below is a list of the information within the file.

Observed monthly average

maximum temperature (C)
min temperature (C)
solar radiation (Langleys/day)
precipitation (mm)

Event data

Day, month, year of event
Total precipitation for the event
The duration and time to peak
The rainfall intensity
Maximum and minimum temperature
Solar radiation, wind velocity and direction
Dew point

WEPP uses these events to simulate the climate of the study site for the duration of the simulation run. The simulation can be over a few years – like the climate for the 1982 and 1984 storm seasons used in the short-term assessment validation – or over a long period of time which was done for the long-term assessment validation. For the long-term assessments, the events are simulated using CLIGEN. For the short-term assessments, a climate file in the CLIGEN format was created based on observed data. A similar process could be used for the long-term assessment or for any simulation run.

3 The Visual Basic Subcatchment Creation Program

3.1 Overview

The problem that is faced with the current version of GeoWEPP is that the representative profile that is created using the dominate soil, dominate management, and aggregate slope may not be an accurate representation of the hill, especially if the hill has more than one management and/or soil. One solution to this problem is to create smaller subcatchments so that they can better represent the watershed being studied. The new, smaller subcatchments would follow the same theme TOPAZ used to create the larger ones, but they would be based on how each flows into an individual channel cell, not the channel as a whole. VBFlow, a Visual Basic .NET program, was designed to test this solution.

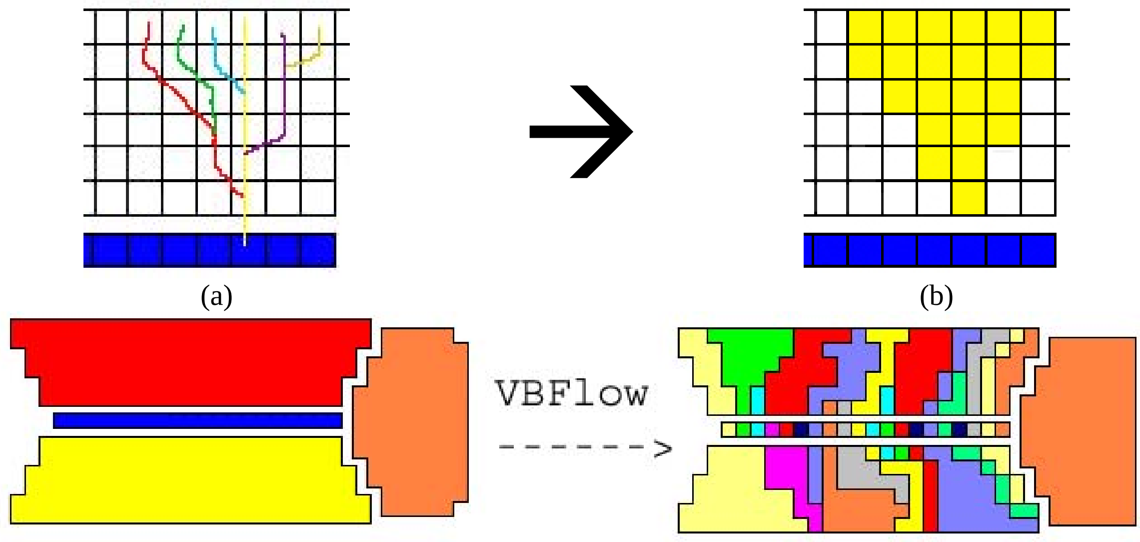
The main purpose of VBFlow was to take the TOPAZ outputs one step further. As state earlier, TOPAZ creates it hills based on how they flow into a channel and from which direction (left, right, and source). This process can result in large subcatchment, which can introduce errors since the dominate landuse and/or soil is being used, as well as a representative slope. This generalization can hide features that may reduce or contribute to the amount of erosion occurring on the particular portion of the watershed – highly erodible soils or vegetation barriers may be missed because of there smaller size in relation to the more dominant parameters. VBFlow changes once aspect of the TOPAZ formula; it creates hill based on how they flow into a single channel cell and from which direction (left, right, and source). This new formula can result in smaller subcatchments that may be able to incorporate the diverse landuse and/or soils found within the watershed that can be missed. One aspect does not change with VBFlow: the source area of a channel flows into on cell, which means that VBFlow and TOPAZ will create the same source hill for each channel.

3.2 Thinking Behind VBFlow

GeoWEPP and the Translator were programmed to work with TOPAZ output files, so the “build a better mouse trap” approach was not an option. Besides, most of the work that VBFlow would need to accomplish was already done by TOPAZ. Therefore, VBFlow would be created to take the TOPAZ output files one step further, which meant that VBFlow needs to run after TOPAZ had completed its calculation, create output files that match the names and formats of those produced by TOPAZ, and be completed before GeoWEPP is able to display the results for the user.

The basic idea behind VBFlow was to determine which hill cells flowed into which channel cells. The subcatchments would be created by assigning the same hill ID to the cells that flowed into the same channel cell. How was this done? TOPAZ creates a file that stores the flow direction of each cell of the entire DEM. By using this file, we can determine where the outflow from a cell will go and which channel cell it will eventually flow into. This would be rather time consuming, so a different approach is used. First, we start with the channel cell itself and determine which of the surrounding non-channel cells flow into it. Then we determine which cells flow into the cells we just found, and so on. In essence, we are back tracking the flow path from the end point (the channel cells) to all the starting points. Once all the cells have been identified, we assign them a side (left, right, or source). This process is repeated for each channel cell.

The end result is a number of smaller subcatchments that flow into individual channel cells, as depicted in figure 5. Each channel cell will have 0 to 3 subcatchments flowing into it, and each channel will have 1 to (number of channel cells x 2) +1 subcatchments.



(a) (b)

(c)

Figure 5 – Conversion process from TOPAZ subcatchments to VBFlow subcatchments. (a) All the flow paths into one channel cell are calculated. Once this is done, that portion of the watershed becomes a subcatchment (b). This process is repeated until for all channel cells and flow paths. (c) An example of a simple 3 subcatchment watershed and the new subcatchments for the same watershed. Note that some channel cells (dark blue) do not have contributing subcatchments.

Before and after the subcatchment creation process, the tables will have to be modified to match the original format. SUBWTA.ARC will also be modified to reflect the subcatchment changes. In the end, the Translator will not "see" any difference from the files TOPAZ creates and the files created by VBFlow.

3.3 Necessary Topographical Input Parameters for VBFlow

VBFlow uses several of the TOPAZ output files to create the new subcatchments and to create new network and subcatchment tables. The following sections describe the various TOPAZ output files and their importance within VBFlow.

3.3.1 Watershed Boundary

The watershed boundary file, BOUND.ARC, is an ASCII GRID file where 1 signifies the location of watershed cells, while 0 denotes those cells that are outside the watershed. This input parameter is used as a form of restriction during the search algorithms; this file is used in Boolean expressions to determine if the cell in question is within the boundary of the watershed.

3.3.2 Channel Network

The channel network file, NETFUL.ARC, is used in conjunction with the watershed boundary to determine which channels cells are within the watershed. The main focus of VBFlow is to create subcatchments based on how they flow into a single channel cell. By creating Boolean expressions with VBFlow, the program will be able to differentiate those channel cells that are located within the watershed from those that are outside the watershed.

3.3.3 Drainage Direction within the Watershed

The most important input file deals with the drainage within the watershed. The flow vector file, FLOVEC.ARC, contains the drainage direction of each raster cell in one of eight directions. Each cell is assign a number based on the direction of flow out of the cell; the numbers range from 1 to 4 and 6 to 9 (0 is used for indeterminate flow direction and 5 is not used). The following diagram, figure 6, depicts how this number would be assigned.

1	2	3
4	X	6
7	8	9

Figure 6 - Flow Direction Values for FLOVEC.ARC. The value found in the square in which water flows from X is assigned to the raster cell where X is located.

In the diagram above, X represents the cell surrounded by 8 other cells. The value to be placed in FLOVEC.ARC is the number located in the above diagram in which cell X flow into. For example, if cell X flows to the left, it would flow into the cell with the value 4. Thus, cell X's value in FLOVEC.ARC would be 4. If the flow was to the upper right, then the value would be 3.

This file is very important. VBFlow uses this file to determine how the watershed flows. Since the idea is to create subcatchments based on how they flow into an individual channel cell, VBFlow needs to know the flow direction of all cells within the watershed. This is also important for determining the location and order of each channel cell. This will be discussed in more detail in the program description section.

3.3.4 Original Subcatchment Delineation

This file, as state above, contains the derived subcatchments for the watershed in question. This is the file VBFlow intends to modifying, but it is also an important input file for VBFlow. This file contains the indices for each cell of the subcatchments and channels in the form of (index number * 10) plus 1, 2, 3, or 4. For example, if the index number is 2, then the four possible indices are 21, 22, 23, and 24, depending on the type of cell. In this case, all channel cells will have the value 44, source subcatchment cells will have a value of 21, right bank subcatchment cells will be 22, and left bank subcatchment cells will be 23. This is illustrated in figure 7.

The index number is not important, but the last number (1, 2, 3, or 4) is important since we wish to keep the same naming convention that TOPAZ uses. To do this, VBFlow store the last digit in a 2D-Array so that it can access it toward the end of its run. This way, each cell in the new SUBWTA.ARC will have the same position (left, right, source, and channel) it originally had – something that is necessary for the Translator to operate properly. This will be explained more during the program description portion.

The previous files are used to modify the SUBWTA.ARC file, but VBFlow also needs to modify the two table files: SBCT.TAB and NETW.TAB. To do this, several other files need to be accessed.

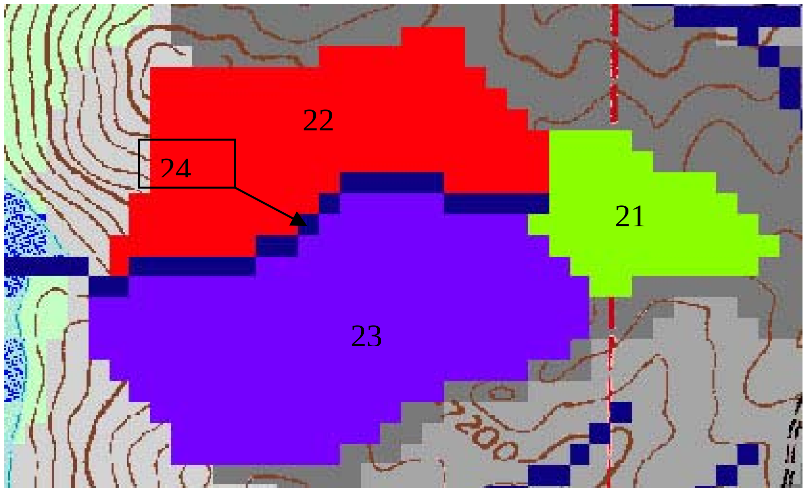


Figure 7 – Watershed cell assignments. The cells that represent the right bank (the red subcatchment) are each assigned the value 22. The source subcatchment cells (lime green) are assigned 21 and the left bank (purple) cells are assigned 23. The channel cells (blue) are assigned the value of 24.

3.3.5 Accumulated Upstream Drainage Area

The accumulated upstream drainage area, UPAREA.ARC, contains the accumulated upstream area draining into a particular cell; this area is measure in the number of cells that eventually flow into the cell in question. This information is needed to complete the network table, NETW.TAB, since it has several columns that contain upstream area drainage information. This is done by using the coordinates each channel cell within the watershed and finding the value contain within the cell at those coordinates within the UPAREA.ARC ASCII GRID file. This process is discussed later in the table creation steps.

3.3.6 Modified Elevation

Another file that is important in the complete of the network table in the modified elevation file, INELEV.ARC. This file contains the elevation values of the input DEM. These values are round to the nearest decimeter, but upon reformatting by RASFOR, the elevation values are returned in meters with a precision of 1/10th of a meter (Garbrecht and Martz 2000 p.48). One important note is that this file contains the elevation data of the smoothed DEM, not the original inputted elevation data. The network table contains two columns that represent the starting and ending elevation of a channel. To complete these columns, the coordinates of each channel cell is used to find the elevation data at the corresponding coordinates with INELEV.ARC. This is the same process used to find the upstream drainage area values described above and will be in more detail later.

3.4 Program Discussion

The basic idea has been established and the parameters are set, so how does the program actually work? This section goes into more detail about what the program does. VBFlow is broken down into three separate stages: preprocessing, subcatchment creation, and post-processing. Each stage of the program is described below. One important note: data read in from the files are read in as text. They need to be converted to decimal or float number so that they can be used as numbers in the VBFlow code. This is done because the text values can not be manipulated like numbers. It would be like trying to add two phone numbers together – it can not be done. This is done through several different procedures with in VBFlow, as shown in figure 8 below; all numbers read in are considered numbers not text within the program.

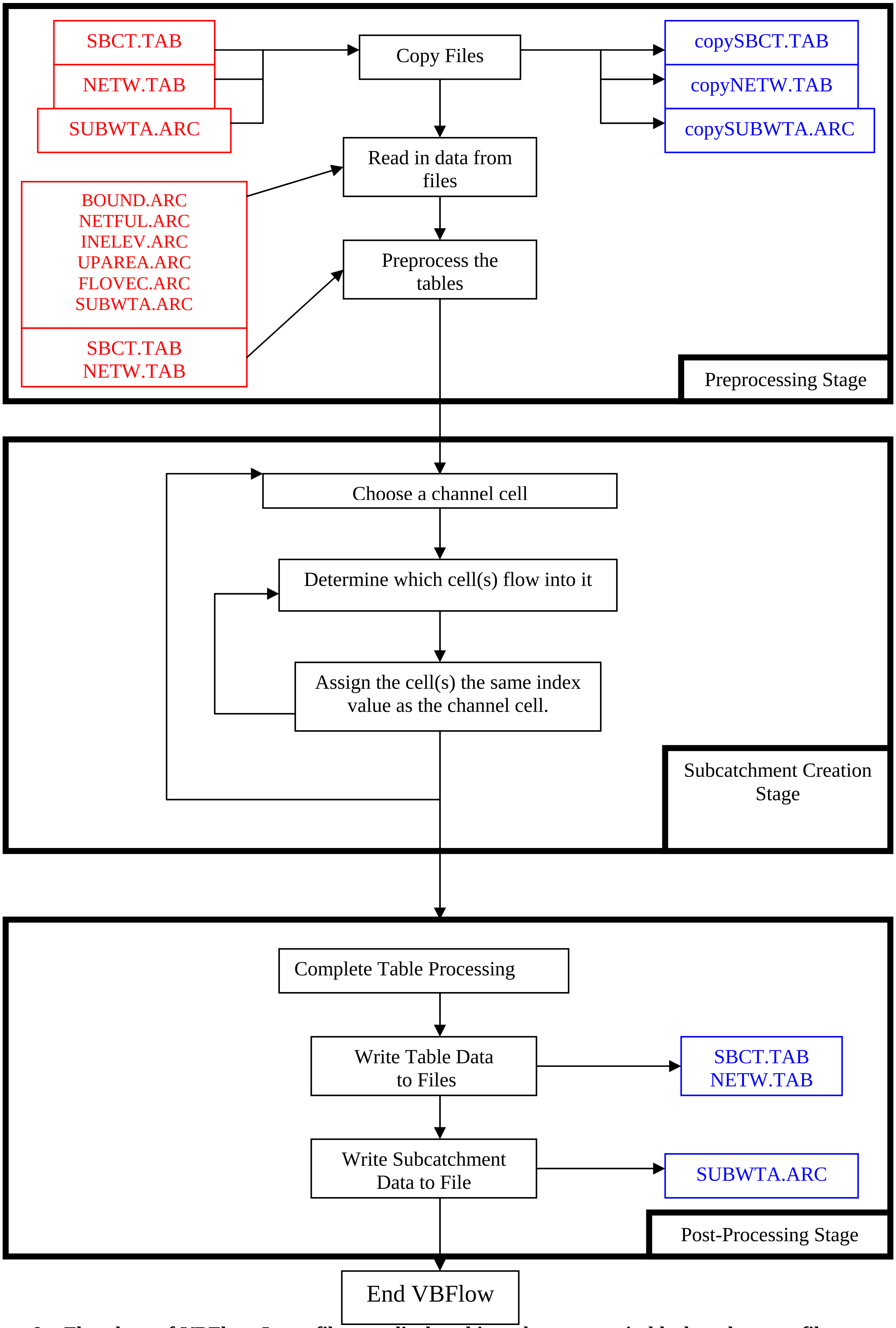


Figure 8 – Flowchart of VBFlow. Input files are displayed in red, processes in black and output files in blues. Bold boxes represent the three stages of VBFlow.

3.4.1 User Interaction with VBFlow and GeoWEPP

VBFlow is intended to be an integrated part of GeoWEPP, therefore there will not be any user interaction with VBFlow. VBFlow will be executed by GeoWEPP and all files will be created without any input from the user. In fact, the user may not even be aware that VBFlow is running. At present, VBFlow does require user interaction to help with the debugging process. This user interaction involves click a button when prompted to.

The current version of VBFlow is a research version which requires some user interactions due to the current version of GeoWEPP. GeoWEPP is written in Avenue script and uses DOS batches to run external programs. It was decided that it would be best to have the researcher control the timing of when VBFlow should run and when to return to ArcView. In this research version, a window appears when VBFlow is started. This window contains a text box displaying the message “Not Done” in it and a command button labeled Convert. The current version of GeoWEPP was modified so that a message box would prompt the researcher to run VBFlow. This message box prompt occurs after TOPAZ has completed its run and before any information is visualize within ArcView. When the researcher received the GeoWEPP prompt, the user would click the Convert button, executing the program. When VBFlow has finished it task, the text box message would change to “Done”. Once this message appears, the research would respond to the prompt message by clicking the “OK” button, returning control back to GeoWEPP. From this point on, all GeoWEPP functions are the same as the release version and all calculations are now based on the newly created VBFlow subcatchments.

3.4.2 Some Considerations Made When Creating VBFlow

In the research version of VBFlow, the only indication that the researcher has that the program has completed it task is the “Done” message. So, what is actually happening that the researcher does not see? VBFlow contains a “main” program and several subroutines and functions. Each plays a part in the program’s three stages to its run: Preprocessing, Subcatchment

Creation, and Post-processing. Clicking the Convert button starts the “main” program, StartConversion, thus initiating the first stage: preprocessing.

VBFlow is a program designed to read in several files, copy and manipulate them, and write out three new files. VBFlow was developed with the goal of being incorporated into the new ArcGIS version of GeoWEPP; with this in mind, VBFlow was written as a Visual Basic .NET program outside of the GeoWEPP and ArcView programs. A few modifications to the original VBFlow and to GeoWEPP had to be made to allow the two programs to interact. Only a single line of code needed to be added to the Avenue code of GeoWEPP – a simple line that activated a message box to alert the researcher that it was time to run VBFlow. Once VBFlow was completed, the research would click OK in the message box and GeoWEPP would continue normally.

The modification to the alpha version of VBFlow was to add code so that VBFlow would be able to read in the working directory in GeoWEPP from a text file; the text file would be created and modified by the researcher. The modified code looks for vbwkdir.txt which only contains one line that VBFlow reads into a variable. This line is the directory in which all the files VBFlow needs in located, for example “C:\geowepp\VBFlowWrkDir\”. Once this has been assigned, the program can continue on to the preprocessing stage.

3.4.3 Preprocessing Stage

The preprocessing step prepares the information that is need by the rest of the program; this includes backing up the original files (SUBWTA.ARC, NETW.TAB, and SBCT.TAB) that will be modified by VBFlow, reading in the necessary data from the files, setting up the variables to be used, and “fill in” some of the data for the two table files.

Copying Files

It is very important to back up the files that will be altered; this will prevent the destruction of data that may be needed in the future. During the debugging process, the same files were used over and over; backing them up each time insured that no accidental deletions occurred. Essentially, VBFlow makes a copy of the three input files.

VBFlow needs to create new files that represent the new subcatchment, but the names of these files need to match the ones create by TOPAZ for GeoWEPP and its programs to run properly. The result is that the original files created by TOPAZ will be modified. The decision was made to have VBFlow make copies of NETW.TAB, SBCT.TAB, and SUBWTA.ARC, just in case these originals need to be accessed later. The corresponding copies are: copyNETW.TAB, copySBCT.TAB, and copySUBWTA.ARC.

Assigning Input Parameters to Variables

The best way to work with the data contained in the ARC/INFO files is to assign each cells value in each file to a variable. To preserve the spatial arrangement of these cells, each files information is assign to a two dimensional array (2D array). A 2D array is essentially a list of lists; it works very well when trying to store row/column data (or, in the case of our spatial data, xy-coordinate data); a 2D array is a matrix. By using 2D arrays, the value of a cell can be accessed by just searching for its x,y address. All the spatial input files are store within 2D arrays with the same extend (the same xy-coordinates); this will make searching and obtaining values easier and faster. The following paragraphs go into more detail about how this process is done.

The next step in the preprocessing stage is to read information from the input parameter files – SUBWTA.ARC (Subcatchment), BOUND.ARC (Watershed Boundary), NETFUL.ARC (Stream Network), FLOVEC.ARC (Raster Cell Flow Direction), INELEV.ARC (Cell Elevation), UPAREA.ARC (Cell Up Area Contribution Value), NETW.TAB (Stream Network Table), and SBCT.TAB (Subcatchment Table) – into variables within VBFlow. This process includes the creation of the two dimensional arrays (also know as 2DArrays) which will hold the values of the raster cells from each input grid files - ARC file; these files are ASCII raster files. These files are set up as a series of rows and columns that represent the extent of the area being analyzes. These rows and columns are read in from the ARC files and stored within 2DArrays. To do this, the program reads in a line from the matrix within the ARC file, removes the whitespace at the ends of the line, breaks up the line so that each value is now a single "entity", and assigns each "entity" to an element of an array. This array is then assigned to an element of another array, creating a 2DArray or a matrix. By reading in the information is this way, it preserves the xy coordinates of the raster; the upper left hand corner of the 2DArray becomes the origin (0, 0). To access a value in one of the 2DArrays, the column number and row number are used, for example: SubCatch (3, 5) refers to the 6th elements in the 4th array of the 2DArray (arrays start at element 0). By using this method, the same raster cell can be accessed in each of the 2DArrays.

One important step in the above process involves the SUBWTA.ARC. The raster information in all the ARC files begins on the seventh line of the file; the first six lines contain other information: number of columns, number of rows, the upper left x and y coordinates (usually listed in meters, representing Universal Transverse Mercatur (UTM) coordinates), the size of the raster cell (in meters), and the No Data value. The only information that VBFlow needs is the number of rows and the number of columns. The number of rows will equate to the y-axis, while the number of columns will be the x-axis. These values will be stored in the variables GRIDx and GRIDy and will help create the 2DArrays mentioned above. But, the value stored in these variables is not the same as the values listed in the first six lines. Remember, arrays elements start at position 0; therefore, the value taken from the first six lines must be reduced by 1. So, instead of having rows 1 to 234, the 2DArray would have rows 0 to 233. Even though only the number of rows and columns is needed for VBFlow to run its course, the first six lines of the SUBWTA.ARC file need to be stored since ArcView and GeoWEPP need this information to visualize the subcatchments. Once VBFlow has calculates its subcatchments, these lines will be added to the beginning of the file; none of the information within these lines are changed. This process is only applied to SUBWTA.ARC.

By the end of this portion of the preprocessing stage, all the ARC files have been read into 2DArrays: NETFUL.ARC is saved in Network, BOUND.ARC is saved in Boundary, FLOVEC.ARC is saved in FlowVect, INELEV.AC is saved in InElev, and UPAREA.ARC is saved in UpArea. They all have the same number of rows and columns. The first six lines of SUBWTA.ARC have been saved in the array FirstSixLines.

Subcatchment and Network Table Preprocessing

The final portion of the preprocessing stage is the preparation of the two table files: SBCT.TAB and NETW.TAB. A similar method to the one for the ARC/INFO file is used for the two tables; all the rows and columns of the tables are stored in 2D arrays providing a similar table structure within the program. Once the 2D arrays for the tables are set up, VBFlow can begin to alter them to represent the new subcatchment delineation. These table files are created in two steps. The first is done before the subcatchment creation since some of the information in these tables will be needed to create the subcatchment. The remaining information needed to complete the tables will be done after the subcatchment creation stage since this information is taken from the subcatchments. The remainder of this section covers this process.

Determining the Number of Channels

Before the table preprocessing steps can begin, VBFlow needs to determine the number of channels cells that are located within the watershed. The original tables have a number of rows equal to the number of channels within the watershed plus one row for the outlet point. This same structure is needed in the new table. Since VBFlow concentrates on individual channels cells instead of the whole channel, the process is simple: count the number of channel cells located in the watershed and add one for the outlet. This is the number of rows needed in each table.

As mentioned earlier, TOPAZ creates subcatchments based on how they drain into a channel. VBFlow creates subcatchments based on how they flow into each individual channel cells. To calculate this, the number and location of each channel cell must be determined and what order they flow within the network. The first task VBFlow works on is the number of the channel cells. A simple counter and Boolean expression within nested *for loops* will take care of this. Essentially, the program asks if the value in location (i, j) in the boundary grid (BOUND) and the network grid (NetworkGrid) are both 1. If they are, then that location is a channel cells within the watershed. This process is repeated for all locations within the extent of the DEM (0 to GRIDx, 0 to GRIDy). Every time the answer to the question is true (i.e. both are 1), the counter is increased by 1. The final counter value equals the number of channel cells within the watershed and plus 1 for the outlet point. This value will be needed to create the new tables.

Original Subcatchment Table Deconstruction

The subcatchment table file contains the table as well as other information. VBFlow only needs the table information from the file, so the other information most be passed over. Fortunately, this information before and after the table does not change, so VBFlow can easy extracted the table. It is not know how the table is read into WEPP, so the structure of the file will need to be maintained. The information before and after the table, dubbed "useless", is stored to be put back into the table file once VBFlow has constructed the new table; this is covered later. The deconstruction of the subcatchment file and the subcatchment table is discussed below. What is important to note is that the table will be increased from the number of rows it currently has to a number of rows equal to the number of channel cells plus the outlet point. Rows need to be inserted between the current rows and is also explained below.

Once the number of channel cells has been determined, the program begins to dismantle the tables and save the data within different variables. SBCT.TAB is the first tables to be preprocessed since some of the information created here needs to be put into NETW.TAB.

SBCT.TAB is broken up into three section; the first and last section contains data (i.e. strings) that is not necessary for the program (in fact, this information is meant for the user, not a computer), but they are saved and put back into the new modified table to keep the format of the files intact, just in case the Translator looks for line numbers and not certain data flags. These "useless" section are read in line by line and store in an array the same way the first six lines of the SUBWTA.ARC grid were read in and saved. Once that first group of "useless" lines - which includes the column headings - is stored, the program reads in each line of the middle section (the table) and stores the line in an array. Since the order of the channels needs to be kept, VBFlow uses some of the tables existing data to create the new table setup. For example, when VBFlow reads in a line from the table, it stores the data that contains the number of cells within the channel (the seventh column in SBCT.TAB) in an array that will be used later to add lines to the table.

The process used to extract the data from each line of the table is the same as the process used to store the raster cell values from the *.ARC files. Each line, which corresponds to a single channel of the network within the watershed, is read in from the table file and "broken" apart by removing the whitespace. Each "broken piece" is then stored as an element of an array. This array is then stored in a 2DArray, along with a number of copies equal to the number of channel cells read in earlier minus 1 – in other words there are a number of identical arrays within the 2DArray that matches the number of channel cells for each channel – for each line in the table. This process is continued for each line of the table, except for the last line. The final line in the table corresponds to the outlet point and is just copies once. The remaining "useless" lines are stored within another string array to be saved for later. The end result is the creation of a 2DArray - SBCTtab - that contains a number of arrays equal to the number of channel cells found within the watershed plus one array for the outlet point. Each element of these channel/outlet point arrays corresponds to the column entry found in each line of the table.

Original Network Table Deconstruction

The network table is deconstructed in a similar fashion as the subcatchment process. The network table is longer (i.e. more columns) than the subcatchment file, but it will contain the same number of rows.

A similar process is used for NETW.TAB. As with the previous table file, NEW.TAB contains information before and after the table that will be store like before. Each line, which also corresponds to a channel with the network of the watershed, is read in, “broken” apart, and stored within an array. This array - along with several copies - is assigned to a 2DArray. The process is the same as before and the end result is the same – the 2DArray, NETWtab, contains all the data from the table file in a number of arrays that equals the number of channel cells within the channel network of the watershed plus one.

The copying of the table lines severs several purposes. First, the original table contained a line for each channel within the watershed. VBFlow will create subcatchments based of individual channel cells, so the table needs to store information based on the channel cell not just the channel. This means that the tables will need to contain a number of lines equal to the number channel cells within the watershed plus one for the outlet point. Second, some of the data that is stored for the channel is the same for the channel cell; for example, the stream order for a channel and one of its cells is the same. This process also keeps the table in the same structure and pattern as the original tables, thus helping VBFlow to mimic the input parameter files the Translator expects to receive.

Preprocessing the Subcatchment Table

Some of the information in the subcatchment table can be derived before the new subcatchments are created. In fact, some of this information – like the channel index numbers (column 3) – is need by VBFlow to create the subcatchments.

Only certain columns can be modified before the subcatchment creation stage of VBFlow. For SBCTtab, only columns 1 (Chan. Cntr.), 3 (Chan. Index), and 7 (Num of Channel Cells) need to be modified. Column 1 is modified by changing the value each row to the row number – the row array element number plus 1; column 1 will contain ascending numbers form 1 to the number of channel cells within the network plus 1 (for the outlet point). For column 3, the reverse process is used. The first value will be the number of channel cells plus 1; the next row will have a value one less then the previous row, until the final row, the outlet point, is reached, which will have the value of 1. Column 7 contains the number of channel cells within the channel. In the origin format, this number is based on the number of cells found in the channel; since the new subcatchments are based on a single channel cell, the value found in column 7 for each row will be 1.

Preprocessing the Network Table

Much of the information store within the network table can be derived from the other ARC/INFO files before the subcatchments are created. This is where the benefits of the 2D arrays come in handy. Several columns are based on cells values from different files. To access this information, the location of the cell needs to be determined. Fortunately, columns 3 through 8 contain the xy location of the cells, but these columns needed to be filled first. The first cell's location has already been recorded in the table deconstruction phase; all that needs to be done is find the coordinates of the other cells. This is done by looking at the flow direction of the channel cell and obtaining the coordinates of the cell it flows into. This process is repeated for each channel and each cell, until columns 3 through 8 have been filled. Now the data contained in the other 2D arrays can be accessed by referencing the location recorded in columns 3 – 8.

A number of columns need to be modified in NETWtab; columns 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, and 16. Column 16 is the same as column 3 in SBCTtab; therefore these numbers will be copied from SBCTtab to column 16. There are six columns that represent the coordinates of the channels cells based on how they flow within the network; VBFlow needs to determine the coordinates of each of the cells. Column numbers 3, 4, 5, and 6 contain the coordinates of the current cell while columns 7 and 8 contain the location of the next channel cell in the network. The odd columns contain the row value and the even columns hold the column value based on the cells location with the GRID.

The original file contained the starting location of each channel; this information was preserved when it was copied into the 2DArray. This is where the program starts from. Earlier the program recorded how many cells are within each channel within an array and this will be used to go through the table without writing over the needed data.

The process starts with the first row of NETWtab. The starting location for the first cell is also the starting location of the first channel. This information will remain in columns 3 and 4 and will be copied into columns 5 and 6. To determine the next cells location within this channel, the program uses the currents cells location and finds that location within the FLOWVEC file. Once the value of the flow direction of the cell is found, VBFlow will look determine the row and column numbers of the location in which the current cell flows into. Once this value has been determined, it is assigned to columns 7 and 8 of the current row and columns 3 and 4 of the next row if the next channel cell is still part of this channel. The process is repeated a number of times equal to the remaining number of channels cells within the channel.

Column 10 contains the elevation of the current cell, while column 11 holds the elevation of the next cell in the channel network. The elevation of these cells is determined using the row column coordinates determine earlier. To find the elevation data for column 10, the coordinates in columns 3 and 4 are used; VBFlow finds this cell location within the Elevation 2DArray (INELEV.ARC). The value found at that location is stored in column 10. The same process is used to find the value for column 11, except that columns 7 and 8 are used as the coordinates. This process is repeated for each row (each channel cell).

Column 12 and 13 contain the Upstream Are Flow for the current cell and column 14 contains the value of the upstream area flow for the next cell of the channel network. A similar method is used for the upstream area flow that was used for the elevation columns. VBFlow uses the UpArea 2DArray to find the value for the location in question. The value found for the current cell is stored in columns 12 and 13. The value for the next cell in the network is stored in column 14. The outlet point information within these columns does not need to be changed. This process is repeated for each channel cell in the table

Calculating Channel Cell Flow Lengths

The last bit of information that can be added to the network table can not be derived from the file; it needs to be calculated. The channel flow length column contains the distance water travels through the cell. It is assumed that the water will travel from either a corner or the midpoint of the cell and will exit at a corner or through the midpoint of a side after it passes through the center of the cell. With this assumption and the Pythagorean Theorem, the distance can be determined.

The final table modification is the channel length column, measured in number of cells. The channel length is the total flow length through the channel cells and is calculated based on the flow of the channel through the center of each cell. All flow paths travel from one corner or side, passes through the center of the cell, and then leaves through a side or corner. Even though there are a number of different paths a flow can take through a cell, the travel length is only one of three different values: 1, 1.21, and 1.41. Any flow that passes from on side to the opposite side will have a value of 1. If a flow travels from one corner of the cell to the opposite corner (creating a diagonal of the cell) will have a value of 1.41. If a flow enters from a side to a corner (or vice versa), the value will be 1.21. Any other combinations will fall into one of the above values. For example, flows that enter from one side and leaving through a non-opposite side still have a value of 1 since they must travel from a side to the center then to another side. The same is for corners to corners, which will have a value of 1.41.

The total length of the channel has already been calculated by TOPAZ and it is not known if any divergence from this value will cause errors within the Translator. Therefore, the TOPAZ length will be maintains. VBFlow does this by assigning the original channel length to a variable. Each time a channel cells flow length has been determined, that value will be subtracted from the total TOPAZ length variable. This process begins with the second channel cell in the channel and continues until the last cells flow length has been determined; the final value of the TOPAZ channel length variable will then be assigned to the first channel cell's length, thus making sure the sum of all the channel cell lengths equals the original TOPAZ length.

3.4.4 Subcatchment Creation Stage

The subcatchment creation phase is easy to comprehend, but difficult to program. Essentially, VBFlow needs to determine which subcatchment cells flow into which channel cells. Basically, VBFlow is looking at all the possible flow paths within the watershed and grouping these flow paths based on there end point. It is easier to start with the channel cell and work up the subcatchment. The process is simple:

1. Choose a channel cell
2. Determine which cell(s) flow into it
3. Assign the cell(s) the same index value as the channel cell
4. Go to each cell(s) found in step 2 and determine which cell(s) flow into them and assign them the same index value as the channel.
5. Repeat step until no more cells can be found.
6. All the cells found become a subcatchment
7. Repeat the entire process again with a new channel cell.

Since the flows within the watershed do not diverge, a subcatchment cell can only flow into one channel cell. Below are the more detail steps on how this entire process is done within VBFlow. The process becomes complex because VBFlow can not reason at the same level as a human, but the steps it takes mimic the reasoning process – it just needs a slight push.

Once VBFlow has completed the preprocessing stage, it can begin to create the subcatchments. First, VBFlow creates a temporary 2DArray, called FlowCatchGrid, with the same dimensions as the original subcatchment grid created by TOPAZ; this is where all the data will be stored as it is created for each cell. The next step is to assign to each network cell within FlowCatchGrid the channel ID determined in NETWtab by "reading" through the table, finding the x and y coordinate (row/column location) of each network cell and entering its channel ID into the corresponding location within FlowCatchGrid.

After the network channel IDs have been recorded, VBFlow can begin the process of determining which portions of the watershed flow into which channel cells; this process is done using recursion. VBFlow finds the first channel cell within the watershed and begins the subcatchment process for that cell. VBFlow creates a 3 by 3 matrix, called Neighborhood, with the channel cell being the center cell. In the remaining 8 cells, VBFlow assigns a value based on what type of cell it is: channel cell or non-channel cell. Channel cells always flow into a channel cell, so VBFlow needs to place a flag in the matrix so that the recursion process does not try to follow the channel (see below). Once the channel cell's Neighborhood has been created, the recursion can begin.

VBFlow needs to determine which cells within the watershed flow into each channel cell. To do this, VBFlow follows each flow path from the channel cell up to the starting point within the watershed. By retracing the path up to the starting point, VBFlow will be able to identify which cells flow into the channel cell. There may be many flow paths into the channel cell, so VBFlow must check all possibilities by using recursion; this will allow VBFlow to continue up one flow path, and then back track to check other paths. Starting at the channel cell, VBFlow analyses at the first non-channel Neighborhood cell and determines if it flows into the channel cell using the value that location has within FlowVect – the 2DArray that contains the flow direction of each cells. VBFlow determines what value the cell would have if it does flow into the channel cell based on the location of the cell in relation to the channel cell using the following:

9	8	7
6	C	4
3	2	1

Figure 9 - Neighborhood Numbering Scheme. These are the values the cell requires if it is to flow into cell C. These values are compared with the values found in the flow vector raster file for each cell's location in relation to C's location with the file. If the values match, the cell flows into C.

where C is the Cell of Interest (COI), in this case the channel cell. Each number represents the value to be found in FlowVect if a cell in that location relative to C is to flow into C. Therefore, if the first cell VBFlow is checking is the upper left cell in relation to the channel cell C, then the same location in relation to C within FlowVect must have a value of 9 if it is to be able to flow into C. Therefore, by comparing what the value a cell needs to have to flow into C and the value it actual has in FlowVect, VBFlow will be able to determine if the cell does actually flow into the channel cell. If the two values are not the same, then VBFlow checks the next cell in Neighborhood in a clockwise fashion around the channel cell, until all cells have been checked; VBFlow moves on to another channel cell if all the cells have been check around the current channel cell. Since the channel cells within Neighborhood are marked, VBFlow will not check this path since the result would be subcatchments that contain all the cells that flow into all the channel cells that flow into this channel cell – not what the program is looking for.

If the cell being check does flow into the channel cell, the recursion process begins. The same process used on the channel cell is repeated for this new cell; the new cell becomes the COI. When a cell surrounding the COI has been determine to flow into the COI, the recursion procedure calls itself again, and uses the new cell as the COI and so on. The power of the recursion procedure is when it has checked all the cells around a COI; it records the current channel cell ID within FlowCatchGrid at the current COI location, returns to the previous COI and checks the remaining cells. This way, VBFlow can travel up one "branch" in this flow and then return and check another "branch". This is like climbing up a tree from the base to the end of the uppermost branch, then back tracking until the start of another branch is found and following that out to the end, and then repeat.

Once all the flowpaths have been determined for a channel cell, VBFlow moves to the next channel cell it finds until all channel cells have been processed; the subcatchment creation is almost complete. Every cell within FlowCatchGrid now either contains a zero (a cell not within the watershed) or a value equal to a channel cell id. The last step is to assign the TOPAZ cell types to the values. The cell type is based on the naming convention TOPAZ uses - 1 (source cell), 2 (right bank cell), 3 (left bank cell), and 4 (channel cell). Since these types have already been determined, VBFlow only needs to remove the last digit from the original cell values (found in SubCatchGrid) and add it t the end of the new subcatchment cell values found in FlowCatchSub. A simple mathematical equation will complete this process: add the remainder of (SubCatchGrid divided by 10) to the result of (FlowCatchSub time 10).

FlowCatchGrid(i, j) = (FlowCatchGrid(i, j) * 10) + (SubCatchGrid MOD 10) **(Eq 9)**

Essentially, the subcatchment process determines which channel cell each watershed cell will eventually flow into, assigns it the channel cell id, and then determines if that cell is on the left bank, right bank, or part of the source. The end result is a new subcatchment distribution based on how the watershed flows into each channel cell within the boundary of the watershed.

3.4.5 Post-processing Stage

The final steps involve the completion of the tables and changing the values in the subcatchment 2D array to match the TOPAZ numbering scheme. The information needed for the tables is based on the subcatchments, so the TOPAZ numbering scheme needs to be applied before the tables can be completed. As stated before, the number scheme is (index number * 10) plus 1, 2, 3, or 4. The index number are currently stored in the new subcatchment 2D array, so all that is needed is to determine which number to assign to each cell. Fortunately, these numbers have already been assigned by TOPAZ to each cell. Each cells “role” does not change when the new subcatchments are created; a cell on the right bank of a channel is still on the right bank of a single cell of that channel. The task of assign the TOPAZ numbers to each new subcatchment cell is simple: take the current cells value, multiple by 10, add the original TOPAZ number (1, 2, 3, or 4), and then assign it back to the subcatchment cell. Once this is done, the tables can be completed.

The tables only require the number of cells that are found in each right bank, left bank, and source area. This is done by adding up the number of cells that have the corresponding TOPAZ number. For example, to determine the number of cells in the right bank of channel index 5, all that needs to be done is count the number of cells that have the value of 52. This is done for the remaining columns in the tables. Once the tables are completed, VBFlow writes the tables and the new subcatchment information into the required files. This process also includes putting the “useless” data back into the files. In the end, the structure of all three files is maintained. The following paragraphs go into more detail on how VBFlow completes its assigned task.

Now that the subcatchments have been created, VBFlow can complete the modifications to the tables; NETWtab only needs to complete column 15 (Drainage Area), while SBCTtab still needs four columns to be finished. VBFlow will complete SBCTtab first since the final column of NETWtab needs the information from these columns. Columns 4, 5, 6, and 8 all deal with the number of cells for the contributing areas of the watershed. Column 4 holds the number of cells for the source area of the channel cell; this value will be -1 for all channel cells that are not the first channel cell of a first order stream. To determine the value of a head channel cell of a first order stream, VBFlow counts the number of cells that contain the value of:

$$(\text{channel cell ID} * 10) + 1 \qquad \textbf{(Eq 10)}$$

Column 5 holds the number of cells found on the left side of the channel cell while column 6 holds the number of cells found on the right side of the channel cell. The same procedure for the source area is used to determine the number of cells on the left and right banks:

(channel cell ID * 10) + 2 (right bank) **(Eq 11)**
(channel cell ID * 10) + 3 (left bank) **(Eq 12)**

Finally, column 8 is the summation of columns 4, 5, 6, and 7, with one exception: if the value found in one of the columns is -1, that column is not included within the summation. Remember, column 7 contains the number of channel cells in the channel and was modified earlier to make each entry a 1, except for the outlet point where it is -1.

Column 15 of NETWtab is determined by adding up the left area, right area, and the number of channel cells (in this case 1). Since the number of cells in the right and left sides have been determined in SBCTtab, they are added together, increased by one and the final value is stored in column 15 of NETWtab.

This entire process is repeated for each channel cell within the watershed. For both tables, the values located within the outlet point row are not changed.

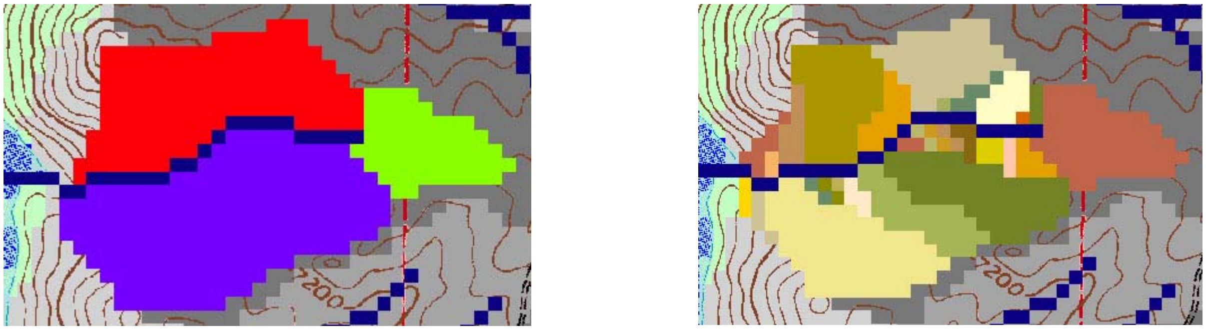
All modifications have been made at this point. The only step that remains in the entire process is to rewrite the three files: SUBWTA.ARC, SBCT.TAB, and NETW.TAB. The steps needed to write each file are almost the same. For the tables, the first set of “useless” lines is written to the files. The data we need to transfer to the files are currently being store in arrays. To transfer this information, VBFlow must first retrieve the data, convert it to a string and then write the string to the file. VBFlow reach each element of an array, writes it to a string, inserts a space and then gets the next element. Once a row (an entire array) has been converted in this manner to a string, the string is written into the file. This process is repeated for each row in the two tables and each row of the new subcatchment grid. Finally, any “useless” lines found at the end of the original files are written into the new files. Once the last line has been written, the file is closed and VBFlow has completed its task; the converted files can now be accessed by GeoWEPP, WEPP, and the Translator.

3.5 VBFlow Outputs versus the Original TOPAZ Inputs

VBFlow modifies three files TOPAZ output files: SUBWTA.ARC, NETF.TAB, and SBCT.TAB. This section describes the differences between the original TOPAZ files and the newly modified VBFlow output files. In each section, the original data for a simple watershed is compared with the VBFlow modified data of the same watershed.

3.5.1 Original TOPAZ Subcatchments versus VBFlow Subcatchments

The only modifications to the original TOPAZ delineations that the user will become aware of is the creation of the subcatchments. Once VBFlow has completed the modifications, GeoWEPP displays the new subcatchments the user. The original subcatchments were based on how the watershed flows into the entire channel and from which direction. This means that each channel can have no more than three subcatchments. VBFlow changes this cap based on how the watershed flows into a single channel cell. The result is the possible breaking up of each subcatchment into smaller contributing areas; the result is that each channel can have a number of subcatchments equal to two times the number of changes plus one. What is meant by possible is that VBFlow looks at the flow of the watershed’s drainage pattern and creates the new subcatchments based on this pattern. In the case of source subcatchments, VBFlow does not break up the subcatchment because the entire region flows into one channel cell already – the stream’s source cell. But, this may not be the case for other subcatchments; they may have a number of flowpaths that drain into a channel at different points, resulting in more than one subcatchment. There is still a possibility that a TOPAZ created subcatchment will only have one flow path into a channel. If this is that case, VBFlow will also only create a single subcatchment. Figure 10 shows the difference between the original TOPAZ created subcatchments for a small watershed and the VBFlow created subcatchments for the same watershed.



3 subcatchments versus 29 subcatchments
(a) (b)

Figure 10 – The subcatchments created by VBFlow and TOPAZ. TOPAZ creates three subcatchments (a) based on how the watershed flows into the single channel resulting in a left, right and source subcatchment. VBFlow (b) creates a subcatchments based on how the watershed flows into each channel cell; the result being a potential increase in the number of subcatchments within the watershed.

3.5.2 Original versus Modified Subcatchment Tables

Below is an example of a TOPAZ produced subcatchment table (table 4) of a simple watershed followed by a VBFlow modified version of the same table (table 5). The TOPAZ table has two lines: one for the single channel (made up of 22 channel cells) and one for the outlet point. The modified table has 23 lines: one row for each channel cell and a row for the outlet point. The table has been modified so that each channel cell is represented instead of just the channel. The channel counter column has changed to account for the new number of rows. The channel order column has not changed since each cell of the channel still belongs to a first order channel.

The channel index has drastically changed. The TOPAZ version has a certain procedure for creating this order. The modified table just lists the numbers in decreasing order from the largest channel counter to 1. In the example below, 21 lines were inserted between the channel row and the outlet point. This new channel index is used in the modified subcatchment file.

The remaining columns are calculated in a similar fashion to TOPAZ. First, the first cell of a first order channel always has a source. The remaining channel cells of a first order channel and all channel cells that belong to higher order channels have a value of -1. The first cell in the modified table has the same number of cells in its source as the channel does in the original

TOPAZ table. The left and right subcatchments represent the number of cells that flow from the left and the right into that channel cell. It is possible that this number is 0. Column 7, Number of Channel cells is always going to be one since the program looks at an individual channel cell. Column 8 is treated the same for both tables. Finally, the entries for the outlet point remain the same.

Table 4 - Original Example of SBCT.TAB

CHAN. CNTR.	CHAN. ORDER	CHAN. INDEX	SUBCATCHMENT AREA IN NUMBER OF CELLS SOURCE	LEFT	RIGHT	CHANNEL	TOTAL
1	1	2	59	200	138	22	419
2	1	1	-1	-1	-1	-1	-1

Table 5 - Example SBCT.TAB using VBFlow

CHAN. CNTR.	CHAN. ORDER	CHAN. INDEX	SUBCATCHMENT AREA IN NUMBER OF CELLS SOURCE	LEFT	RIGHT	CHANNEL	TOTAL
1	1	23	59	0	0	1	60
2	1	22	-1	0	3	1	4
3	1	21	-1	6	1	1	8
4	1	20	-1	3	0	1	4
5	1	19	-1	4	0	1	5
6	1	18	-1	0	12	1	13
7	1	17	-1	4	5	1	10
8	1	16	-1	0	0	1	1
9	1	15	-1	2	1	1	4
10	1	14	-1	2	43	1	46
11	1	13	-1	2	0	1	3
12	1	12	-1	2	0	1	3
13	1	11	-1	57	0	1	58
14	1	10	-1	0	13	1	14
15	1	9	-1	30	0	1	31
16	1	8	-1	4	0	1	5
17	1	7	-1	1	0	1	2
18	1	6	-1	2	0	1	3
19	1	5	-1	2	49	1	52
20	1	4	-1	0	9	1	10
21	1	3	-1	75	0	1	76
22	1	2	-1	4	2	1	7
23	1	1	-1	-1	-1	-1	-1
			59	**200**	**138**	**22**	**419**

To confirm that the modified table is equal to the original TOPAZ table, the source, left, right, channel, and total columns can be added up and the resulting values will match the values in for the channel in the original TOPAZ table.

3.5.3 Original versus Modified Network Tables

Similar modifications to NETW.TAB have also been made. Below are two NETW.TAB tables: the first one is from the original TOPAZ NETW.TAB file from the earlier example, the other is the modified table for the same example using the new program. There are several similarities between the modifications made in the table compared to the SBCT.TAB.

The same process to create the number of rows is used to modify the NETW.TAB that was used in the modification of SBCT.TAB. The number of rows in the modified table equals the number of channels cells found in the single watershed channel plus on row for the outlet point. This is done by insert a number of rows after the channel row so that the number of inserted rows (in this case 21) plus the channel row equals the number of channel cells in the channel (22 for this channel).

The creation of the data for the columns is done in a similar fashion used in the original TOPAZ NETW.TAB table (see table description section). The first column of the table, Channel Counter matches the values entered in the same column in SBCT.TAB. The same is true for the Channel Order column.

The coordinates group is a little more difficult. Since the original channel row contains the coordinates of the first cell of the channel, this location will be used to determine the location of the remaining cells. This is done by looking at the flow direction of the first cell and determining where it flows to. Once this is done, the location is recorded in the table and the process contains with this new location until the end of the channel is reached. For the three coordinate pairs in this section, the Upstream and the Downstream Previous are the same location since there is only one cell. The Downstream Last is the location of the cell in which this cell flows into. The only points where this concept falls apart is the last cell of the channel network and the outlet point. For both of these rows, the Upstream, Downstream Previous and Downstream Last are all the same location.

The channel length in number of cells column is calculated the same way as the channel length in the original TOPAZ table. The difference is that once the distance across a cell has been determined, it is recorded in the table. The distance across the first cell is not calculated in the usual manner. Instead, the first cell's distance is the original channel length determined by TOPAZ minus the sum of the channel cell lengths just determined. The result is that the summation of the lengths for each channel cell will equal the TOPAZ determined length.

The remaining columns are determined using the same procedure that is described in the NEWT.TAB description section. All values that need to be determined from SBCT.TAB are taken from the modified SBCT.TAB table. The final result is a new network tables with the same column totals as the original network table. Table 7 shows, in bold, the values that appear in table 6; those columns that can be summed are at the bottom of the table, in bold; these totals are equal to the values found in table 6.

The comparison of the original network table and the modified table shows that the structure is the same and the vital information is present. This, along with the confirmation that the structure and content of the subcatchment table and ARC/INFO file, confirms that the program is ready for testing. The next section discusses the validation runs preformed using the original GeoWEPP version and the GeoWEPP results using the VBFlow created subcatchments.

Table 6 - Original Example of NETW.TAB

CHAN. CNTR #	CHANNEL ORDER #	COORDINATES UPSTREAM ROW	UPSTREAM COL	PREV. ROW	PREV. COL	DOWNSTREAM LAST ROW	LAST COL	CHANNEL LENGTH IN # CELL WIDTHS	TERRAIN ELEVATION IN METERS UPSTR.	DWSTR.	UPSTREAM AREA FLOWING INTO FOLLOWING NODES UPSTR. [ALL AREAS IN NUMBER OF CELLS]	DWSTR.-1	DWSTR.	DIRECT DRAINAGE AREA	NODE INDEX (MULTIPLE NODES) 1	2	3	4	5	6	7	SLOPE * 1000 DIRECT	SMOOTHED
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	255	288	259	268	259	267	24.90	2195.0	2096.9	59	418	418	360	2	0	0	0	0	0	0	-1.000	-1.000
2	1	259	267	259	267	259	267	0.00	2096.9	2096.9	418	418	418	0	1	0	0	0	0	0	0	-1.000	-1.000
-1																							

Table 7 - Example NETW.TAB using VBFlow

CHAN. CNTR #	CHANNEL ORDER #	COORDINATES UPSTREAM ROW	UPSTREAM COL	PREV. ROW	PREV. COL	DOWNSTREAM LAST ROW	LAST COL	CHANNEL LENGTH IN # CELL WIDTHS	TERRAIN ELEVATION IN METERS UPSTR.	DWSTR.	UPSTREAM AREA FLOWING INTO FOLLOWING NODES UPSTR. [ALL AREAS IN NUMBER OF CELLS]	DWSTR.-1	DWSTR.	DIRECT DRAINAGE AREA	NODE INDEX (MULTIPLE NODES) 1	2	3	4	5	6	7	SLOPE * 1000 DIRECT	SMOOTHED
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	**255**	**288**	255	288	255	287	1.19	**2195.0**	2193.9	**59**	59	63	1	23	0	0	0	0	0	0	-1.000	-1.000
2	1	255	287	255	287	255	286	1	2193.9	2191.1	63	63	71	4	22	0	0	0	0	0	0	-1.000	-1.000
3	1	255	286	255	286	255	285	1	2191.1	2185.5	71	71	75	8	21	0	0	0	0	0	0	-1.000	-1.000
4	1	255	285	255	285	255	284	1	2185.5	2182.0	75	75	80	4	20	0	0	0	0	0	0	-1.000	-1.000
5	1	255	284	255	284	254	283	1.21	2182.0	2176.9	80	80	93	5	19	0	0	0	0	0	0	-1.000	-1.000
6	1	254	283	254	283	254	282	1.21	2176.9	2171.8	93	93	103	13	18	0	0	0	0	0	0	-1.000	-1.000
7	1	254	282	254	282	254	281	1	2171.8	2170.2	103	103	104	10	17	0	0	0	0	0	0	-1.000	-1.000
8	1	254	281	254	281	254	280	1	2170.2	2164.8	104	104	108	1	16	0	0	0	0	0	0	-1.000	-1.000
9	1	254	280	254	280	254	279	1	2164.8	2158.4	108	108	154	4	15	0	0	0	0	0	0	-1.000	-1.000
10	1	254	279	254	279	255	278	1.21	2158.4	2157.0	154	154	157	46	14	0	0	0	0	0	0	-1.000	-1.000
11	1	255	278	255	278	256	277	1.41	2157.0	2150.6	157	157	160	3	13	0	0	0	0	0	0	-1.000	-1.000
12	1	256	277	256	277	257	276	1.41	2150.6	2144.5	160	160	218	3	12	0	0	0	0	0	0	-1.000	-1.000
13	1	257	276	257	276	257	275	1.21	2144.5	2139.9	218	218	232	58	11	0	0	0	0	0	0	-1.000	-1.000
14	1	257	275	257	275	258	274	1.21	2139.9	2132.5	232	232	263	14	10	0	0	0	0	0	0	-1.000	-1.000
15	1	258	274	258	274	258	273	1.21	2132.5	2127.8	263	263	268	31	9	0	0	0	0	0	0	-1.000	-1.000
16	1	258	273	258	273	258	272	1	2127.8	2121.4	268	268	270	5	8	0	0	0	0	0	0	-1.000	-1.000
17	1	258	272	258	272	258	271	1	2121.4	2113.4	270	270	273	2	7	0	0	0	0	0	0	-1.000	-1.000
18	1	258	271	258	271	258	270	1	2113.4	2107.4	273	273	325	3	6	0	0	0	0	0	0	-1.000	-1.000
19	1	258	270	258	270	258	269	1	2107.4	2104.2	325	325	335	52	5	0	0	0	0	0	0	-1.000	-1.000
20	1	258	269	258	269	259	268	1.21	2104.2	2099.0	335	335	411	10	4	0	0	0	0	0	0	-1.000	-1.000
21	1	259	268	**259**	**268**	259	267	1.21	2099.0	2096.9	411	411	418	76	3	0	0	0	0	0	0	-1.000	-1.000
22	1	259	267	259	267	**259**	**267**	1.21	2096.9	**2096.9**	418	**418**	**418**	7	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**-1.000**	**-1.000**
23	1	259	267	259	267	259	267	0	2096.9	2096.9	418	418	418	0	1	0	0	0	0	0	0	-1.000	-1.000
								24.90						**360**									

4 Validation

The validation process is dividend into several stages. The first stage involves determining if the topography is accurately represented within the model; this includes determining if the derived channel network accurately depicts the study site's channel network. Any error within the topography will affect the results of the remaining stages. Once the topography has been confirmed, the modeled study sites hydrology must be confirmed. The hydrology consists of both the rainfall and the runoff within the watershed. The amount of rainfall into the modeled watershed and the runoff through the outlet point should approximate the observed rainfall and runoff. Once it has been established that the model is accurately representing this parameter, the validation process can move to the geomorphology. The final stage is to determine if the soil loss and sediment yield within the modeled watershed provides a good estimation compared to the observed measurements. If all three stages have been confirmed, then VBFlow is a working validated model.

This section includes the validation stages described above. Two approaches are taken to validate VBFlow: short-term and long-term assessments. The short-term assessment uses two storm seasons within the watershed, along with the other input parameters previous discussed. The goal is to confirm the model's results with observed data over a short period of time. Both GeoWEPP and VBFlow will be used and the results will be compared with the observed runoff, peak runoff, and sediment yield. Once the short-term assessments have been validated, VBFlow can be validated for long-term assessments.

The long-term assessment uses a 50-year simulated run. The same input parameters used for the short-term assessment are used except for the climate data. In this run, the climate data is created using CLIGEN – a climate generator program. Since the same topography is being used, the hydrology and geomorphology only needs to be confirmed.

In all three scenarios, the simulation results from both GeoWEPP and VBFlow will be compared to observed measurements. The validity of the results will be based on R^2 values and on the Nash-Sutcliffe model efficiency values (Nash and Sutcliffe 1970). The Nash-Sutcliffe model efficiency formula “is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation” {Krause, 2005 #65}. The formula determines a models goodness of fit when compared to the observed measurements; the formula is shown in equation 13.

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2}$$

(Eq 13)
{Krause, 2005 #65}

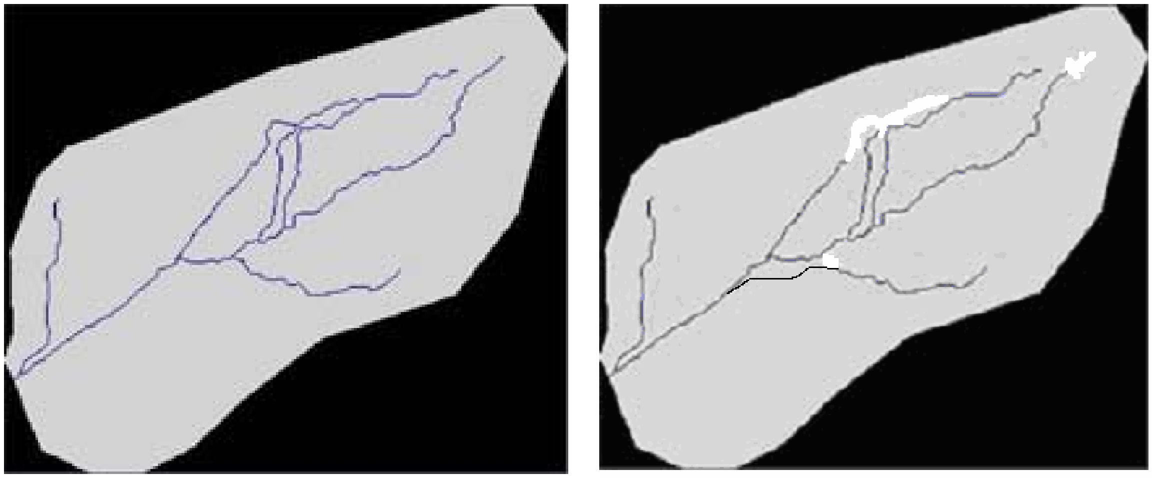
where *O* is observed and *P* is predicted values, and *n* is the number of events

The result, *E*, ranges from 1 (which is considered a perfect fit) to $-\infty$. A value of zero means that there is no difference between using the model’s predicted results and the mean of the observed values. An efficiency value below zero indicated that it would be better to use the mean of the observed values instead of the predicted results.

The benefit of applying the Nash-Sutcliffe model efficiency, along with R2 values, to the scenarios is to demonstrate how well or how far off VBFlow and GeoWEPP predictions are compared to the observed values. The R2 value will show the correlation between the observed and predicted, but the correlation will not demonstrate how well the predicted results perform against the mean of the observed values. The Nash-Sutcliffe model efficiency values will demonstrate that the predicted values are closers to the observed values than the mean of the observed values, thus suggesting that the model will predict values that are more like the observed values.

4.1 The Topography

The topography is the most important aspect of the model. The topography consists of three pieces: the digital elevation model, the channels and the subcatchments. The DEM was provided by Dr. Mary Nichols, a research hydraulic engineer for the USDA- Agriculture Research Service and one of the researches involved with the Lucky Hills site, therefore the DEM is accurate. TOPAZ uses this DEM to delineate the channel network. Through trial and error, and channel network that match the hillshade representation of the DEM was created; a critical source area (csa) of 5 and a minimum source channel length (mscl) of 100 were used. The resulting channel network was sent to Dr. Nichols to determine if this channel network was an accurate representation of the channel network within the Lucky Hills nested watershed. Figure 11a shows the channel network derived by TOPAZ. Figure 11b is the modified image supplied by Dr. Nichols. Only a few differences existed between the two. These differences may be due to the characteristics of the landscape that are smaller than the 1 meter resolution of the DEM and/or the filling of the sinks within the DEM. More trial and error with the csa and mscl parameters did not produce any better results. The end result is that several first order channels begin further down stream than simulated. Also, note that one stream should enter the main channel further down the watershed that predicted. These differences can be attributed to the differences between the DEM and the landscape and the application of the critical source are and minimum stream channel length to all streams.



(a) (b)

Figure 11 – TOPAZ channel network versus observed Lucky Hills channel network. The TOPAZ channel network (a) was sent to researches at the Lucky Hills, Arizona, study site. This network was compared to the observed network and the differences can be seen (b).

The DEM and the channel networks have been determined to be good representation of the watershed. The final step is confirming the subcatchments. TOPAZ creates the subcatchments based on the DEM and the channel network. Since these input parameters have been validated, the resulting subcatchments should be accurate as well. Initially, the subcatchments are created using the current version of GeoWEPP. Next, VBFlow creates the new subcatchments based on the TOPAZ generated subcatchments. The total area of the VBFlow subcatchments should match the total area of the TOPAZ subcatchments, which equals the area of the watershed. Table 8 confirms that the area for the upper watershed and the area for the large nested watershed are the same for both GeoWEPP and VBFlow.

Table 8 – Number of Channels and Subcatchments Created by VBFlow and GeoWEPP

	GeoWEPP/TOPAZ	**VBFlow**
Upper Watershed		
Area	1.35 ha	1.35 ha
Channels	5	468
Subcatchments	13	490
Large Watershed		
Area	3.66 ha	3.66 ha
Channels	11	938
Subcatchments	28	996

The major difference between the two resulting subcatchments is that VBFlow creates more, smaller subcatchments near the channel and only a few further away. This can be seen by the placement of the arrows within the figure 12. Figure 12b shows the subcatchments created by TOPAZ. Both arrows in this image are within the same subcatchment. The same arrows are place within the figure 12a; the result is that each arrow is within a different subcatchment. The subcatchment within figure 12b has been broken up into to medium size subcatchments (where the arrows are) and a large number of small subcatchments – all near the channel. This means that a majority of the watershed only flows into a few section of the channel network. By breaking up the TOPAZ subcatchments, VBFlow may only be giving a slightly better result by providing a different slope input data.

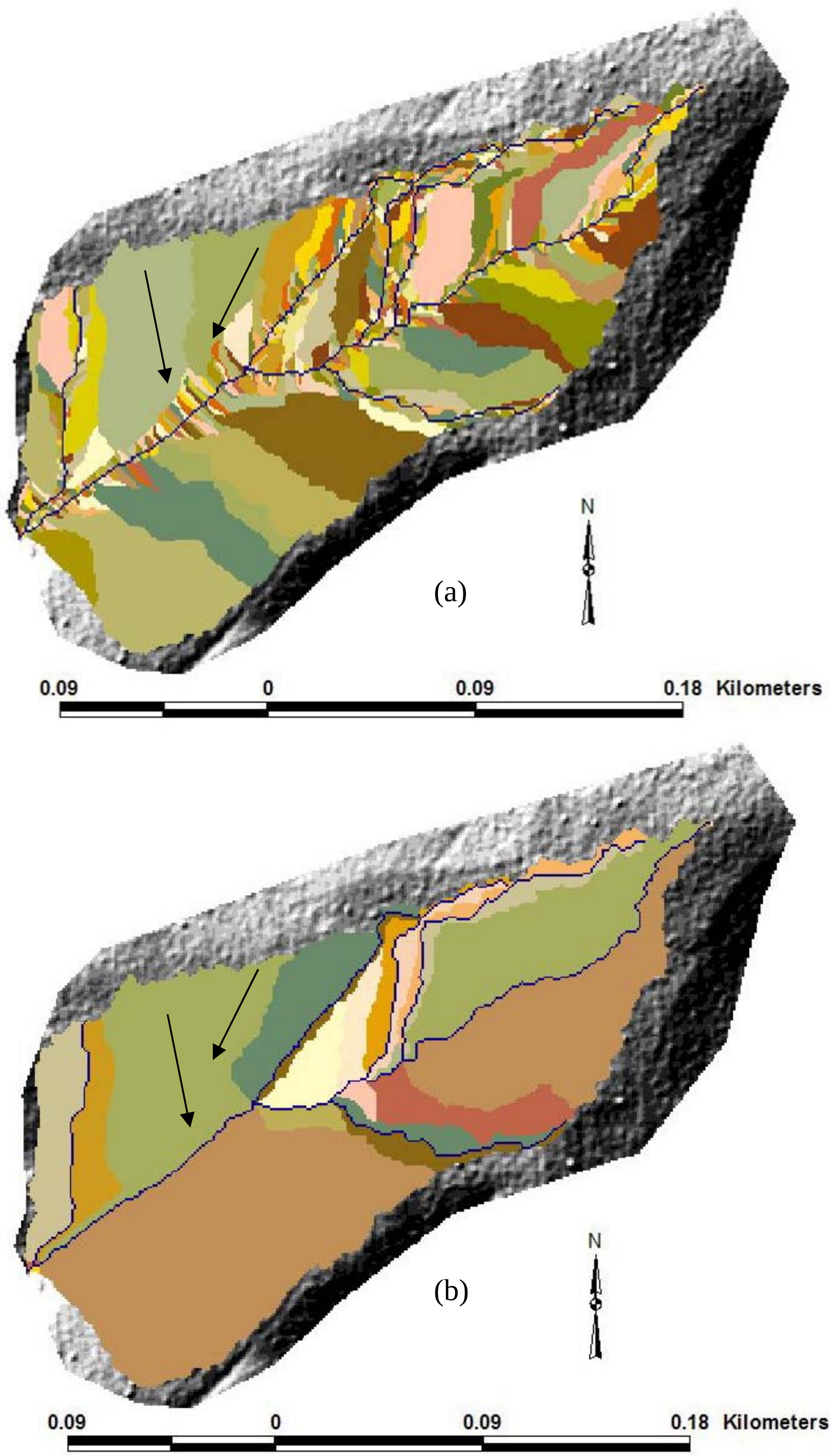


Figure 12– Comparison between VBFlow and TOPAZ created subcatchments for Lucky Hills. (a) VBFlow created more subcatchments near the channel, but only subdivided the upper portions into only a few new subcatchments. This shows that a majority of the watershed only flows into a few sections of the channel network. The arrows show the same region within both images, but the arrows are within the same subcatchment in (b), but are in different subcatchments within (a).

The major difference comes into play near the channel. VBFlow has created a large number of small subcatchments near the channel. By creating a better diversity near the channel, VBFlow may be able to provide a better representation that more closely models the real world Lucky Hills. This type of diversity is lost within the large TOPAZ subcatchments.

The topography within the model has now been confirmed. The DEM, the channel network, and the subcatchments provided an accurate representation of the study site being modeled. This topography will be used as input parameters for both the short-term and long-term assessments. The next step will be to validate the hydrology for each assessment; first is the short-term assessment.

4.2 Short-Term Assessment Validation

The short-term assessment is performed using both GeoWEPP and VBFlow. The short term run consisted of a two year simulation using the topography discussed earlier, the soil and management WEPP file discuss in section 2.4, and a climate file that contained the rainfall data for the 1982 and 1984 storm seasons. The purpose of these runs is to determine how well VBFlow and GeoWEPP estimate the runoff and sediment yield for these two storm seasons.

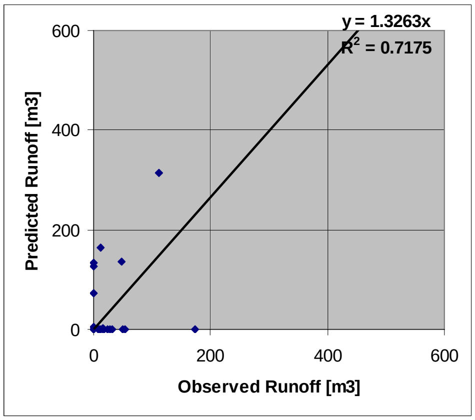
The parameters were applied to the upper watershed of Lucky Hills (outlet point being the estimated location of flume 101) and the entire Lucky Hills nested watershed. Two outlet points were chosen for the simulations. One point (589682N, 3512453E) defined the upper watershed, while the other (589546N, 3512375E) defined the entire study site watershed (including the smaller upper watershed). The resulting watersheds had the same area for both GeoWEPP versions: 3.66 ha (9.04 acres) for the large watershed and 1.35 ha (3.3 acres) for the small upper watershed. The results for the large watershed are discussed below. Not all the data has been collected for the small upper watershed, so only a short discussion about the runoff is provided.

The original GeoWEPP simulations used both the watershed method and the flowpath method provided by the Translator. The modified GeoWEPP version using VBFlow only used the watershed method. Using the flowpath method for this version is redundant, since only the subcatchments were modified by VBFlow; no flowpaths were modified. This was confirmed in early tests runs of VBFlow, resulting in identical results for both programs. After the initial simulations for both GeoWEPP versions, the tolerable soil loss value (T) was changed to 2.5 t ha^{-1} yr^{-1} to closer match the range of the sample sites. This meant that the tolerable soil loss/sediment yield values ranged from 0 to 2.5 t ha^{-1} yr^{-1}, while the range for those regions that exceed the tolerable levels ranged from greater than 2.5 to 10+ t ha^{-1} yr^{-1}. Deposition was recorded as 0 to 2.5 t ha^{-1} yr^{-1}, and greater than 2.5 t ha^{-1} yr^{-1}.

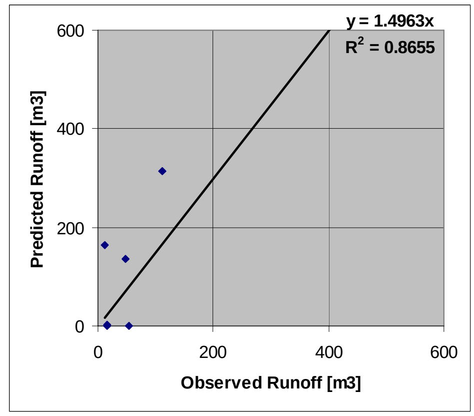
4.2.1 The Hydrology

The next stage in the validation process is to determine if the hydrology for the study site is accurate. In the case of the short-term assessment, the runoff and runoff peak calculated by the models are compared with the observed values. Figures 13 show the statistics for the large watershed runs using GeoWEPP. There is a correlation between the observed measurements and the GeoWEPP calculate measurements. There is a higher correlation when only matching storms are compared. Furthermore, the Nash-Sutcliff model efficiency values for these matching storms are 0.793 for the runoff and 0.783 for the peak runoff. This shows that GeoWEPP is modeling the hydrology very well.

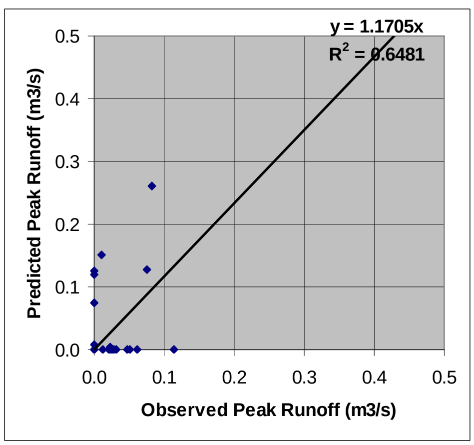
Similar results can be found when the VBFlow subcatchments are used. The runoff and peak runoff graphs are in figure 14. VBFlow models the runoff slightly better than GeoWEPP. For the runoff, the R^2 value increases from 0.8655 for GeoWEPP to 0.909 for VBFlow. The Nash-Sutcliff model efficiency values for these matching storms are 0.857 for runoff and 0.717 for peak runoff. This shows that both GeoWEPP and VBFlow model the hydrology for the large watershed very well; the final validation is the geomorphology for the short-term assessment.



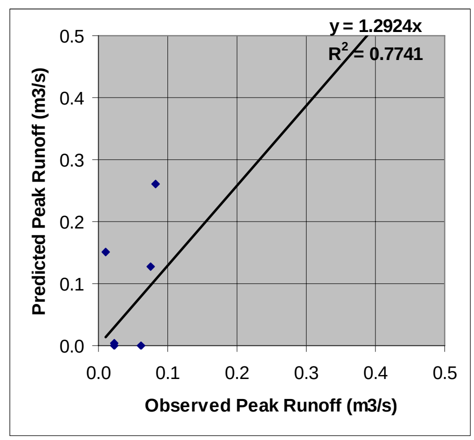
(1a) ME = 0.347



(1b) ME = 0.793

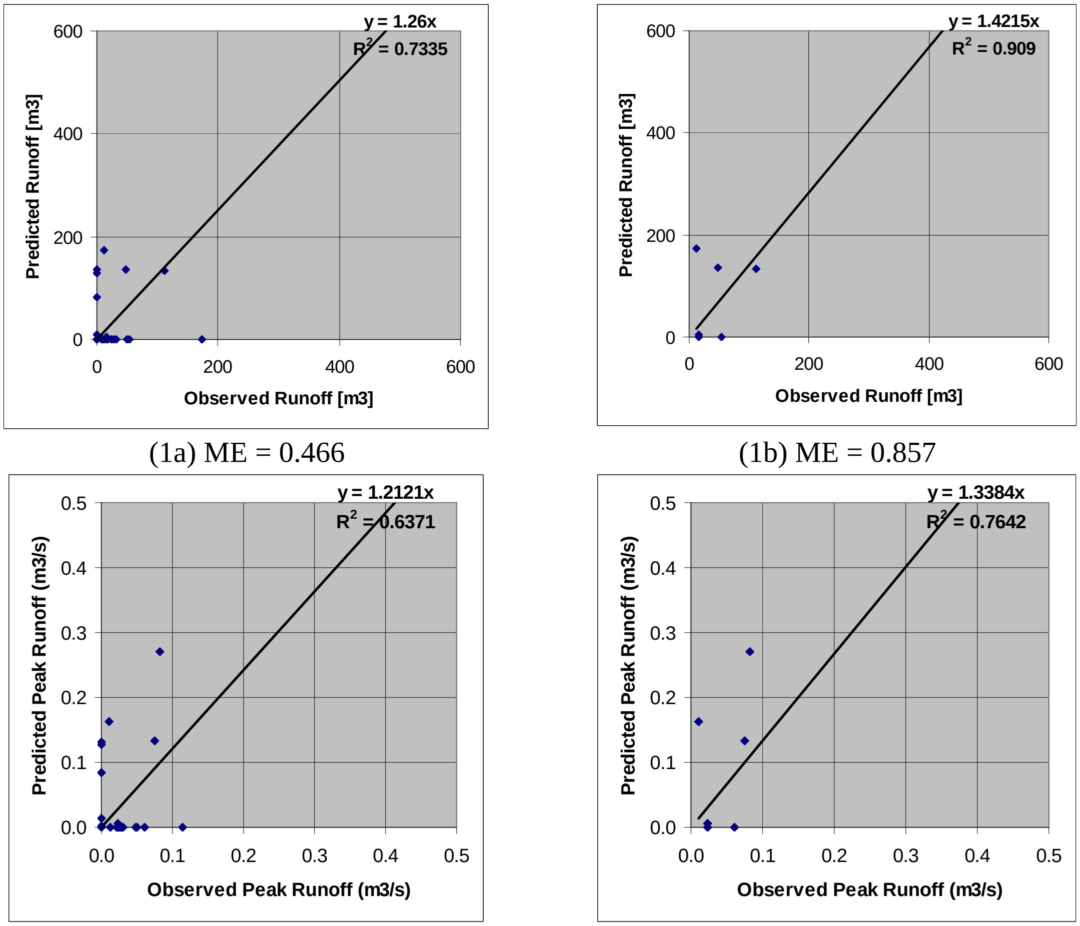


(2a) ME = 0.425



(2b) ME = 0.783

Figure 13 – GeoWEPP predicted values versus observed values during the '82/'84 storm series for the nested watershed. (a) All simulate storms were used in correlation. (b) Only simulated storm events that matched actual storms within series were used in correlation.



(1a) ME = 0.466 (1b) ME = 0.857

(2a) ME = 0.349 (2b) ME = 0.717

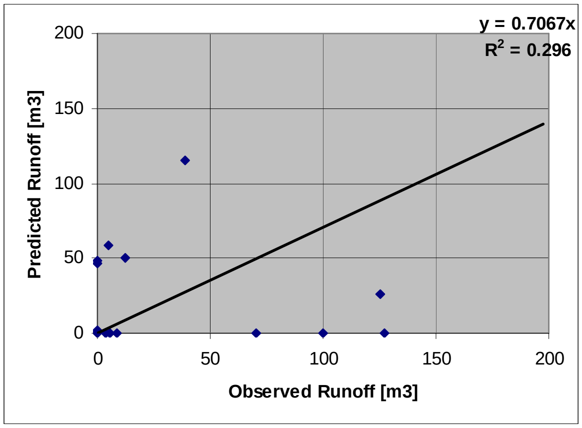
Figure 14 – VBFlow predicted values versus observed values during the '82/'84 storm series for the nested watershed. (a) All simulate storms were used in correlation. (b) Only simulated storm events that matched actual storms within series were used in correlation.

This high correlation breaks down when the small upper watershed is compared. The correlation between the observed hydrology values and the predicted hydrology values are very low. The observed hydrology data was obtained from the flume data located at the outlet point of the small watershed. This information contains gaps; storms that appear in the large watershed data do not appear in the small watershed data. These gaps may have an affect of the resulting model efficiency and R^2 values. More precise rainfall and runoff data is currently trying to be obtained. Figures 15 and 16 show the correlation between GeoWEPP's and VBFlow's hydrology predictions compared to the observed hydrology. There could be a number of reasons why this correlation is so low, while the correlation between the observed and predicted values for the nested watershed is so high. There could exist processes within the upper watershed that

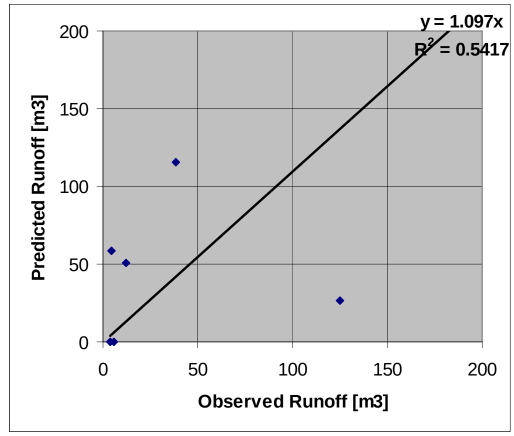
GeoWEPP and WEPP are unable to simulate, but are counteracted when the upper watershed flows into the lower watershed. The upside of this comparison is the GeoWEPP and VBFlow had similar R^2 numbers for the upper watershed. This means that they performed at the same level, so any errors that exist may be from the observed data records or how WEPP runs the simulation within the watershed.

Even though the R^2 values for the upper watershed are very low for both GeoWEPP and VBFlow, the Nash-Sutcliffe model efficiency values for matching storms are not so low; they are actually larger than the values determined for the large watershed. For the runoff, GeoWEPP has a value of 0.819 while VBFlow has a 0.823. The Nash-Sutcliffe model efficiency computations for the peak runoff show very large negative values for both GeoWEPP and VBFlow; GeoWEPP has an ME value of -33.51 when all of the observed peak runoff values and all the simulated peak runoff values are compared. In any case, the rainfall, runoff, and peak runoff data will need to be look into to confirm or expand on the results presented here.

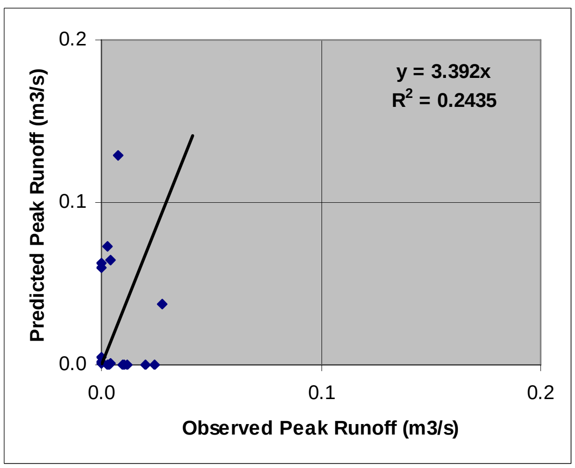
The final step in the short-term assessment validation processes is the geomorphology.



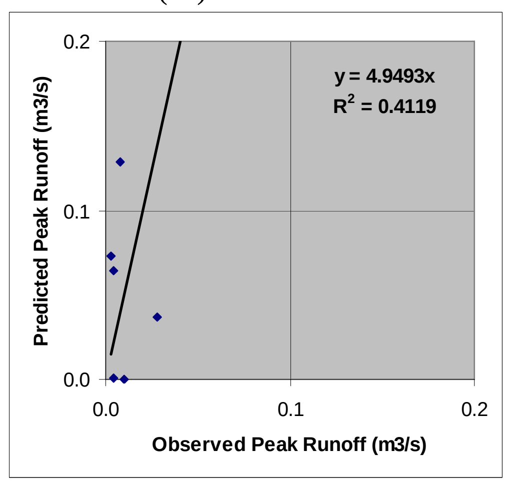
(1a) ME = 0.360



(1b) ME = 0.819

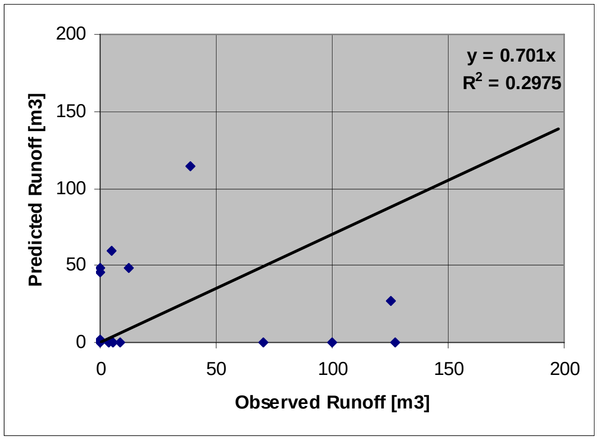


(2a) ME = -33.51†

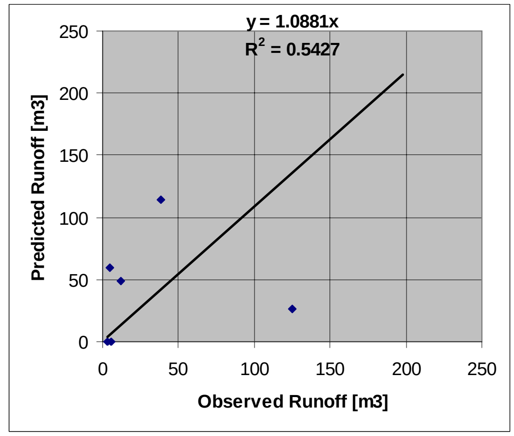


(2b) ME = -53.23†

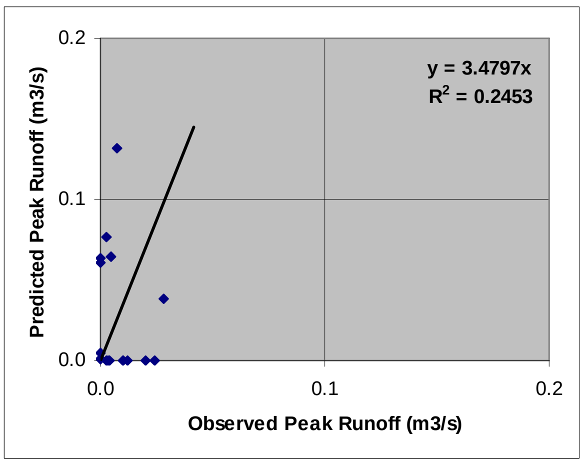
Figure 15 – Comparison between observed and GeoWEPP predicted hydrology for the upper watershed. (a) Comparison of all simulated storms with observed values. (b) Comparison using only simulated storms that match observed storms. †Data gaps may affect ME.



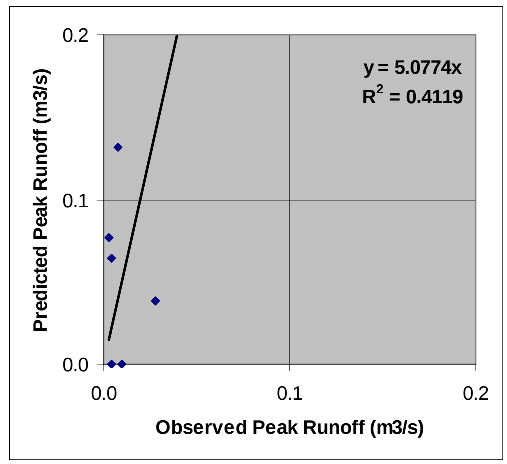
(1a) ME = 0.368



(1b) ME = 0.823



(2a) ME = -35.53†



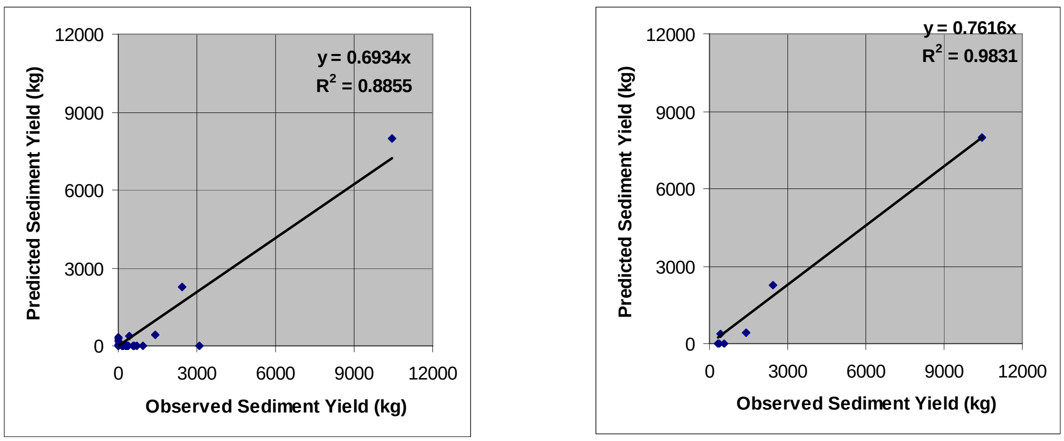
(2b) ME = -56.56†

Figure 16 - Comparison between observed and VBFlow predicted hydrology for the upper watershed. (a) Comparison of all simulated storms with observed values. (b) Comparison using only simulated storms that match observed storms. †Data gaps may affect ME.

4.2.2 Sediment Yield

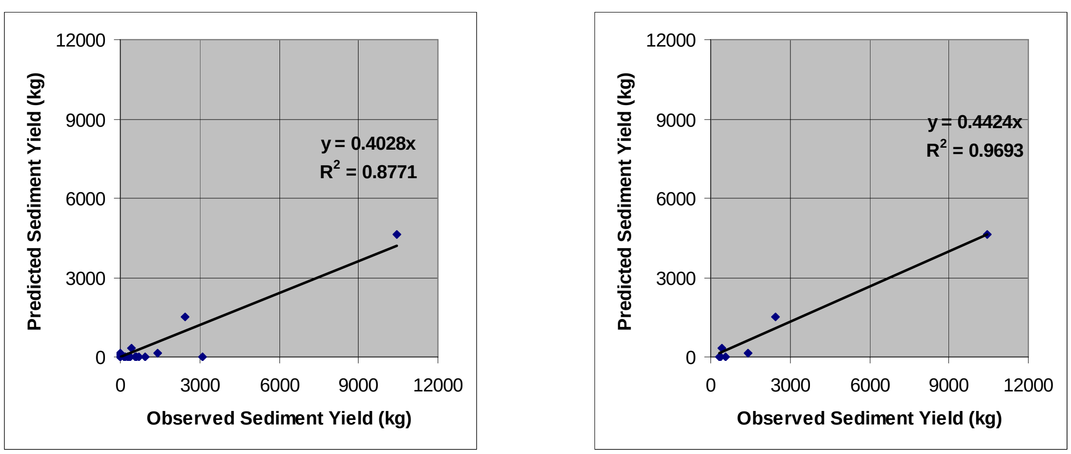
The final validation involves the sediment yield for the 1982 and 1984 storm seasons. The comparison between the sediment yields for the observed storms and for the matching simulated storm have a correlating R^2 value greater than 0.95 (see figures 17 and 18). The result is that both methods predict almost the same values that were observed within the study area for a one year simulation using the storm data. The difference between the two methods is due to the match up of the subcatchments within the nested watershed. But, the Nash-Sutcliff model efficiency shows that GeoWEPP (with a 0.971) models the sediment yield better than VBFlow (with a 0.856). In either case, both GeoWEPP and VBFlow are very good at modeling the sediment yield within the large watershed.

A comparison can not be made between the sediment yields for the upper watershed. The data required to continue with the upper watershed short-term assessment is held by the Walnut Gulch researchers located at Tombstone, Arizona. At this time, the researches are collecting field data for the current monsoon season and will provide the needed data once the season is over.



(3a) ME = 0.847 (3b) ME = 0.971

Figure 17 - Comparison between observed and GeoWEPP predicted sediment yield for the upper watershed. (a) Comparison of all simulated storms with observed values. (b) Comparison using only simulated storms that match observed storms.



(3a) ME = 0.614 (3b) ME = 0.856

Figure 18 - Comparison between observed and VBFlow predicted sediment yield for the upper watershed. (a) Comparison of all simulated storms with observed values. (b) Comparison using only simulated storms that match observed storms.

The comparison between the observed and simulated results for the large nested watershed has shown that both GeoWEPP and VBFlow can bee used with acceptable results. The topography, hydrology, and geomorphology have been validated for this particular study area. The next stage is to test short-term assessments on other study areas to finalize the validation process; this will insure that GeoWEPP and VBFlow can be applied to other watersheds and not just the Lucky Hills. The next step is to test if VBFlow can be used for the long-term assessment.

4.3 Long Term Assessment Validation

It has been established that VBFlow and GeoWEPP for very well for the large watershed for the short-term assessments. The next step is to test the models for long-term assessments. Both the large nested watershed and the small upper watershed will be tested, even though the short-term assessment for the upper water is not completed at this time. The same topography and input parameters used fro the short-term assessment will be used, except that the climate for these simulations will be generated using CLIGEN – a climate generating program. The input file for CLIGEN was created for the GeoWEPP/WEPP runs used in the Nearing, Jetten et al. research (Nearing, Jetten et al. 2005).

4.3.1 The Modeled Rainfall and Runoff

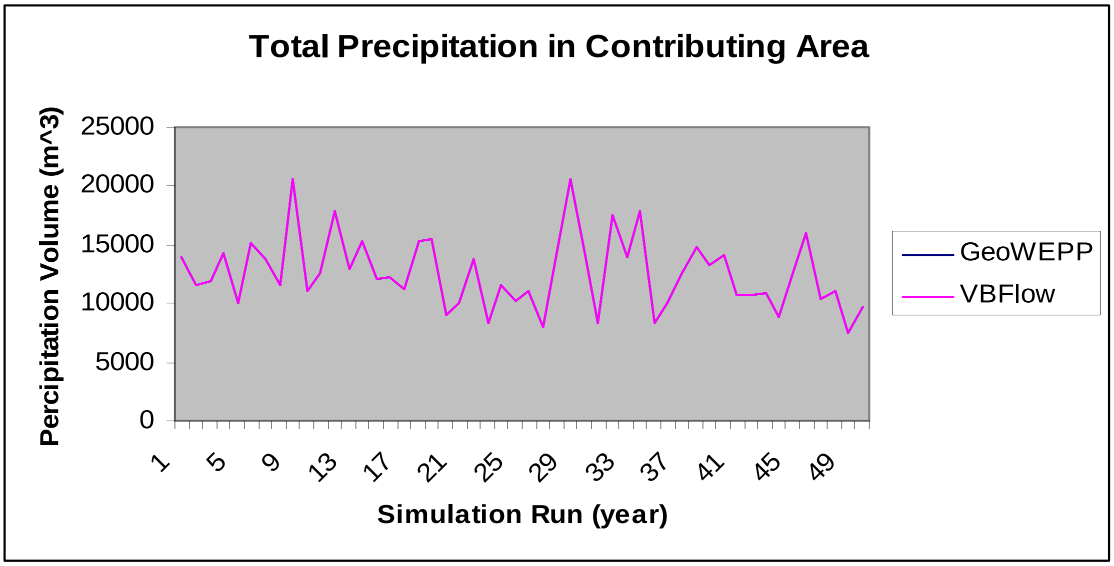
Hydrology is very important part of modeling; without a good hydrology, the fluvial processes may not be depicted correctly. The results of the runoff for the large and small watersheds for both versions are shown in tables 9 and 10. A comparison shows that the resulting runoff over 50 years and the average runoff for each storm are close to each other. Variations in these numbers are due to the statistical calculations within CLIGEN and the climate file. This comparison shows that the hydrology for the new VBFlow is about the same as the current GeoWEPP Hydrology. Figure 19 shows the fluctuations over time for both VBFlow and GeoWEPP for the large watershed. Figure 19a shows the total precipitation in the watershed over time; VBFlow and GeoWEPP overlap so that only one line is visible. Figure 19b shows the discharge from the outlet; there is a slight variation between GeoWEPP and VBFlow.

Table 9 – Hydrology for Small Watershed

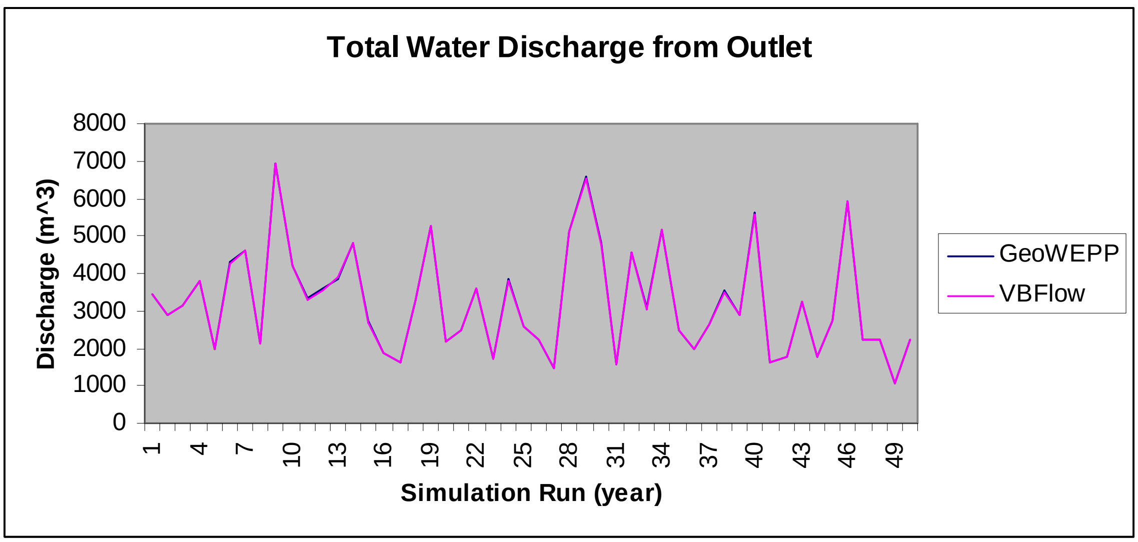
	GeoWEPP	**VBFlow**
Storms	836	880
Runoff (m^3)		
Total Volume	59,930.32	58,531.91
Average Volume per Storm	71.69	66.51
Min Volume	0.01	0.01
Max Volume	808.28	804.69
Std Dev	97.7	96.18

Table 10 - Hydrology for Large Watershed

	GeoWEPP	**VBFlow**
Storms	916	904
Runoff (m^3)		
Total Volume	162,781.3	162,089.7
Average Volume per Storm	177.7	179.3
Min Volume	0.01	0.01
Max Volume	2,199.32	2,195.79
Std Dev	260.2	261.1



(a)



(b)

Figure 19 – Total precipitation and total discharge for GeoWEPP and VBFlow in the large watershed. (a) The total precipitation is exactly the same for both GeoWEPP and VBFlow. (b) Only a slight variation in the discharge can be seen between GeoWEPP and VBFlow.

The next step would be to compare the observed measurements with the calculated measurements. The data available for the site gives only a small snap shot of the entire climate within the watershed. The rain gages present do not record the daily rainfall year round; these gages tend to be turned off for a few months to a few years. To get a better comparison between the observed and the generated, a more detailed and reliable source is needed. This is also true for the discharge. We will assume, since the hydrology in the short-term were very similar and were valid, that the hydrology for the 50-year simulation is also valid. Once the rainfall and discharge data can be obtain, this assumption can be confirmed. The small watershed hydrology has not been completely validated, but we will assume the hydrology is correct so that the sediment yield can be tested.

4.3.2 The Modeled Sediment Yield

Once the hydrology has been shown to be correct, the sediment yields need to be check. This is not as critical as the hydrology, since these parameters can be modified to fit the type of soil within the region. If the hydrology is wrong, especially if the network itself is off, the processes within the watershed will not be accurately depicted within WEPP. In the previous section, the hydrology for the VBFlow simulations are very similar to the hydrology used in the GeoWEPP simulations. The next step is to analyze the soil erosion results.

Unfortunately, the results are not what were expected. The erosion predicted using the VBFlow subcatchments was recorded in millions of tons of sediment. Why was so much sediment reported? There are two possibilities: the subcatchments are producing large amounts of eroded material or the channel processes are reporting an excess of sediment yield at the outlet point. Table 11 contains the results for the first year and fiftieth year of the simulation.

The table shows that even though the hydrology is nearly identical, there is a large difference between the sediment reported by GeoWEPP and the sediment reported by VBFlow. There is only a slight difference between the two in the first year of the simulation. Variations in results were to be expected since the hypothesis of VBFlow is that the watershed will be better represented. This new representation could increase or decrease the amount of soil loss because of the different aggregated slopes and slope lengths used.

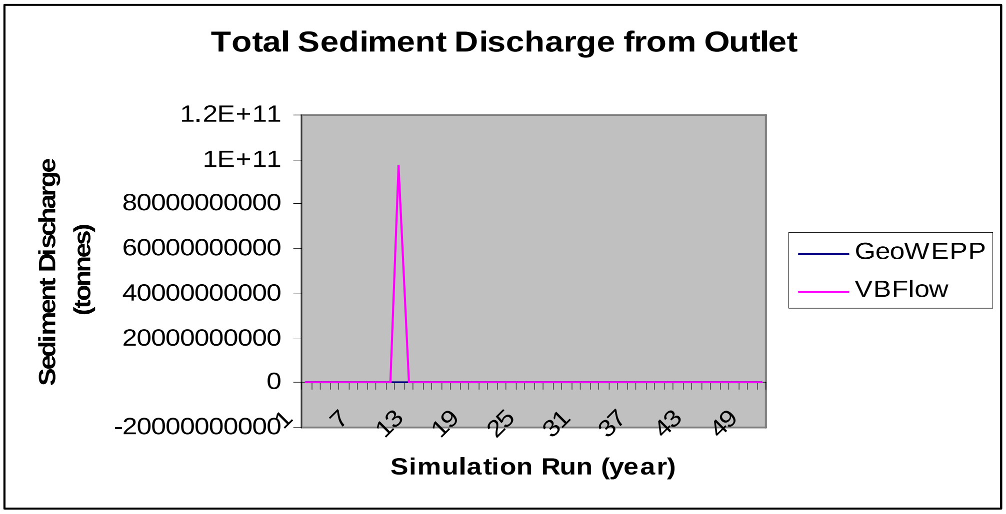
The output summary files for all the simulation years shows that the amount of soil loss for year 50 for the GeoWEPP version is about 5 tonnes per year from the hillslopes and the remainder coming from channel processes, resulting in 5.9 tonnes per year. The VBFlow summary files show that there is a total of 16.8 tonnes of soil loss per year from the hill slopes; this means that the remaining 158.4 million tones per year comes from the channel process; the error involves the channel routing functions between VBFlow and the Translator/WEPP.

Table 11 – Simulation Results for Year 1

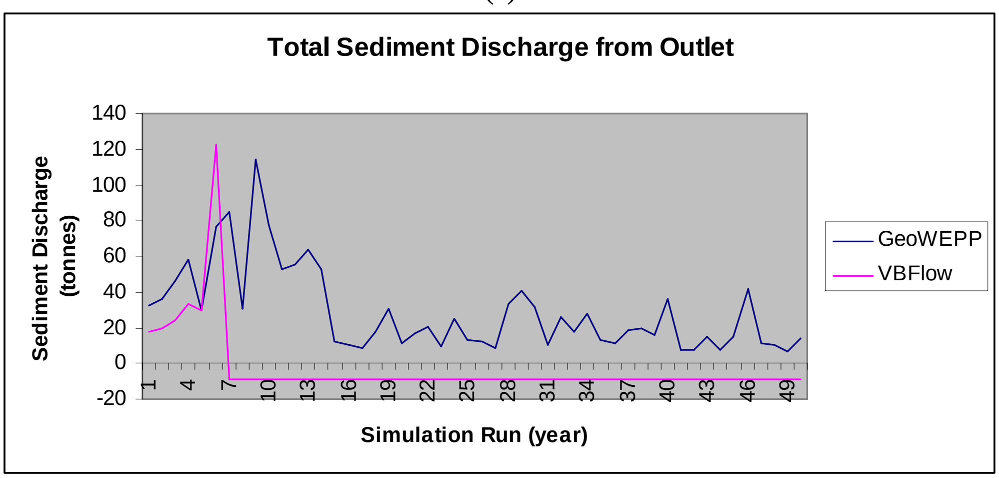
	Year 1 Simulation		Year 50Simulation	
	GeoWEPP	VBFlow	GeoWEPP	VBFlow
# of Storms	53	53	48	48
Rainfall produced (mm)	381.3	381.3	343.6	343.6
# events that produce runoff	16	16	16	18
Amount of runoff (mm)	94.67	92.51	89.11	87.03
Total contributing area to outlet (ha)	1.35	1.35	1.35	1.35
Total precipitation volume in contributing area (m^3)	5129	5129	4622	4622
Total water discharge from outlet (m^3)	1273	1244	1199	1171
Total sediment discharge from outlet (tonnes)	4.5	3.6	5.9	158,403,406.7
Sed. delivery per unit area of watershed (t/ha)	3.4	2.7	4.4	117,766,457.0

The sediment values for the VBFlow simulation runs may actually be under reported. The summary files report the amount of sediment being transported along the hillslopes and through each channel cells. After approximately 10 simulated years, some of these sediment values are reported as "**************", meaning the value exceeds the maximum measurable value within WEPP. Towards the end of the 50 year simulation, a large number of the subcatchments and channel cells report stars as their sediment yield. Since these values are not included in the final sediment yield average for the simulation, the resulting sediment yield is under estimated.

The amount of sediment reported by VBFlow was larger for the smaller watershed than the larger watershed. In the small watershed, 68 of the 880 storms had sediment yields that exceed this cap; but the larger watershed had 144 of its 904 storms report this value. A closer look at the event data for the upper watershed shows once the 10th year of the simulation began, the sediment yields at the outlet point began to increase to large amounts, jumping into the hundred thousand to millions of kg per storm. After the 22nd year of the simulation, the sediment yields became so high for some storms reported stars as the sediment result. The same situation occurs for the larger watershed, except the exaggeration begins at year 7, with star series results occurring in year 10. Figure 20 illustrates the sediment yield issue. Figure 20a shows that around year 13 of the simulations, the sediment yield recorded at the outlet point sharply increases to 80 billion tonnes; beyond this point, the values are reported as stars; this is represented in figure 20a as a zero value. Figure 20b shows the same simulation with the large sediment yield values changed to negatives. The variability of the GeoWEPP results can be seen in figure 20b as well. After year 7, the sediment yields are grossly over estimated.



(a)



(b)

Figure 20 – The GeoWEPP and VBFlow reported sediment discharge for the 50 year simulation. (a) VBFlow reports the sediment yield increase to nearly 80 billion tonnes by year 13; the remainder of the simulation has sediment yields that exceed the maximum value possible within WEPP. (b) The same simulation with all gross over estimations removed; the result is over 7 years of reportable sediment yields.

There are several possibilities why the extreme sediment yields occur. The first possibility was that WEPP could not handle the single channel cell approach. In the model, water and sediment must flow from one point to another point; for a single cell approach, there is only one point. A modified version of VBFlow was created to determine if the single cell method was the cause; the modified version used two to three channel cells as a single unit to create the subcatchments. These subcatchments were used in a new 50 year simulation, but the extreme sediment yield results were the same.

The remaining possibilities lie in the Translators code. The Translator was designed to handle a watershed with up to 2900 subcatchments and up to 1000 channels. Even with these limits, there may be some array or memory allocation issues that could result in an additive effect on the sediment yield as the simulation years pass. This additive effect could result in the exponential sediment yield growth observed in the summary files. A review of the Translator code may provide some insight. The Translator code may reveal any errors in the VBFlow code as well or the effects of formatting macros within the modified files that are not present in the original files; these macros, like carriage return, may be read in as values and cause calculation errors. A review of the code and discussion with the programmers of the Translator should shed some light on why this error occurs.

The hydrology and geomorphology for the short-term assessment has been shown to be acceptable; for the long-term, the hydrology is correct, but the geomorphology is not. A new approach needs to be used to determine if VBFlow could be used for long-term assessment. This new approached will run short term simulations over the course of 50 years, attempting to remove these extreme sediment yield values from the simulation. The results should be a series of simulations that predict similar sediment yield values to GeoWEPP's long-term simulation. Since it has been observed that the errors occur during the seventh simulation year for the nested watershed – year 10 for the small watershed – the simulations will be broken into 10 five year simulations. The next section discusses the procedures used and the results.

4.3.3 Second Long-term Simulation: Five Year Series

The 50 year simulation for VBFlow resulted in extreme sediment yields, therefore it is not known if VBFlow could produce similar values to those reported by GeoWEPP. Since the extreme sediment yields began after the seventh year of the simulation, a new set of simulations were done for the small upper watershed and the nested watershed; these simulations consisted of 10 five year runs. The goal is to determine how well VBFlow performed compared to GeoWEPP if the errors did not exist.

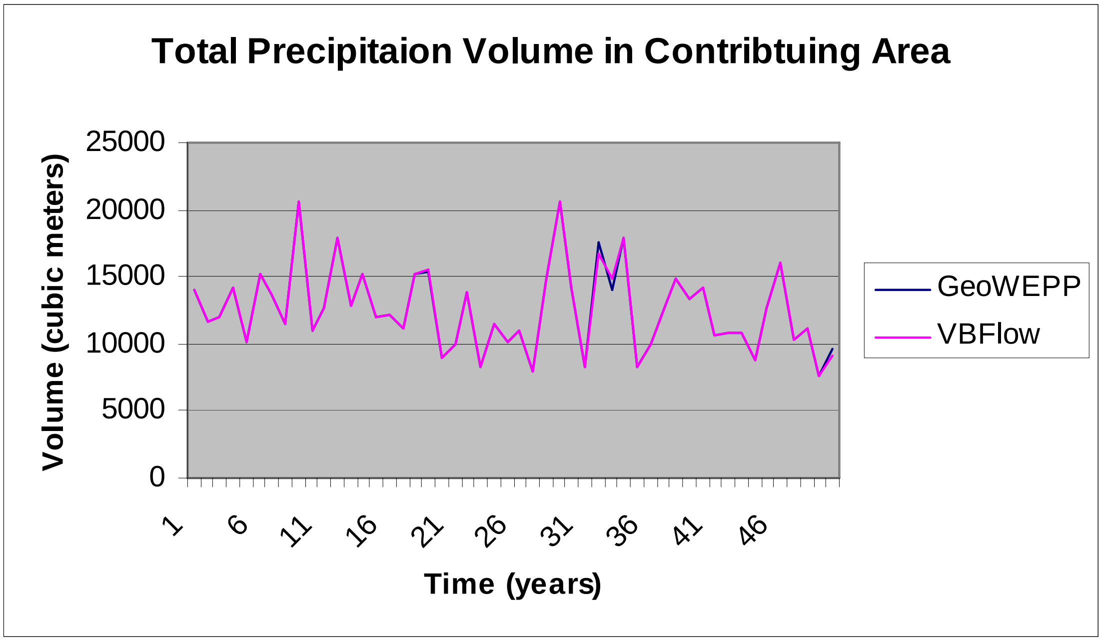
The GeoWEPP long-term simulation used 50 years of climate data; the simulation series needed to the same climate input data. Ten new climate files were created as input parameters for the simulation series. These files were based on the original climate file used by GeoWEPP; the 50 years used were divided into 10 5 year sections. Each of these sections was placed at the beginning of a new climate file. Thus, each new climate file represented a five year portion of the original 50 years of data used in the GeoWEPP long-term simulation; the ten files simulated years 1-5, 6-10, 11-15, 16-20, 21-25, 26-30, 31-35, 36-40, 41-45, and 46-50.

Each five year simulation used all the same input parameters as the GeoWEPP long-term simulation, except for the climate. Each climate was used once and only the watershed method was used to determine the results. The discussion of the results follows the same format as earlier; the hydrology for both watersheds will be addressed, followed by the geomorphology results of the nested watershed, and, finally, the geomorphology of the small upper watershed.

Hydrology

The first step is to insure that the hydrology of each watershed for these runs is correctly represented. Previously, the hydrology of the 50 year simulation was confirmed; since the same stream network is being used for this series simulation, the series rainfall and runoff volumes needed to be compared with the original GeoWEPP volumes. The VBFlow precipitation volumes for both watersheds are nearly the same as the precipitation volumes simulated by GeoWEPP;

only slight variations occur, as represented in figure 21a for the nested watershed and figure 22a for the small watershed. Previously, the total discharge in the nested watershed for VBFlow was nearly identical to that of GeoWEPP; this is not the case for the new set of runs. Figure 21b shows the total discharge for the nested watershed. The values reported by both GeoWEPP and VBFlow differ, but the patterns are alike. The small watershed also shows a similar pattern between the two programs (figure 22b). The rainfall volumes mirror those used in the 50 year simulation and the runoff (discharge) follows a similar pattern to the GeoWEPP 50 year simulation. Therefore, the hydrology for both watersheds can be assumed to be acceptable. Now that the hydrology is concerned to be correct, the simulated sediment yield for each watershed needs to be analyzed.



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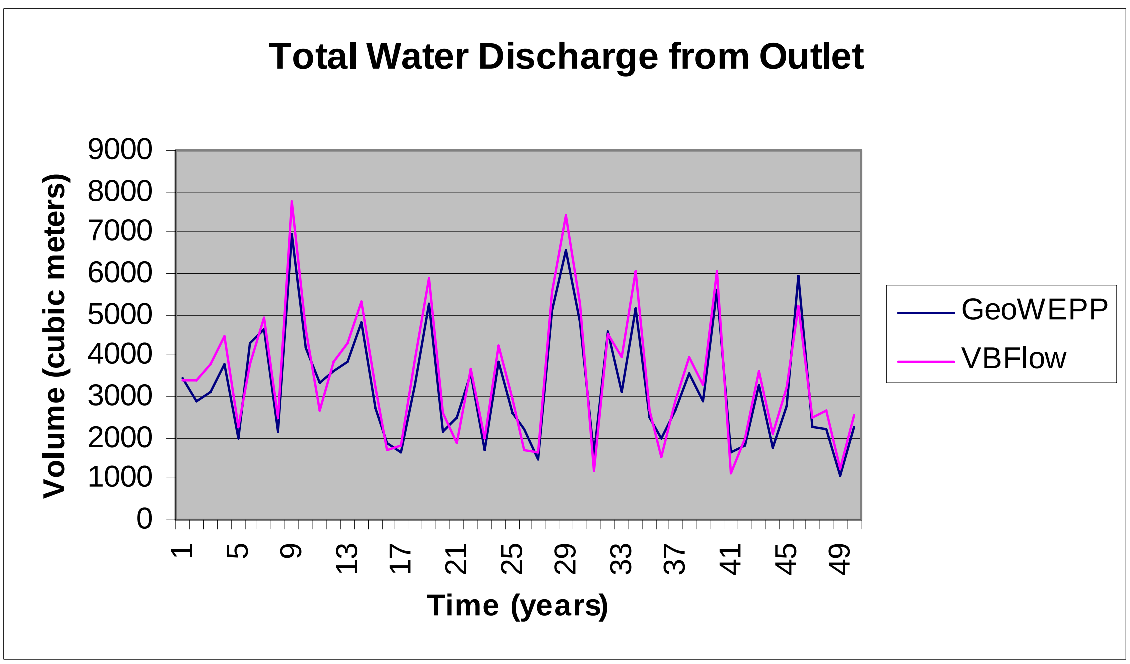
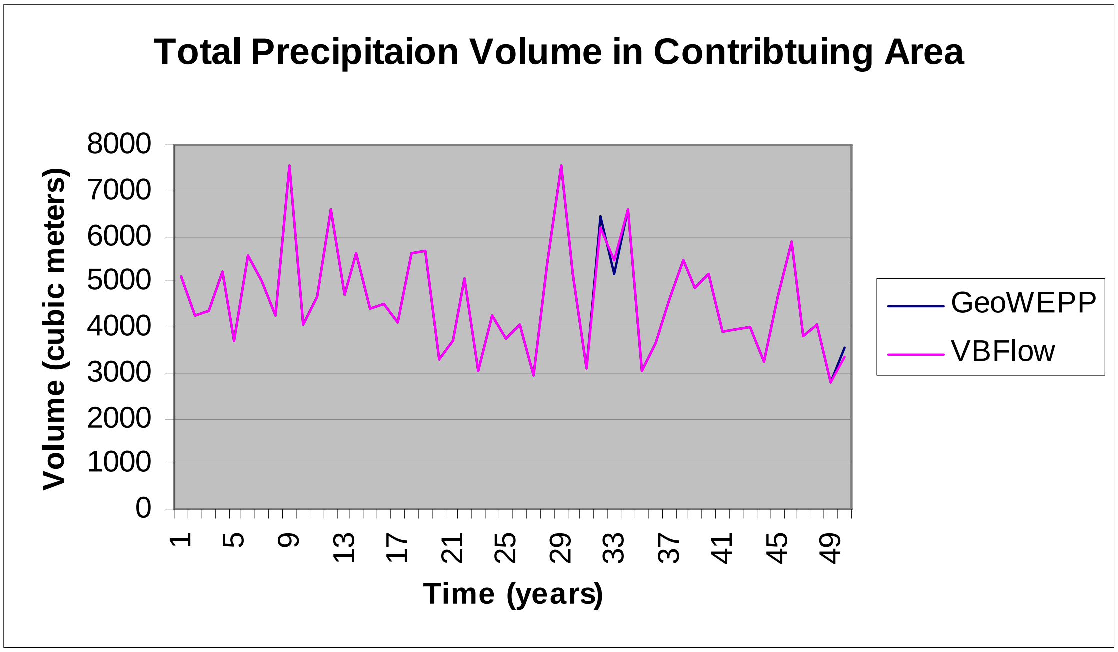
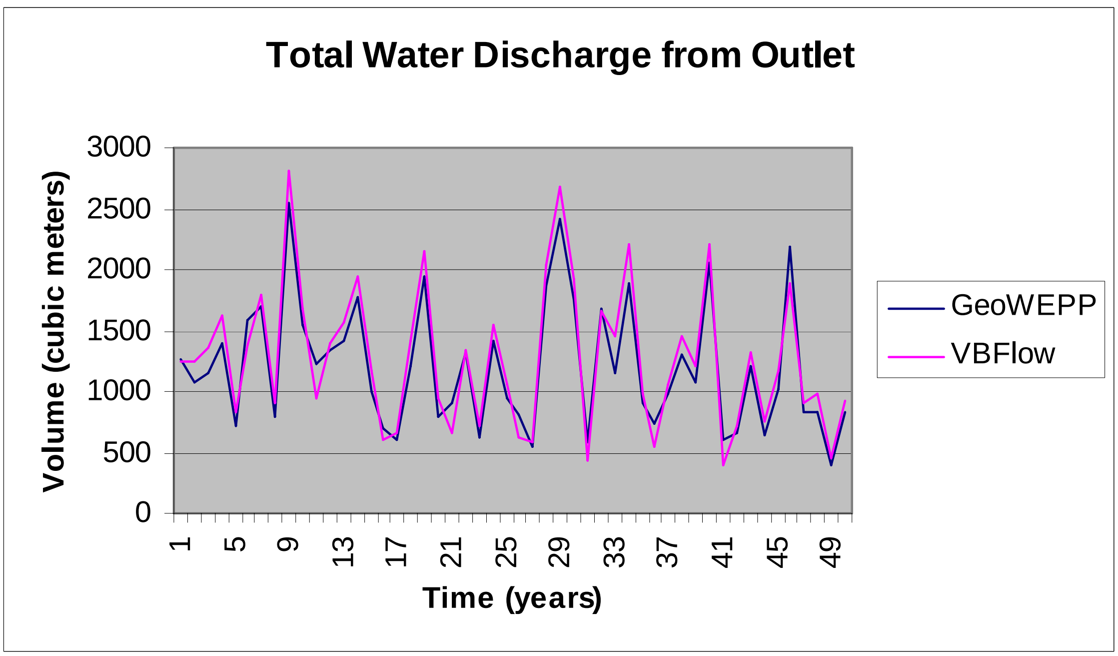


(b)

Figure 21 – Total precipitation and total discharge for GeoWEPP and VBFlow in the nested watershed for the 10 five year runs. (a) The total precipitation is nearly the same for both GeoWEPP and VBFlow. (b) The pattern for GeoWEPP and VBFlow are similar for the total discharge.



(a)



(b)

Figure 22 – Total precipitation and total discharge for GeoWEPP and VBFlow in the small watershed for the 10 five year runs. (a) The total precipitation is nearly the same for both GeoWEPP and VBFlow. (b) The pattern for GeoWEPP and VBFlow are similar for the total discharge.

Modeled Sediment Yield for the Nested Watershed

The topography parameters (DEM, soil, landuse, and VBFlow subcatchments) used in the previous VBFlow 50 year simulation for the nested watershed were used for the new set of simulations. Essentially, the only difference was the way the runs were executed – 10 five year runs instead of one 50 year run. The resulting sediment yield from the VBFlow simulations can be seen in Figure 23. As indicated in the figure, there are 3 years where large sediment yields values were reported; these outliers occurred during simulation year 10, 30, and 50. There are no extreme values or stars reported during this series of simulations. The GeoWEPP average modeled total sediment discharge for the nested watershed was 28.9 tonnes, while the average modeled sediment discharge per unit area was 7.82 t ha^{-1} y^{-1} for the 50 year simulation.. With the 3 outliers, the average modeled total sediment discharge and average modeled sediment discharge per unit for this VBFlow simulation series is 114.1 tonnes and 31.14 t ha^{-1} y^{-1}, respectively. This results in a four to one ratio between the two results.

A different picture develops when the outliers are removed from the series; figure 24 shows the sediment yield information after the outliers have been removed. Now the sediment yield range reported by VBFlow is within the range reported by GeoWEPP, 30 to 115 tonnes. The average total sediment discharge for VBFlow without the outliers drops to 40.6 tonnes; the sediment discharge per unit area drops 11.1 t ha^{-1} y^{-1}. The ratio between VBFlow and GeoWEPP now drops to 1.4 to 1.

VBFlow does report a considerably higher sediment yield that GeoWEPP for the period between year 25 and year 40. During this period, VBFlow estimated a higher runoff discharge than GeoWEPP; this resulted in higher sediment yields. This difference could be due to the new subcatchments created by VBFlow; the new subcatchment creation program is meant to create a better approximation of the real world. The new subcatchments may provide a better drainage system that results in more runoff and a larger modeled sediment yield. This will be confirmed once the observed sediment yield amounts can be obtained and analyzed.

The outliers and the higher estimations for the sediment yields by VBFlow may also be the result of the same error that exists during the 50 year simulation. There is a pattern within the series simulations; the sediment yield, for the most part, increases from the first year to the fifth year of each simulation. When the next five year simulation runs, the sediment yield begins at a lower level and increases. It was observed in the 50 year simulation that the existing error begins after year 7, but it appears that a five year simulation ends with the start of a high estimation. This may be the reason why the sediment yield outliers occur at year 10, 30, and 50 – the years at the end of the 5 year run; these outliers are also 20 years apart – end of 4 five year simulations.

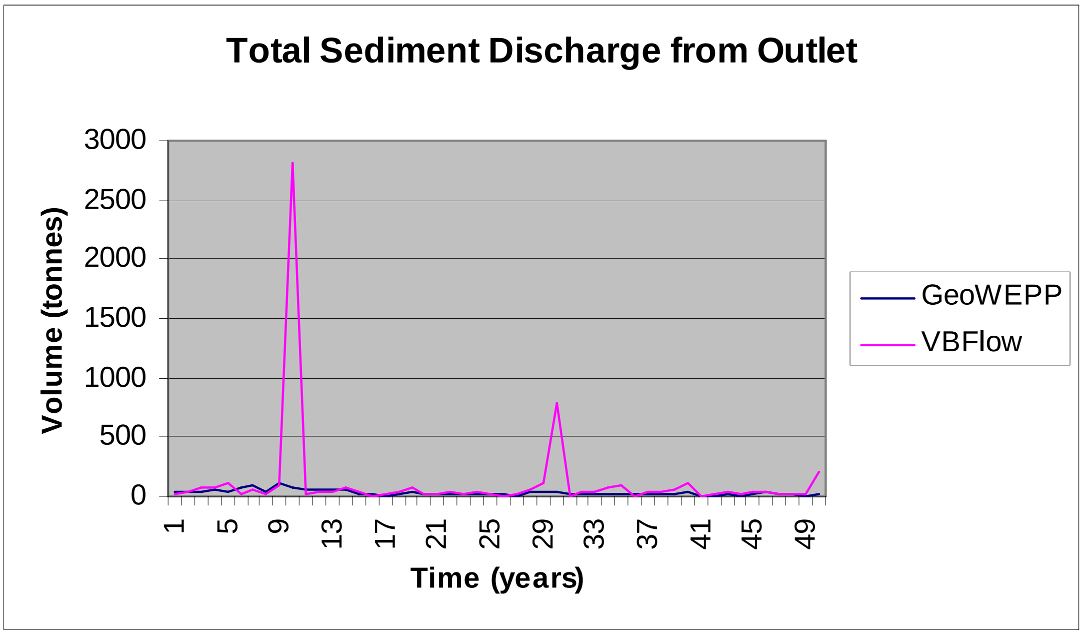


Figure 23 –Total sediment yield and sediment delivery for the large watershed during the 10 five year simulations. There are three spikes that overestimate the total sediment yield at the outlet. These spikes occur at year 10, 30, and 50.

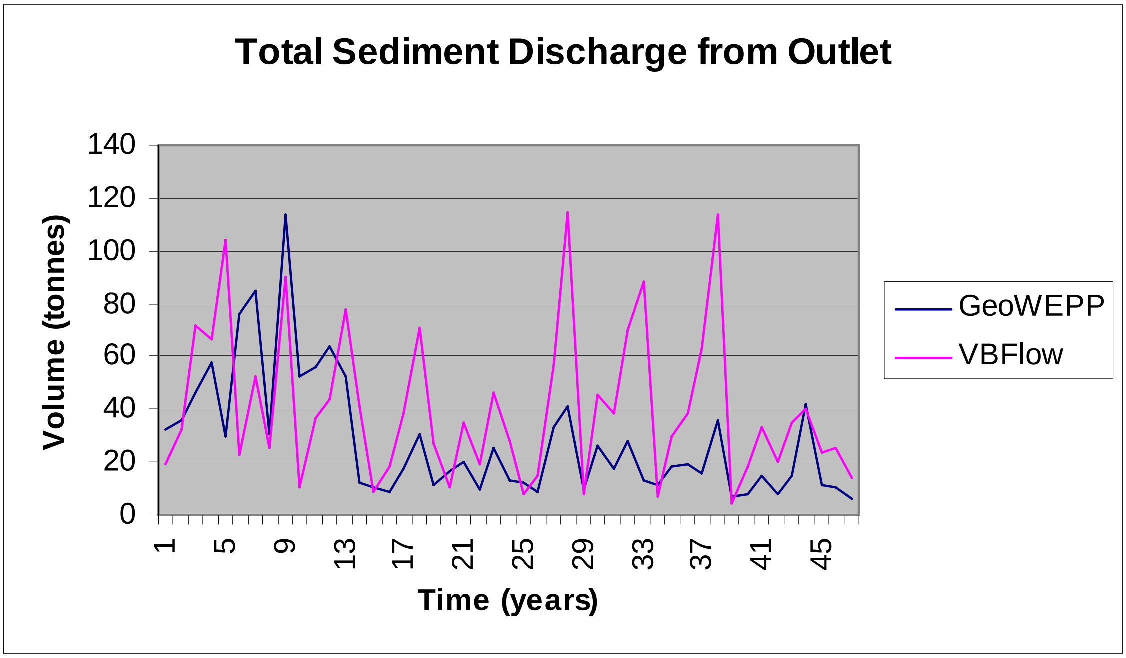


Figure 24 –Total sediment yield and sediment delivery for the large watershed after the outliers are removed. Without the outliers, there are only a few higher estimates exist. Most of these occur during the 25th and 40th years of the simulation.

Modeled Sediment Yield for the Small, Upper Watershed

The same process used for the nested watershed was applied to the small watershed; the results are presented in figure 25. For most of the simulated years, VBFlow reports a higher sediment yield than GeoWEPP, but the difference between these modeled values is only a few tonnes. This difference ranges from a reported value 6.1 tonnes higher than GeoWEPP to 6.4 tonnes lower than GeoWEPP. The average difference is only 1.5 tonnes higher than the modeled sediment yield for GeoWEPP. These differences may show that VBFlow has created a better representation of the watershed in the model; a comparison with the observed sediment yields may confirm that the VBFlow subcatchments are a better representation of reality than the current TOPAZ created subcatchments created in GeoWEPP. Further analysis is needed once the observed sediment yields are obtained. The result is that the average total sediment discharge for VBFlow is 7.5 tonnes, which is slightly higher than the 6.0 tonnes modeled by GeoWEPP. The average sediment discharge per unit is for VBFlow is 5.58 t ha^{-1} y^{-1}, only slightly higher than the

GeoWEPP average of 4.46 t ha^{-1} y^{-1}. This results in a 1.25 to 1 ratio; this is better than the nested watershed without the outliers.

What is also important about the small watershed simulation series is that 1) there are no outliers or extreme values within the results and 2) there does not seem to be a pattern in the sediment yields as seen in the large watershed. During the 50 year simulation performed earlier, errors did not begin in the small watershed simulation until year 10; by ending the current runs after 5 years, the errors experienced in the previous 50 year simulations do not have a chance to impact the calculations. This information, along with the pattern seen in the large watershed, will narrow down the beginning of the errors and may shed some light onto why this error exists.

The series simulations has shown that once the error that causes the extreme values has been corrected, VBFlow will be able to produce similar modeled results to that of GeoWEPP. Comparison between observed sediment yields and modeled sediments yields will be able to demonstrate which version produces more accurate results. The assumption is that VBFlow will provide a better model of the watershed than TOPAZ.

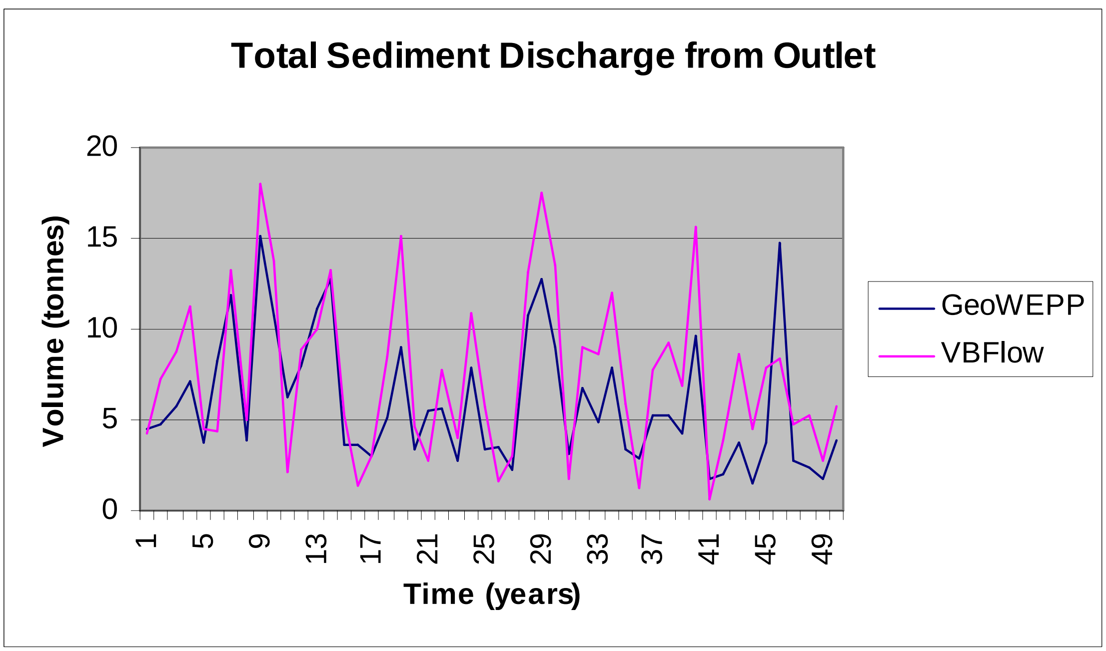


Figure 25 –Total sediment yield and sediment delivery for the small watershed during the 10 five year runs. Difference between the VBFlow estimates and the GeoWEPP estimates are only a few tonnes. This difference can be explained by the different subcatchments used in the runs. Unlike the large watershed, no overt patterns exist in the VBFlow sediment yield estimates.

4.3.4 Comparing the Simulation Measurements and Observed Measurements

The long-term and short-term assessments presented earlier focuses on the sediment yield, the amount of soil that is removed from the watershed through the outlet point. The focus of these assessments was how well the difference in subcatchment creation methods represented the observed sediment yields. This approach represented the "offsite" assessment; the measurement of how much erosion is occurring within the entire watershed. GeoWEPP also provides an "onsite" assessment; the measurement of the amount of soil loss or gain at the raster cell level. This section discusses the comparison between the onsite result produced by GeoWEPP and VBFlow with the observed sample site data collected by Richie et al. (2005). The goal of this comparison is to validate the simulated long-term onsite assessment.

The onsite assessment, or flowpath method as it is called in GeoWEPP, disaggregates the entire watershed into its individual flow paths. These flow paths are then sent to WEPP as individual representative profiles to be processed; these profiles follow the same format discussed earlier. Each profile contains the dominant soil and dominant landuse found along the flowpath. The only difference is the profile slope and profile length are the flowpath's slope and length; this is the only point where the nuisances of the topography can be integrated into a profile. Once all the flowpaths have been processed, the flow paths are aggregated. The result is a raster map that displayed the amount of soil loss (or gain) for every raster cell within the entire watershed. While the watershed method discusses earlier displays the amount of sediment each hillslope contributes to the sediment yield, the flowpath method can display the amount of erosion occurring with the subcatchment; this can reveal areas within the watershed that are highly susceptible to erosion.

Before the analysis can begin, there are two importance pieces of information that need to be addressed. First, the flowpath method does not use the subcatchment layout to determine the amount of erosion within the watershed; the flowpath method divides the watershed into individual flowpaths based on the direction of flow within each raster cell. Since subcatchments do not play a role in this assessment, the flowpath method results for GeoWEPP and VBFlow are the same. The second piece of information is that not all the data points collected by Richie et al. (2005) were used in this analysis. Sample site numbers 0, 1, 23, 24, and 25 where not used because they were located outside the derived watershed. The amount of soil loss or gain recorded at each sample site can be found in the appendix.

Since the sample site data records the amount soil movement over the course of approximately 50 years, the results from the long-term assessments will be used in the comparison. The flowpath method uses the same parameters used for the long-term assessments discussed above. Since this assessment concentrates on the erosion occurring at the raster cell level, extreme channel sediment yields do not occur during this method. As discussed earlier, the topography and the hydrology have already been validated; only the geomorphology needs to be confirmed. A comparison of the observed versus the simulated measurements results in an R^2 value close to zero (R^2 = 0.0147) and a model efficiency value under zero (ME = - 0.873). In other words, there is little correlation between the observed values and the simulated measurements.

There are several factors that contribute to this lack in correlation or poor model efficiency. The first involves the digital topography of the study site and how the drainage patterns are derived from this topography. The topography is based on a 1 meter Digital Elevation Model; from this DEM, TOPAZ determines the drainage pattern for the entire watershed. Any errors or anomalies occur within the DEM will effect the drainage pattern. The smooth of the DEM, i.e. the filling in of pits, will also affect the simulated drainage pattern. Finally, only converging flows are possible within the TOPAZ determined drainage pattern. All these factors affect the drainage network within the simulate watershed. The real watershed contains pits and sinks, has converging flows, and may have variables that affect the flow of water that can not be measured at the 1 meter scale level. Essentially, the drainage pattern created within the simulated watershed may not accurately represent the true drainage network at such a small scale. But, on a larger scale, the channel networks may be better represented.

Another factor involves the landuse and soil parameters used within the simulations. When the sample site data was collected, the environmental conditions around each sample site were also recorded. Descriptions like “Edge of Shrub mound” and “Near Shrub – large rocks” and “Under shrub” where used to describe the location of the sample site. The plant and soil parameters used within GeoWEPP and VBFlow do not provide for a detail disbursement of rocks and shrubs; the shrubs and rocks are not spatially distributed through the simulated watershed. This contributes to the differences since a sample site found under a shrub may not be under a shrub in the simulation and the resolution of the topography may hide the shrub mounds described in the sample data set. All of this contributes to the differences found in the observed measures and the simulated measures.

Unlike the issue with the DEM and the drainage network, the soil and vegetation parameters can be modified to account for some of the differences. The landuse layer can be improved by providing a spatially distributed shrub layer; the layer would consist of raster cells that either contained a shrub or not. A similar process could be used on the soil layer to properly display the concentration of rocks within each cell; both of there processes would be time consuming. A less time consuming method would be to modify the initial input parameters so that the results are more correlated with the data samples. Once this is done, more samples would need to be obtained to ensure that the new modifications are reporting the correct erosion amounts.

One final factor involves the comparison between point data and raster cell data. In the scenario, the soil loss/gain simulated in each raster cell is compared with the observed data recorded at a point. When the values from the simulate are obtained, some of the sample points are located near two different values; the sample point is located within one cell that contains one value, but within a half cell (about 0.5m) or less distance from the point there is a different value.

In most cases, these different values are closer to the sample site value than the value determined by the computer simulation for the sample site location. One reason why these differences exist is that the sample site locations were recorded in UTMS, with the Northing coordinate recorded to one thousandth of a meter while the Easting coordinate was only recode to a tenth of a meter. For the study site raster, the cell size is only one meter, so the sample site measurements beyond the meter mark can shift the location by ±1m.

There may be many other factors that contribute the discrepancy between the observed values and the simulated values, but it all comes down to a matter of scale. Is it necessary to reduce the resolution of the DEM to the same level as the sample site to obtain accurate soil loss data, or is it better to have a close approximation? For the purposes of GeoWEPP and the benefit it provides to it users, it is better for GeoWEPP and VBFlow to provide more accurate watershed and subcatchment sediment yields than it is to ensure that every square centimeter of the watershed is model correctly. Therefore, attempts at altering the input parameters need to be made but the accuracy of the watershed method should not be sacrificed.

4.4 Reality within a Model

The research present in this work is an attempt to improve on how GeoWEPP and WEPP represent reality. It has been discussed earlier that GeoWEPP loose some of the variability within the watershed when the data is passed through the Translator into WEPP. This section provide some insight into what this means by comparing the subcatchments and resulting sediment yield and soil loss/gain for certain areas within the Lucky Hills watershed with images taken within the watershed. Figure 27 displays the difference between the subcatchments created by GeoWEPP and those created by VBFlow when they are compared to actual landscape of Lucky Hills. The center pictures were taken in the Lucky Hills nested watershed in March 2005. To the left of the images are the same locations within the GeoWEPP created watershed. To the right are the same locations within the VBFlow created watershed. The black arrows within the simulated watersheds are a close representation of the white arrows within the image; all arrows represent the downstream flow of water within a channel (rill or gully).

The comparisons shown in figure 27 demonstrate that VBFlow provides a more rough view of the Lucky Hills watershed than the one provided by GeoWEPP. Why is this important? As stated earlier, when GeoWEPP passes the data to WEPP, a representative profile is created. One of the bits of data sent is hill slope and hillslope length. These two pieces of data are based on all possible flowpaths within a hillslope; a best fit slope and length is created to represent the subcatchment. This representative profile loses some of its reality in the process. To limit this loss, VBFlow creates smaller subcatchments. These smaller subcatchments means less flowpaths, which, in turn, provides a better fit for the slope and length. These smaller subcatchments also contribute to the difference in the sediment yields reported by GeoWEPP and VBFlow.

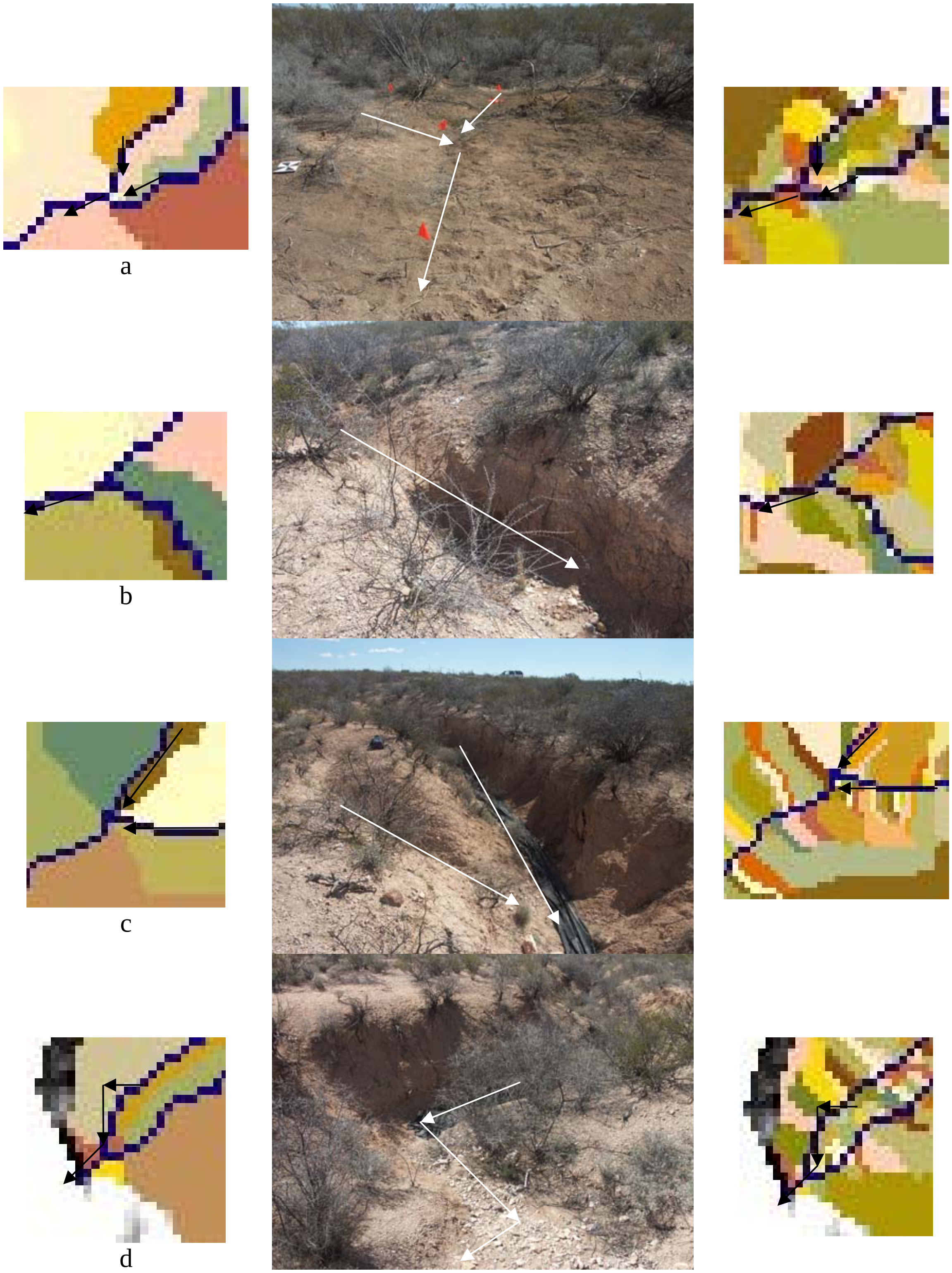


Figure 26 – Comparing TOPAZ and VBFlow subcatchments with Lucky Hills images. The subcatchments created by GeoWEPP (left) do not display the variability of the topography. VBFlow (right) incorporates more variability in the landscape then GeoWEPP. White arrows denote flow direction; all pictures are taken from the downstream point of view. Flow for subcatchments are from right to left.

Figures 28 to 31 show the predicted erosion from the flowpath method (onsite), and the predicted sediment yields for GeoWEPP and VBFlow methods for the same Lucky Hills pictures; figure 28 shows the legend for soil loss and sediment yield values. The sediment yield results for VBFlow (c) show a similar pattern to the erosion pattern found within the onsite results (a). In some instances, the sediment yield reported by GeoWEPP is close to zero in the selected images, while the onsite and VBFlow methods report more erosion and sediment yield. This variability is due to the way the subcatchments are created. The offsite method uses a represented profile for the entire hillslope, resulting in a loss of variability within the hillslope. The onsite uses each flowpath within a hillslope, thus using the variability in the topography to calculate the erosion. This information is then aggregated to produce the onsite erosion values. VBFlow divides the hillslopes into smaller subcatchments, thus incorporating some of the variability near the channel. Overall, the results from the VBFlow simulations approach those of the onsite method; this means that the subcatchments created by VBFlow are able to pass on more of the variability within the watershed than GeoWEPP can.

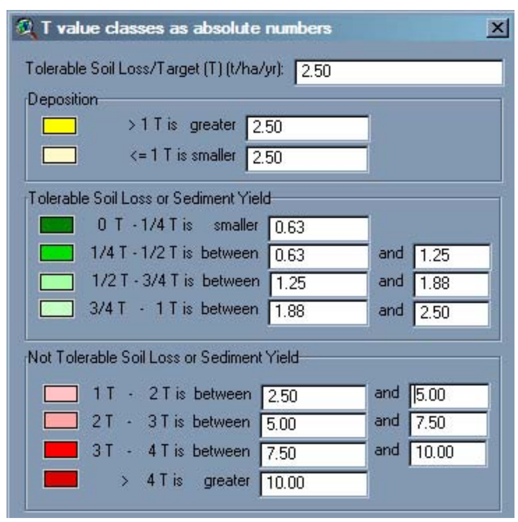


Figure 27 – Sediment yield and soil loss legend for the images presented in figures 28 – 31. The legend is based on a tolerable soil loss value of 2.50 t ha^{-1} y^{-1}.

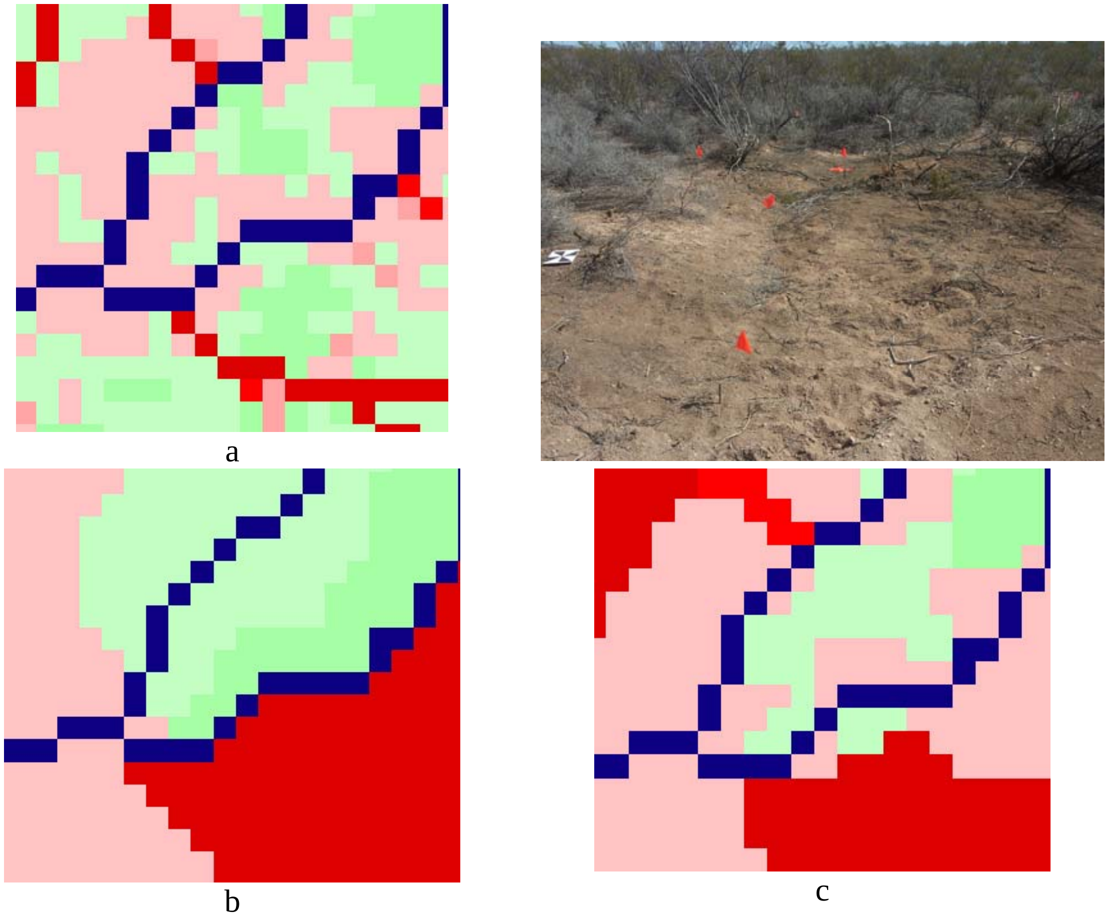


Figure 28 – Image 1 assessment results. The onsite (a), offsite (b), and VBFlow(c) assessments for region depicted in image 1 from Figure 27.

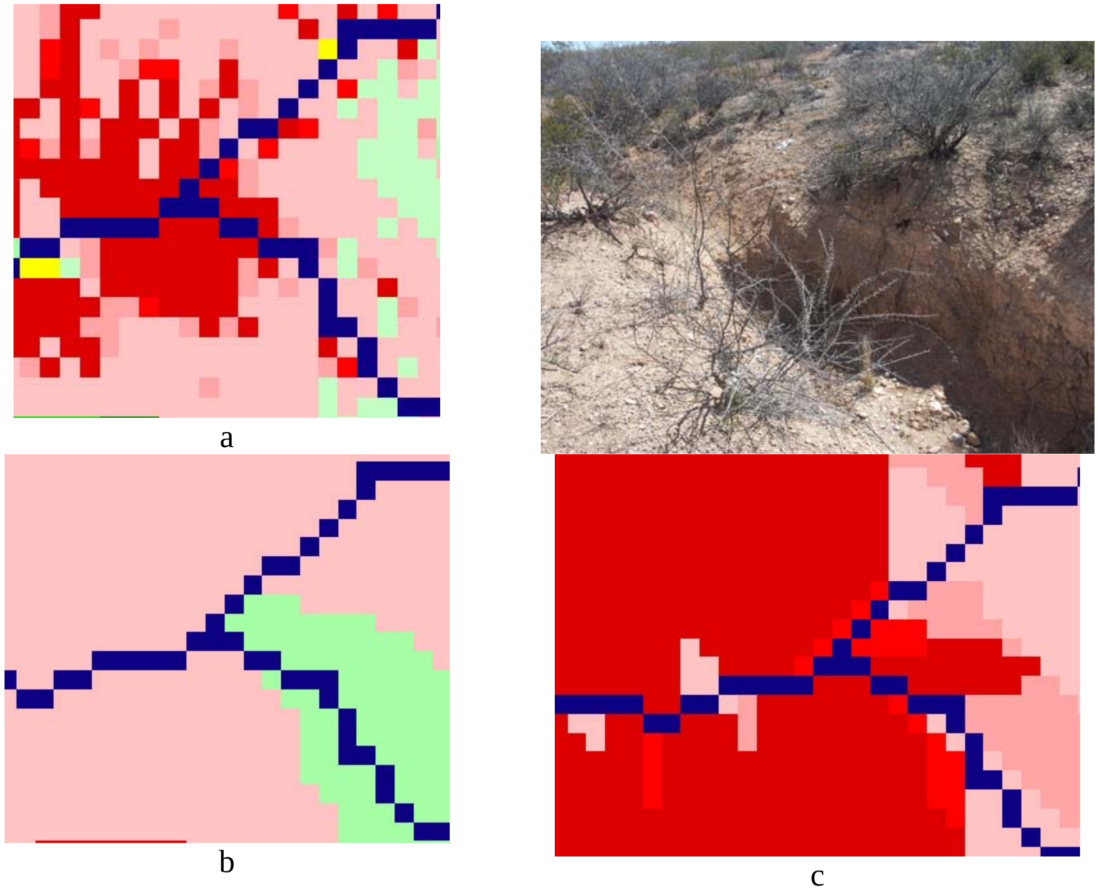


Figure 29 – Image 2 assessment results. The onsite (a), offsite (b), and VBFlow(c) assessments for region depicted in image 2 from Figure 27.

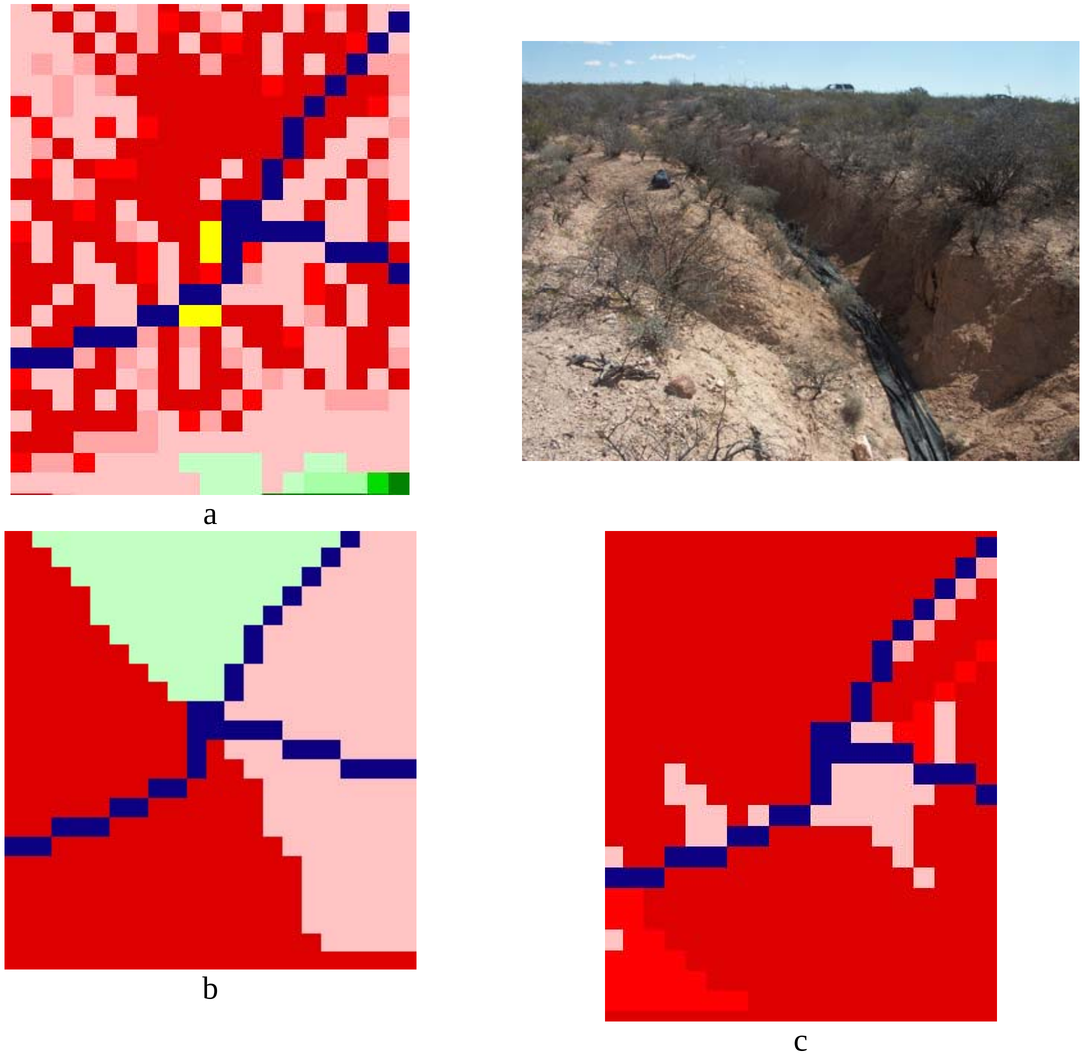


Figure 30 – Image 3 assessment results. The onsite (a), offsite (b), and VBFlow(c) assessments for region depicted in image 3 from Figure 27.

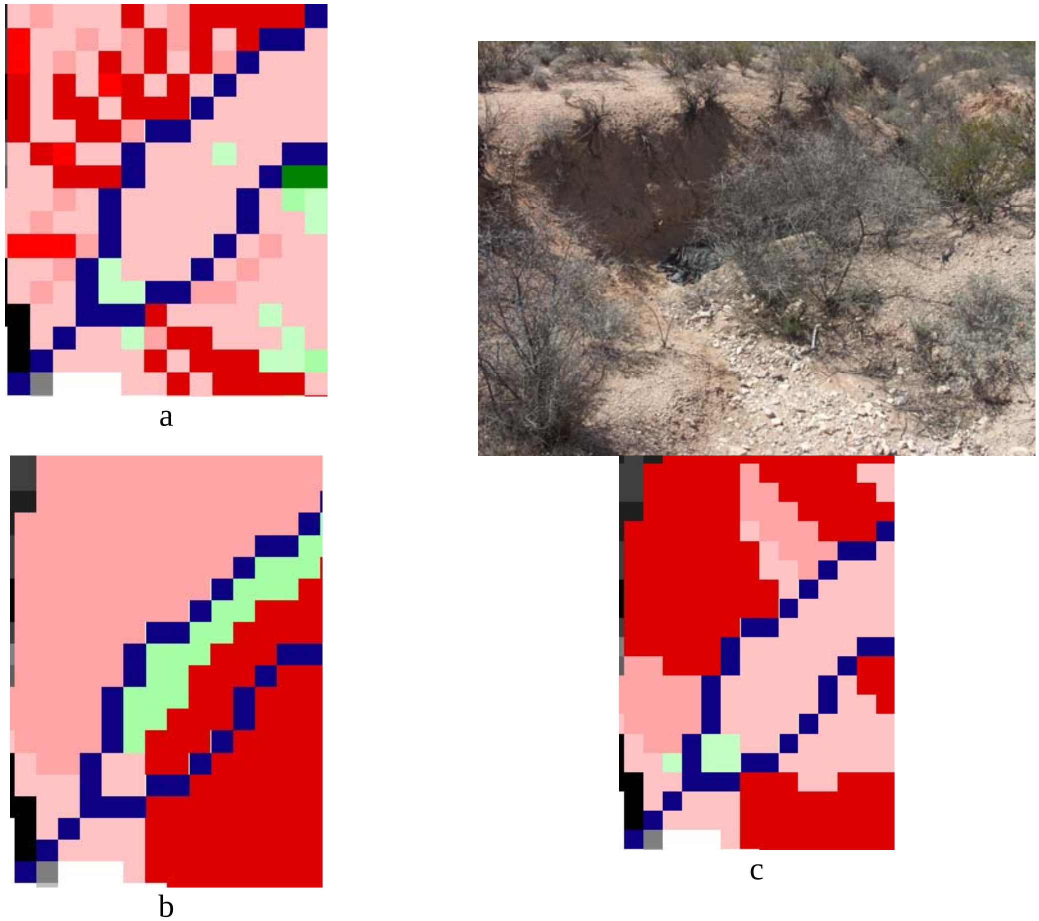


Figure 31 – Image 4 assessment results. The onsite (a), offsite (b), and VBFlow(c) assessments for region depicted in image 4 from Figure 27.

5 Conclusion

The main focus of this research is to improve upon an already existing erosion model. GeoWEPP is the geospatial interface to the WEPP erosion model. GeoWEPP uses commonly available data to construct the input parameters for WEPP. The drawback with this method is that the variation in the soil and landuse and the nuisances of the landscape are lost when GeoWEPP transfer the data to WEPP. GeoWEPP and the Translator convert the spatially distributed soil and landuse data into a representative profile of each subcatchment within the watershed. This profile uses the dominant soil and dominant landuse found in the subcatchment as WEPP input parameters. The profile as includes a slope and hill length that best represents the entire subcatchment. In both cases, the diversity of the landscape is lost.

VBFlow was constructed in attempt to reduce the amount of diversity lost in this process. VBFlow creates smaller subcatchments within the watershed. These new subcatchments are smaller than the ones created by the original version of GeoWEPP, which uses TOPAZ to create the subcatchments. By using smaller subcatchments, more of the diversity of the watershed may be represented within WEPP. To confirm this, simulations were performed using both GeoWEPP and VBFlow and the results where compared to observed values.

Since the way the subcatchments are created is the major cause of the reduction in diversity within the watershed, it is best to only vary the subcatchment parameters to test the results of VBFlow. To this end, a study site was selected that had a uniform landuse, uniform soil composition, and had recorded observed values. The Lucky Hill nested watershed outside of Tombstone, Arizona, was selected as the best candidate for this validation. In all simulation runs, the same topography, landuse, and soil parameters were used. The only variations were the number of years of climate used, which varied between scenarios, and the subcatchment creation method. Two watersheds where used; the upper, smaller Lucky Hills watershed and the larger nested watershed – which contains the smaller watershed.

Three separate scenarios were created to test VBFlow. The first was a comparison between short-term assessments. In the short-term assessment, two storm series where used: the 1982 and 1984 storm seasons. The purpose of this assessment was to determine how well both subcatchment creation methods perform when compared to observed results. The results are promising. The larger watershed performed well when compared with the observed results for both subcatchment creation methods. The hydrology and geomorphology for the upper watershed showed that both creation methods performed very well compared to the observed values; GeoWEPP performed slightly better that VBFlow. For the smaller watershed, it appears that VBFlow performs slightly better in regards to the runoff compared to the observed values, but the remaining variables – peak runoff and sediment yield – can not be compared at this time due to a lack in observed values. Once these data gaps are filled, a complete analysis of the performance of both methods within the smaller watershed can be completed.

The second scenario involves a more long-term assessment. In this case, a 50 year simulation was run using a climate file based on 100 years of climate data. The same two watersheds were used in this scenario as was used in the short-term scenario; the only parameter that differs from the short-term and long-term assessments is the climate. This comparison has not be completed due do several factors. First, there is a lack of observed data at this time; contact has been made with those who have the data, but it will take time to obtain it. The other issue is that VBFlow reports extreme sediment transport values within the channels and extreme sediment yield values at the outlet point. These values begin to occur after 7 and 10 years of simulations for the large and small watershed, respectively. The end result is the reporting of sediment yields that equate to deluge levels – over 150 million tonnes of sediment yield per hectare per year; this is a far cry from the 15+ t ha^{-1} y^{-1} reported by GeoWEPP.

Since these extreme values occur after a certain point, an different approach was used to determine the amount of sediment yield that would be reported by VBFlow. The 50 year simulation was divided into 10 five year simulations; each five year simulations would use a different five years of climate data. The end result was that the same 50 years of climate would be simulated for both GeoWEPP and VBFlow. The end result showed that VBFlow and GeoWEPP provide very similar results. Therefore, the problem exists between how the subcatchment information is being passes through the Translator into WEPP and back; a review of the Translator code may provide some insight into the errors seen in this scenario.

The final scenario deals with a different approach to the erosion model. The previous scenarios used subcatchments and sediment yields as the focus of the analysis. In this scenario, the focus is on what is occurring within each subcatchment, not the watershed as a whole. This onsite assessment, called the flowpath method in GeoWEPP, reports the amount of soil loss or gain that occurs at each raster cell within the watershed during the simulation time. In this scenario, the simulated soil loss/gain for the large nested watershed over 50 years was compared to the sample site data collected by Richie et al. (2005). Unfortunately, no correlation was observed between the observed and predicted values. Some experimentation should be made to improve on the correlation between the sample sites and the simulated results, but the accuracy of the watershed method should not be sacrificed.

The research present in this work shows that VBFlow has the potential to improve upon GeoWEPP, but more testing is needed before this can be confirmed. The scenarios created for VBFlow validation need to be completed before the validation can continue. Once this series of scenarios had been completed and it has been determined that the new subcatchment creation method could be a benefit, more scenarios will be tests by varying soil and landuse data. From that point, more testing is other watersheds will also be necessary to determine the flexibility of the improved GeoWEPP.

6 Further Study

The creation and modification of environmental models is complex task requiring many small stages to be passed through before it has been completed. VBFlow has passed through several of these stages, but there is more that needs to be done before this modification can be presented to the scientific community as an improved model. There is a need for further study; not just to work out the errors that have occurred, but to ensure that the model provides accurate predictions.

Short-term Assessment

The short-term assessment scenario needs to be completed for the 1982 and 1984 storm seasons. Once the missing data has been obtained, the analysis can be completed for both watersheds; this is only the first step. Other storms series within the Lucky Hills watershed should also be tested to provide a more accurate picture of the potential of VBFlow fro short-term analysis.

Long-term Assessment

The most difficult task ahead is to determine the cause of the extreme sediment yield values being reported by VBFlow. The five year simulation series has shown that the sediment yields over the same 50 years from VBFlow approximate those reported by GeoWEPP. Once this issue has been resolved, the results from the long-term simulations can be compared to the observed data.

Onsite vs. Sample Sites

The onsite assessment versus the observed samples has shown little correlation between the two. There are several reasons why this has occurred, but attempts to improve on this relation may result in a reduction in the accuracy of the watershed methods already presented. Some modification of the soil and landuse parameter files may improve both the onsite and offsite results. More sample points could also reveal that there is a correlation between the onsite and the sample sites. Comparisons between simulated and observed measures will be needed to determine it this low correlation is an issue or an anomaly.

Doing it all over again

Completing the above tasks is not the end of the validation phase of VBFlow. This initial research is to determine if the difference in subcatchment creation methods has an impact on the amount of sediment yield predicted by the erosion model. The next phrase is to apply the new subcatchment creation method to a region where the soil or vegetation has spatial variability and repeat the above process. Once this has been complete, the same process needs to be applied to a region where soil and landuse vary within the study site. By the complete of this final round of testing and validation, VBFlow should be able to demonstrate that it provides a more realistic representation of the watershed within the model.

Finally, once the validation of VBFlow has concluded within the Lucky Hills, the program needs to be tested in other regions. The test of a good model is that it can be applied universally; for VBFlow to be a good model, it must be used and validated by using observed data in other sites. Dr. Jerry Richie has offered to provide more sample sites from other regions of the Walnut Gulch Watershed (which contains the Lucky Hills nested watershed), which will provide different soil and management types on which GeoWEPP and VBFlow can be used. The results of these runs will help to validate the GeoWEPP and VBFlow models.

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8 Appendices

8.1 Appendix I – WEPP and GeoWEPP

8.1.1 Water Erosion Prediction Project (WEPP)

The Water Erosion Prediction Project (WEPP) was developed by the US Department of Agriculture. WEPP is a spatial and temporal process-based erosion prediction model that incorporates the fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. The WEPP model used several input parameters to predict erosion and deposition on hillslopes and watersheds. These parameters include hill slope and length, soil and vegetation/management parameters, and climate (Flanagan and Nearing 1995).

WEPP provides a temporal aspect to the vegetation/management parameters. The vegetation files include parameters to simulate the temporal changes in plants that have an effect on the potential sediment yield and runoff. Through simulations, WEPP can calculate plant growth and death based on a number of climatic conditions, thus simulating the changes that may occur in the real world. Plants can grow in certain conditions and enter dormancy in other conditions; annuals will grow and die, resulting in standing or decaying biomass. Factors, like temperature and moisture, can increase or decrease the potential from growth. Factors, like canopy are also included. WEPP simulates plant death and decomposition, thus adding ground cover temporal modifications to the list of factors that effect soil erosion. As time goes on, the standing dead biomass becomes ground cover (dead biomass) which eventually decomposes to reveal the ground layer once again (Flanagan and Nearing 1995).

The soil parameters include a number of components. First, the percentage of sand, silt, clay, organic material, and rock fragments are included in the soil file. These percentages can change with depth, so the soil parameters include layers in which these changes can be listed. The soil parameters also include a number of other important components: random roughness, bulk density, hydraulic conductivity, interrill and rill erodibility, and critical shear stress. Random roughness is associated mainly with tillage, but refers to anything that disturbs the soil. This will have an effect on the amount of erosion that can occur in a given area. WEPP simulates the change in random roughness as the simulation time progresses. Bulk density refers to the pores within the soil, which affects the infiltration rate of water into the soil. Hydraulic conductivity is a key parameter that controls infiltration and runoff predictions. The interrill and rill erodibility refers to the resistance the soil has to detachment due to raindrop impact and to concentrated flow. The critical shear stress factor is the threshold that must be reached before a particle of soil will detach.

Climate can be generated either using either historical data, modified to the file formats, or generated through climate parameter files. "The number and distribution of precipitation events are generated using a two-state Markov chain model. Given the initial condition that the previous day was wet or dry, the model determines stochastically if precipitation occurs on the current day. A random number (0-1) is generated and compared with the appropriate wetdry probability. If the random number is less than or equal to the wet-dry probability, precipitation occurs on that day. Random numbers greater than the wet-dry probability give no precipitation (Flanagan and Nearing 1995)." The result is a climate input file that contains the month, day, year of an event, the amount of precipitation, peak intensity, duration of the event and its time to reach peak intensity, minimum and maximum temperate, as well as the dew point, and the wind velocity and direction during the storm. Incoming solar radiation is also calculated. For all simulations, the number of climate years calculated must be at least twice the number of years within a simulation.

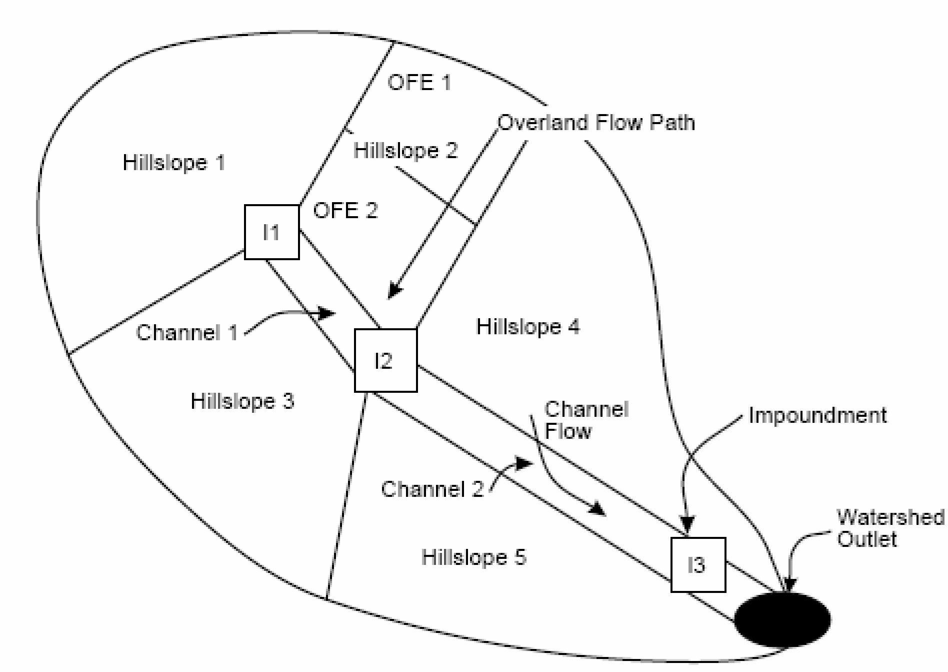


Figure 32 - Schematic of a small watershed to which WEPP can be applied. WEPP can be run on any of the individual hillslopes. Hillslopes with multiple Overland Flow Elements (OFEs, like Hillslope 2) can also be simulated. WEPP can also be applied to the entire watershed (Hillslopes 1 -5, Channels 1 and , and the three impoundments I1, I2, and I3) (Flanagan and Nearing 1995, p. 1.1).

WEPP can perform simulation on individual hillslopes or on entire watersheds. The benefit of the hillslope simulations is that multiple Overland Flow Elements (OFEs) can be placed. OFEs are combinations of soil and management parameters along a hillslope. By incorporating breaks on a hillslope, a more realistic distribution of soil and vegetation can be represented. By including OFEs into a hillslope, the simulation has the capability of estimating spatial and temporal distributions of soil loss. The watershed method runs the hillslope simulations on every hillslope with in the watershed and simulates soil detachment, transport, and deposition within the channel. The watershed simulation also incorporates any impoundments that may occur with the watershed that will result in the deposition of channel sediments.

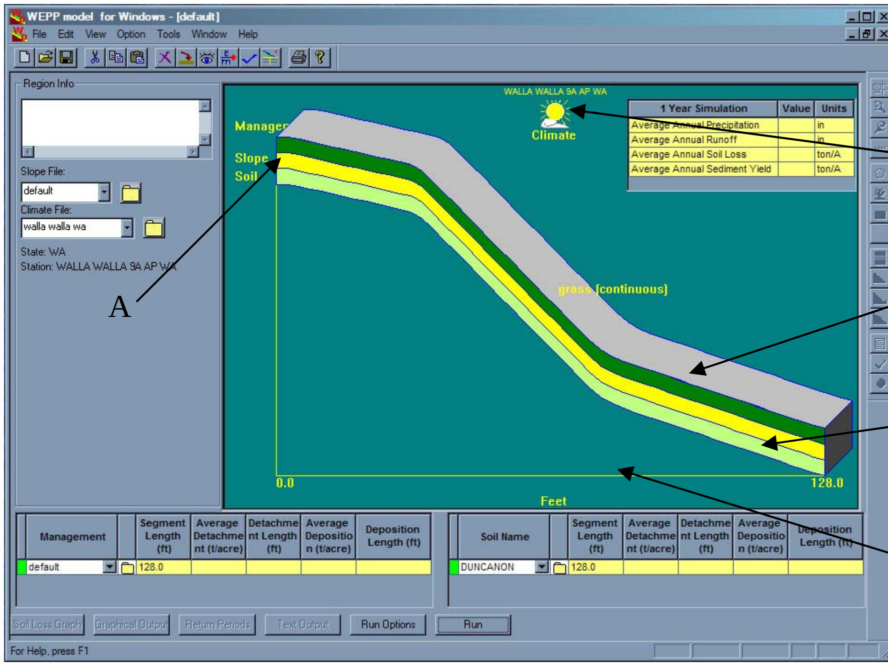


Figure 33 – The WEPP erosion predictions use several parameters. These parameters include slope steepness (A) and slope length (E), Climate (B), vegetation/management (C), and soil (D). This image represents the hillslope simulation method in which all simulation are run on this one hillslope.

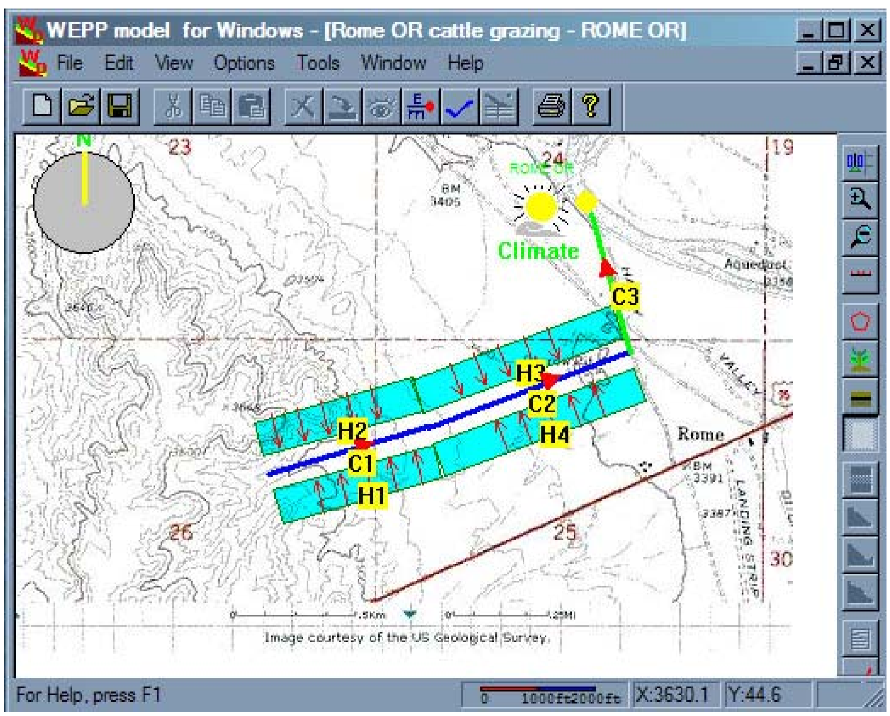


Figure 34 – WEPP can run erosion simulations on watersheds. In the watershed above, four hillslopes and three channels are present. WEPP runs the hillslope simulations on all hillslopes and then runs simulations involving sediment detachment, transport, and deposition within the channels.

8.1.2 Geospatial Interface for WEPP (GeoWEPP)

GeoWEPP serves two purposes: visualization for WEPP inputs and outputs, and the creation of watersheds for WEPP. GeoWEPP allows the user to import ASCII Raster files created from commonly available GIS data source; for example, the USDA National Resource Conservation Service (USDA-NRSC) Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/ - as of July 19, 2005) where some of the data has been acquired for user workshops. GeoWEPP converts the imported ASCII Raster files into raster ArcView Themes and begins to derive the first network using TOPAZ. This first run always uses the default Critical Source Area (csa) and Minimum Stream Channel Length (mscl) of 5 hectares and 100 meters, respectively. Once the first network has been derived by TOPAZ, the csa and mscl can be changed by the user to define a network that best represents the real world stream network. Each time the channel network is recalculated, TOPAZ uses the DEM and the new values to create the new network.

After the user has completed any network modifications, the user selects the outlet point for the watershed they intend to study. This outlet point is located on a non-converging channel cell and its location is used as a new input parameter for TOPAZ, allowing the program to determine the subcatchments of the watershed. The user can only select one outlet point form the entire study area. The subcatchments are the hills that flow into the stream network that eventually flows to the outlet point.

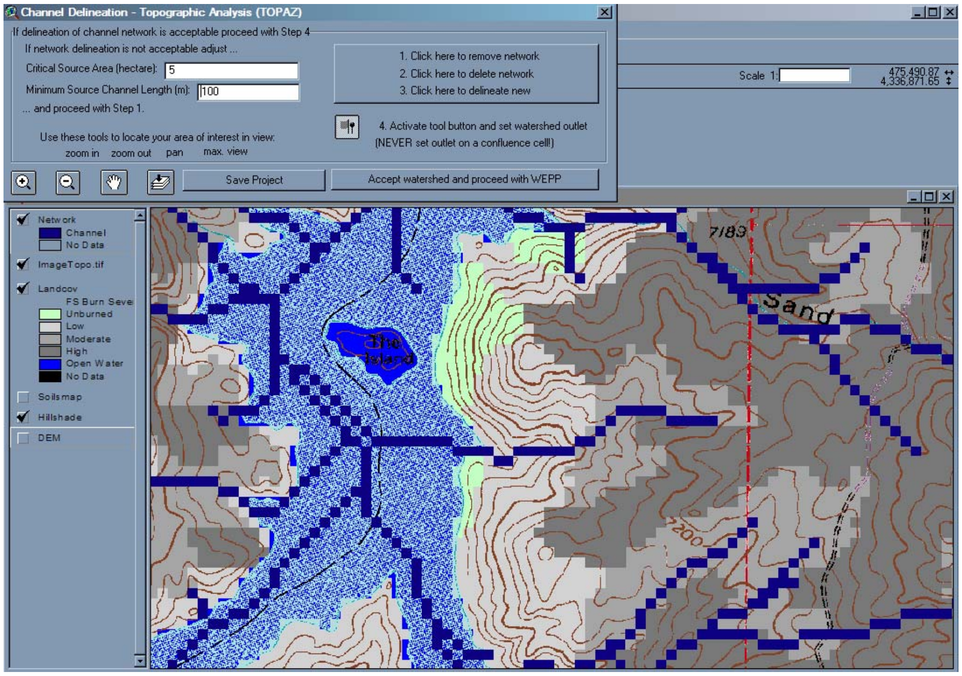


Figure 35 – GeoWEPP uses commonly available data as input parameters for WEPP. This figure depicts the landuse and network parameters. The other parameters, elevation and soil, are not visible, but the corresponding ArcView themes – DEM and Soilsmap, respectively – can be seen in the theme list to the left. The default Critical Source Area (csa) of 5 and Minimum Stream Channel Length (mscl) of 100 was used to derive the network, as can be seen in the Channel Delineation dialog box in the upper left of the figure.

Once the subcatchment has been created and accepted by the user GeoWEPP prepares the final WEPP parameter, climate. GeoWEPP uses a program, Climport.exe, to determine the location of the nearest weather station to the study area; from this station, 100 years of climate will be created. The user has the option to change the weather station or to import an already existing climate file in WEPP format. After this step is completed, the user is given a chance to change the soil, management/landuse, and channel WEPP input parameters before continuing on to the Translator. As stated above, these parameters are not required to be inputted within GeoWEPP, but they are necessary for WEPP to run the model. If the soil and/or management/landuse parameters are not present, GeoWEPP will prompt the user to provide a default value for the missing parameters to be applied to the entire watershed. If the parameters have been inputted into GeoWEPP, the program will prompt the user to "link" the information from GeoWEPP to the soil and management files that can be identified by WEPP. Once this has been completed, the user can now run the erosion model on the watershed.

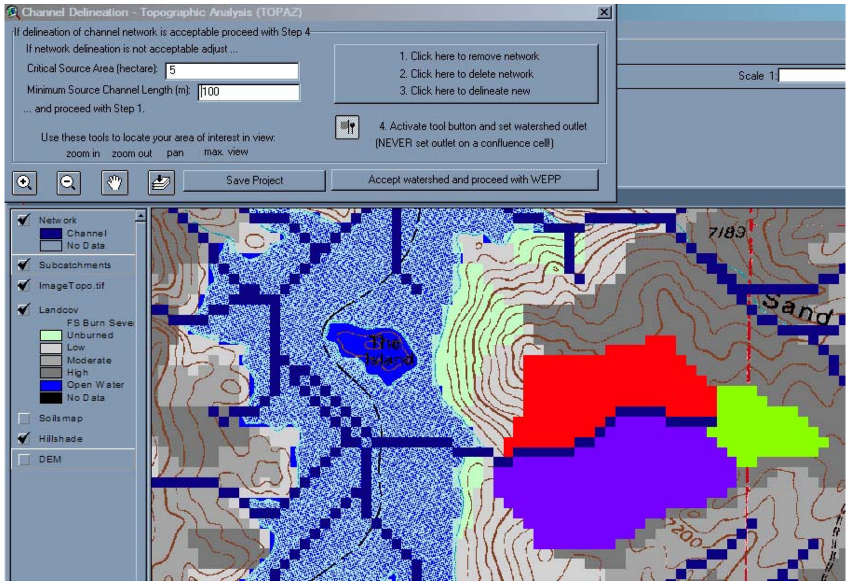
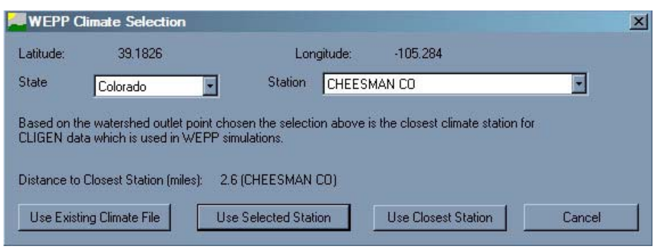


Figure 36 – TOPAZ creates the subcatchments based on an outlet point. Each channel within the watershed will have up to three subcatchments, representing the contributing areas on the left and right sides of the channel and one for the source. In the simple watershed above, only three subcatchments are created; more complex watershed will have a larger number of subcatchments.



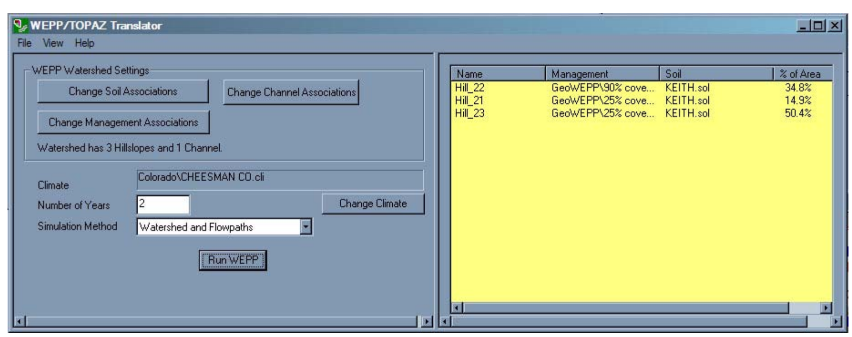


Figure 37 – Images of CLIMPORT and the Translator. (Above) The climate parameters for WEPP are inputted using the Climate program CLIMPORT. Either WEPP database climates or user created climate files can be selected. (Right) Once all the parameters have been entered, The Translator will run simulations based on the number of years inputted by the user. The Translator is the bridge between GeoWEPP and the WEPP prediction engine.

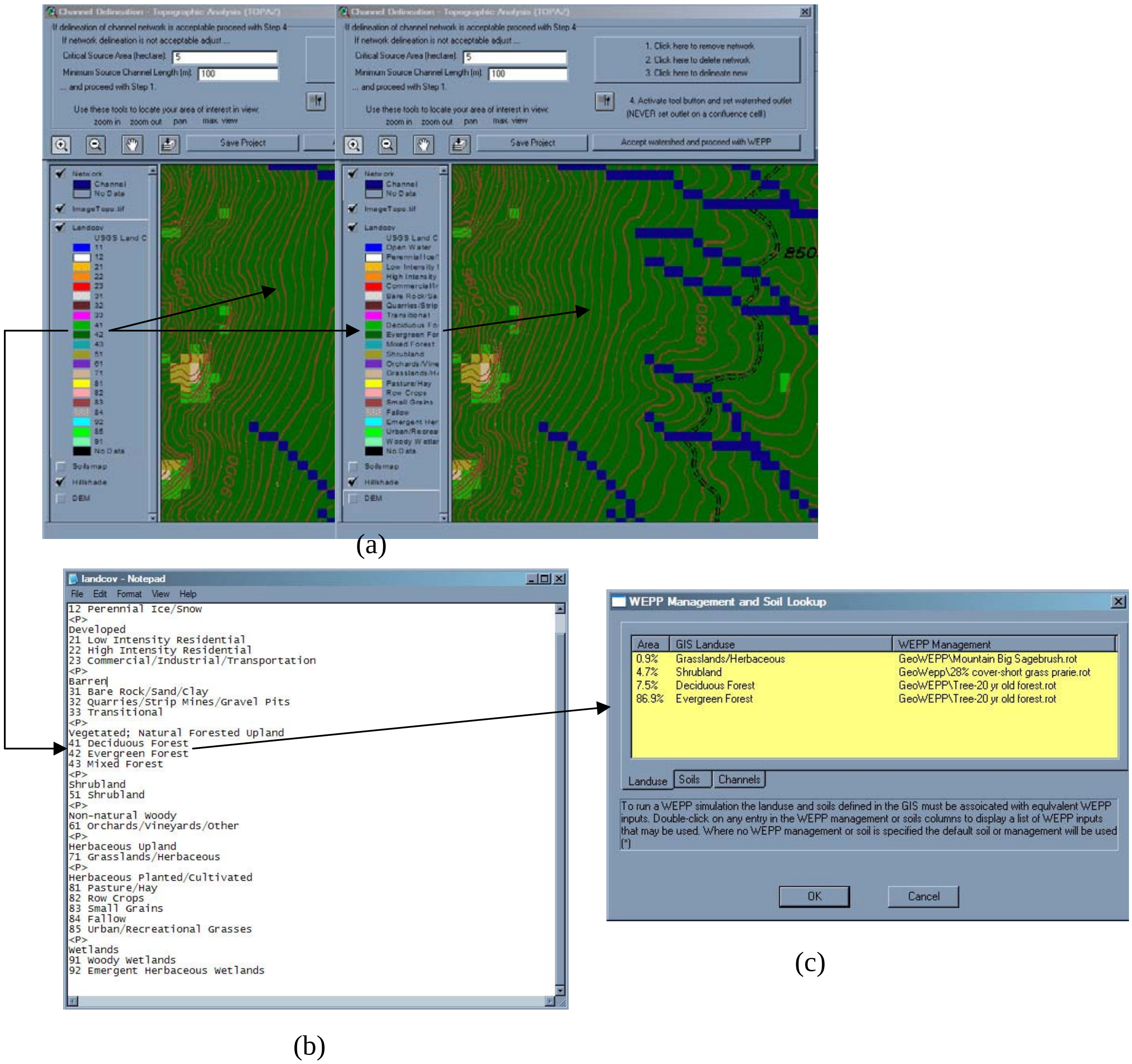


Figure 38 – Linkages between GeoWEPP, text files and The Translator to WEPP. (a) The raster cells within GeoWEPP contain values that correspond with a preset soil or landuse description. (b) The description-value relation ship is stored with in a text file: soilsmap.txt for soils and landcov.txt for landuses. (c) these descriptions are feed into the translator, allowing the user to link the description with previously created WEPP parameter files.

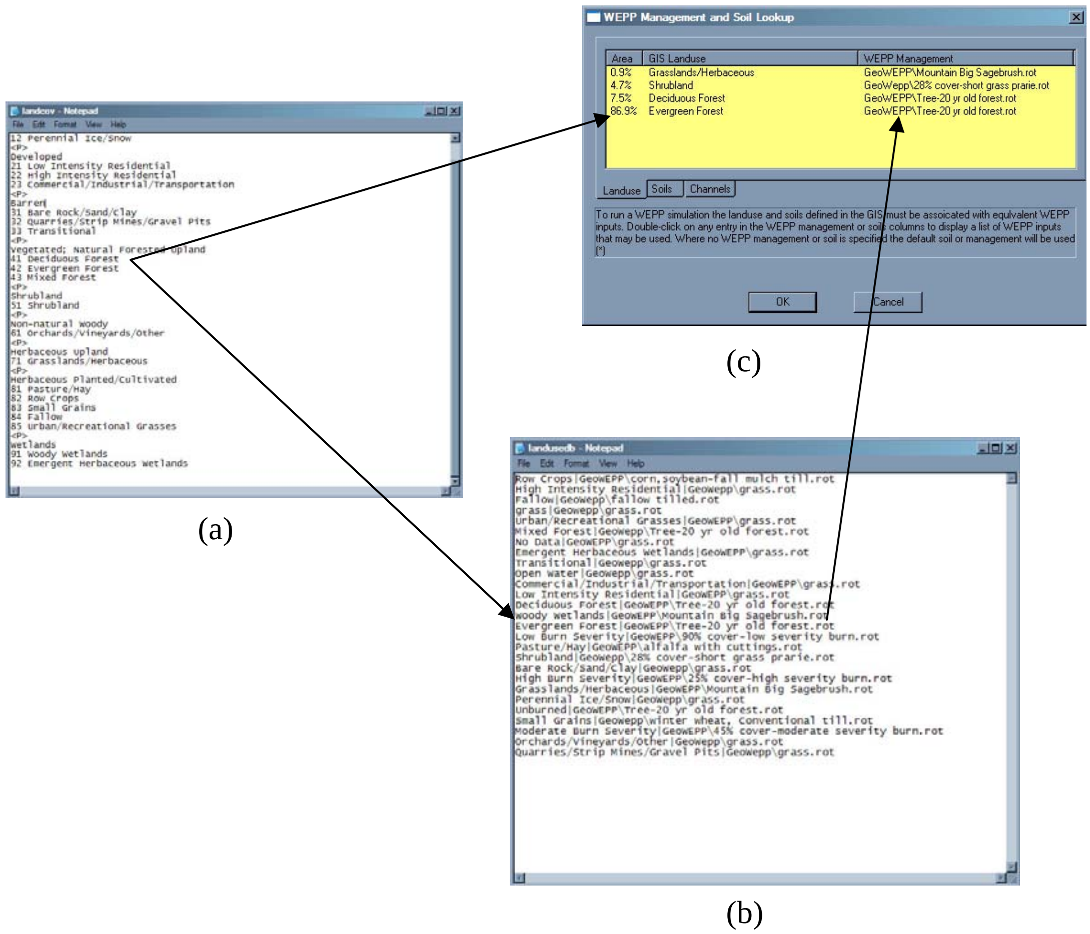


Figure 39 – Linkages between WEPP parameters and the Translator. WEPP parameters are linked to The Translator through a series of text files, like the links created from GeoWEPP. (a) The raster value-description relationship text file provides a link between the GeoWEPP raster images and the database text file. (b) The database text file – soilsdb.txt for soils and landusedb.txt for landuse – provide a description-WEPP parameter relationship for The Translator. (c) The WEPP parameters are loaded into The Translator and correspond with the description from the GeoWEPP linkage.

There are three different types of simulations the user can select from: watershed, flowpath, or both. The watershed method provides an offsite assessment tool that calculates the amount of sediment yield delivered to the channels within the watershed and to the outlet point of the watershed. The flowpath methods, which corresponds to the hillslope method in WEPP, creates an onsite assessment tool that provides spatially distributes soil loss values for every raster cell within the watershed. Once the simulation has ended GeoWEPP displays the results using a default tolerable soil loss (or a target value T) of 1 tonne per hectare per year (t ha^{-1} y^{-1}). This value indicates the acceptable maximum amount of soil loss allow within the study area. The user is able to change this T-value and GeoWEPP will display the new sediment yield and/or spatially disturbed soil loss predictions. GeoWEPP also allows the user to change the soil and/or management layer for any hill, independent from any other hill or the watershed, and run the WEPP model again.

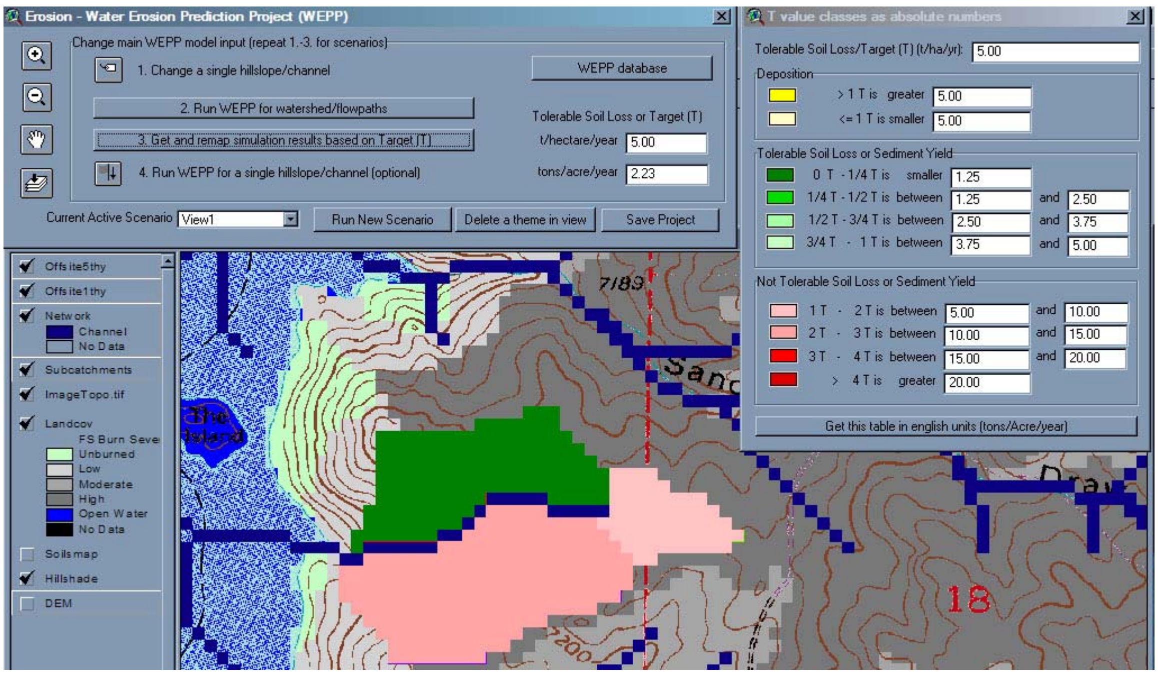


Figure 40 – Results of the watershed method using a T-value of 5 t ha^{-1} yr^{-1}. GeoWEPP visualizes the results of the erosion prediction simulations. Two of the three subcatchments exceed the tolerable soil loss level established by the user. The third subcatchment is well within limits. From this point, the user will be able to plan best management practices for high soil loss subcatchments.

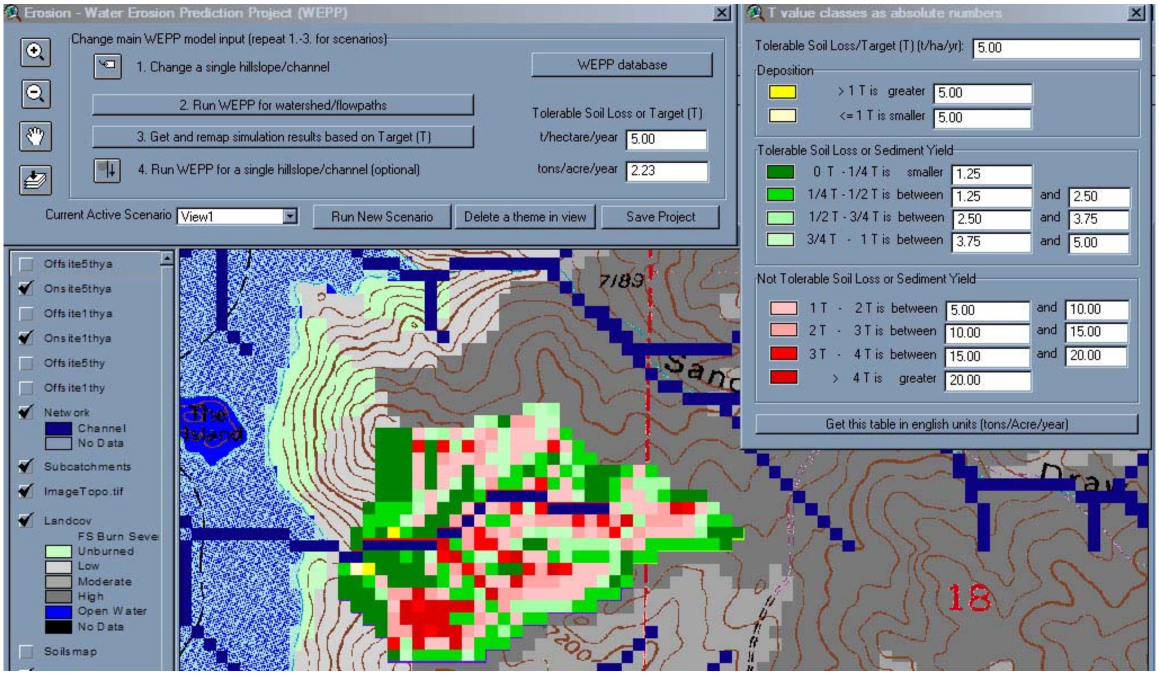


Figure 41 - Results of the flowpath method using a T-value of 5 t ha^{-1} yr^{-1}. This method runs the simulations across each raster cell, not each subcatchment. The result is an onsite assessment tool that can guide the user to the locations that are predicted to have the most amount of erosion. This tool also indicates where deposition within in the watershed may occur (yellow cells).

Finally, GeoWEPP provides a visual link to WEPP for each hill in the subcatchment or for the entire watershed. This link allows GeoWEPP to export the necessary parameters into WEPP allowing the user can continue will their analysis and use the other models and tools provided by WEPP. This link is only one-way; any modifications made in the WEPP interface do not translate back into GeoWEPP.

8.2 Appendix II – Sample Tables

8.2.1 TOPAZ Subcatchment Table Output Example (SBCT.TAB)

```
TOPAZ SOFTWARE : TOPAZ PARAMETERIZATION SOFTWARE SYSTEM
 PROGRAM DEDNM : DIGITAL ELEVATION DRAINAGE NETWORK MODEL PROGRAM
                 VERSION 3.10, APRIL 1999

 J. GARBRECHT, USDA-ARS, EL RENO, OKLAHOMA, USA.
 L. MARTZ, UNIVERSITY OF SASKATCHEWAN, SASKATOON, CANADA.


 TITLE OF CURRENT TOPAZ APPLICATION:

  DATE: 23 AUGUST 1999     WEPP INTERFACE   DEDNM VERSION 3.1
  APPLICATION FOR TESTING AND VERIFICATION; INPUT FILE
  TESTING AND CALIBRATION.


 TABLE OF RASTER-NETWORK SUBCATCHMENT INFORMATION AS COMPUTED BY
PROGRAM DEDNM


 NOTE: FOR COMPLEX JUNCTION NODES ONLY THE SUBCATCHMENT INFORMATION
 PERTAINING TO THE FIRST NODE NUMBER IS GIVEN.  SUBSEQUENT NODES
 ARE HYPOTHETICAL NODES AND HAVE NO CORRESPONDING SUBCATCHMENT
INFORMATION.

 CHAN. CHAN. CHAN.      SUBCATCHMENT AREA IN NUMBER OF CELLS
 CNTR. ORDER INDEX     SOURCE   LEFT   RIGHT  CHANNEL   TOTAL
----------------------------------------------------------------

    1     1      2        59     200     138      22     419
    2     1      1        -1      -1      -1      -1      -1
   -1

 ** NOTE **

 - BECAUSE THERE MAY BE JUNCTIONS WITH MULTIPLE TRIBUTARIES, THE NUMBER
   OF SUBCATCHMENTS MAY BE SMALLER THAN THE THEORETICALLY EXPECTED
NUMBER.

 - THE LAST LINE OF DATA DOES NOT REPRESENT A SUBCATCHMENT.
   IT REPRESENTS THE WATERSHED OUTLET CELL.

 - THE SUBCATCHMENT AREAS INTO THE OUTLET CELL ARE ACCOUNTED FOR IN THE
   LAST CHANNEL LINK (PREVIOUS TO LAST DATA LINE).
   AS A RESULT, THE VALUE OF THE SUBCATCHMENT AREAS OF THE LAST CHANNEL
   LINK INCLUDE, IN ADDITION TO THEIR OWN SUBCATCHMENT AREAS, THE
SUBCATCHMENT
   AREAS INTO THE OUTLET CELL.

 - VALUE OF -1 INDICATES TERM NOT APPLICABLE.
```

8.2.2 TOPAZ Network Table Output Example (NETW.TAB)

TOPAZ SOFTWARE : TOPAZ PARAMETERIZATION SOFTWARE SYSTEM
PROGRAM DEDNM : DIGITAL ELEVATION DRAINAGE NETWORK MODEL PROGRAM
VERSION 3.10, APRIL 1999

J. GARBRECHT, USDA-ARS, EL RENO, OKLAHOMA, USA.
L. MARTZ, UNIVERSITY OF SASKATCHEWAN, SASKATOON, CANADA.

TITLE OF CURRENT TOPAZ APPLICATION:

DATE: 23 AUGUST 1999 WEPP INTERFACE DEDNM VERSION 3.1
APPLICATION FOR TESTING AND VERIFICATION; INPUT FILE
TESTING AND CALIBRATION.

TABLE OF RASTER-NETWORK CHANNEL LINK INFORMATION AS COMPUTED BY PROGRAM DEDNM

CHAN. CNTR #	CHANNEL ORDER #	COORDINATES UPSTREAM ROW	COL	DOWNSTREAM PREV. ROW	COL	LAST ROW	COL	CHANNEL LENGTH IN # CELL WIDTHS	TERRAIN ELEVATION IN METERS UPSTR.	DWSTR.	UPSTREAM AREA FLOWING INTO FOLLOWING NODES UPSTR. [ALL AREAS IN NUMBER OF CELLS]	DWSTR.-1	DWSTR.	DIRECT DRAINAGE AREA	NODE INDEX (MULTIPLE NODES) 1	2	3	4	5	6	7	SLOPE * 1000 DIRECT	SMOOTHED
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	255	288	259	268	259	267	24.90	2195.0	2096.9	59	418	418	360	2	0	0	0	0	0	0	-1.000	-1.000
2	1	259	267	259	267	259	267	0.00	2096.9	2096.9	418	418	418	0	1	0	0	0	0	0	0	-1.000	-1.000
-1																							

** NOTES **

- COLUMNS 1 THROUGH 22 ARE COMPUTED BY PROGRAM DEDNM;
  COLUMNS 23 AND 24 ARE COMPUTED BY PROGRAM PARAM.

- FOR COMPLEX JUNCTION NODES THE CHANNEL LINK INFORMATION
  RELATES TO THE FIRST NODE NUMBER ONLY.

- BECAUSE THE NETWORK MAY CONTAIN COMPLEX JUNCTIONS, THE NUMBER OF CHANNEL
  LINKS MAY BE SMALLER THAN THE THEORETICALLY EXPECTED NUMBER BASED ON
  THE COUNT OF SOURCE NODES.

- THE LAST LINE OF DATA DOES NOT REPRESENT A CHANNEL LINK. IT REPRESENTS

THE WATERSHED OUTLET CELL.

- ELEVATION VALUES ARE REPORTED TO THE NEAREST DECIMETER.

- THE THREE DRAINAGE AREA COLUMNS UNDER THE HEADING OF UPSTREAM AREA DO NOT INCLUDE THE AREA OF THE CURRENT CELL ITSELF. THEY INCLUDE ALL (CHANNEL AND OVERLAND) INFLOWS FLOWING INTO THE CURRENT CELL. THIS LAST COMMENT IS PARTICULARLY RELEVANT FOR THE COLUMN LABELED *UPSTR.*.

- THE DIRECT DRAINAGE AREA IS ALL OVERLAND AREA FLOWING DIRECTLY INTO A CHANNEL LINK. THIS DOES NOT INCLUDE UPSTREAM CHANNEL INFLOW, BUT IT DOES INCLUDE UPSTREAM OVERLAND INFLOW INTO THE FIRST CELL OF A CHANNEL LINK. ALSO, THE DIRECT DRAINAGE AREA FOR FIRST ORDER CHANNELS DOES NOT INCLUDE THE DRAINAGE AREA FLOWING INTO THE CHANNEL SOURCE NODE OR CELL. THIS SOURCE DRAINAGE AREA IS GIVEN FOR FIRST ORDER CHANNELS BY THE COLUMN LABELED *UPSTR.*.

- THE DIRECT DRAINAGE AREA INTO THE OUTLET CELL, AS WELL AS THE AREA OF THE OUTLET CELL ITSELF, ARE ACCOUNTED FOR IN THE LAST CHANNEL LINK (PREVIOUS TO LAST DATA LINE).
  AS A RESULT, THE VALUE OF THE DIRECT DRAINAGE AREA OF THE LAST CHANNEL LINK INCLUDES, IN ADDITION TO ITS OWN DIRECT DRAINAGE AREA, THE DIRECT DRAINAGE AREA INTO THE OUTLET CELL, AS WELL AS THE AREA OF THE OUTLET CELL ITSELF. THIS NECESSITATES THAT THE UPSTREAM AREA LABELED "DWSTR.-1" OF THE LAST CHANNEL LINK ALSO INCLUDES THE DIRECT DRAINAGE AREA OF THE OUTLET CELL, AS WELL AS THE AREA OF THE OUTLET CELL ITSELF.

- VALUE OF -1 INDICATES TERM NOT APPLICABLE.

8.3 Appendix III – Sample Site Data

8.3.1 Sample Site Coordinates and Measurements

Sample Site Number	NORTHING	EASTING	Obs. Erosion
0	3512464.854	589534.9	-3.870000000
1	3512470.928	589550.0	0.482500000
2	3512480.654	589572.9	-1.350000000
3	3512489.989	589596.0	-4.590000000
4	3512496.144	589620.8	-7.180100000
5	3512504.434	589643.8	-6.930100000
6	3512511.410	589667.7	-5.840000000
7	3512517.962	589691.1	6.998500000
8	3512521.416	589715.1	-3.700000000
9	3512523.022	589739.5	0.363300000
10	3512533.459	589761.0	-1.650000000
11	3512535.735	589786.4	-5.370000000
12	3512516.704	589794.4	-5.910000000
13	3512498.564	589800.4	-4.540000000
14	3512482.144	589782.1	-1.430000000
15	3512462.158	589773.2	-1.310000000
16	3512434.079	589759.2	-5.800000000
17	3512425.077	589735.7	-2.210000000
18	3512420.946	589711.0	-6.250000000
19	3512408.071	589695.5	3.162000000
20	3512389.874	589681.6	1.075300000
21	3512370.641	589660.3	5.895000000
22	3512349.101	589639.8	-1.420000000
23	3512326.251	589615.9	-4.640000000
24	3512314.831	589596.4	-4.660000000
25	3512442.589	589544.9	-5.620000000
26	3512419.247	589554.1	1.845300000
27	3512397.778	589563.9	-9.820100000
28	3512393.414	589566.0	-9.820100000
29	3512373.117	589575.3	-8.200100000

Sample Site Number	NORTHING	EASTING	Obs. Erosion
30	3512360.291	589581.1	-2.510000000
31	3512343.608	589586.6	-2.730000000
32	3512346.993	589605.3	-0.880000000
33	3512364.410	589600.6	-8.050100000
34	3512382.338	589592.5	-7.580100000
35	3512398.097	589584.6	-5.340000000
36	3512404.733	589580.0	-9.820100000
37	3512431.475	589570.4	-0.200000000
38	3512452.185	589558.0	-4.660000000
39	3512369.617	589628.3	-7.830100000
40	3512390.783	589617.8	-9.820100000
41	3512405.733	589609.2	-9.820100000
42	3512411.937	589606.3	-9.820100000
43	3512430.948	589596.3	-2.520000000
44	3512452.524	589587.4	-8.250100000
45	3512464.145	589580.6	-3.710000000
46	3512472.220	589605.5	-7.600100000
47	3512451.760	589615.8	-0.200000000
48	3512439.305	589621.7	0.055200000
49	3512421.840	589631.4	-8.050100000
50	3512402.112	589641.2	6.180000000
51	3512415.129	589666.0	-8.360100000
52	3512440.134	589653.2	-2.800000000
53	3512447.885	589652.3	-9.820100000
54	3512457.022	589643.0	-6.510100000
55	3512476.342	589631.6	-3.550000000
56	3512485.332	589653.9	-4.880000000
57	3512464.684	589665.9	-7.810100000
58	3512449.319	589673.5	6.349700000
59	3512430.494	589684.0	-9.820100000

Sample Site Number	NORTHING	EASTING	Obs. Erosion	Sample Site Number	NORTHING	EASTING	Obs. Erosion
60	3512442.770	589700.3	5.563600000	67	3512482.405	589734.0	-8.850100000
61	3512465.087	589689.1	6.263700000	68	3512504.587	589723.1	-6.640100000
62	3512485.682	589678.8	-5.010000000	69	3512505.548	589749.1	-5.660000000
63	3512496.533	589701.1	-1.540000000	70	3512490.907	589756.8	-5.390000000
64	3512476.764	589710.8	-1.440000000	71	3512473.062	589767.0	28.196800000
65	3512457.013	589720.1	1.619400000	72	3512494.051	589776.7	-7.780100000
66	3512460.993	589745.1	0.390900000	73	3512510.221	589770.4	-7.950100000

8.3.2 ^{137}Cs Measuring Technique

The technique used to measure the amount of erosion and deposition at the various sample sites involves the measurement of ^{137}Cs found in the samples. “The manmade ^{137}Cs radionuclide, having a half-life of 30.2 year, was released into the environment as a result of nuclear weapons testing occurring from the mid 1950s to the late 1970s. A peak value of the ^{137}Cs fallout occurred in 1963 (Stefano, Ferro et al. 2005, p. 149).”

The fallout was mostly deposited by rainfall. Even tough rainfall within the study site maybe patchy, it is assumed that, over the 20 years of radioactive fallout, the area would receive approximately uniform rainfall and fallout (Ritchie and McCarty 2003). ^{137}Cs quickly and strongly absorbed by the soil particles and resists leaching into the soil profile, resulting in a tagging effect on the soil. Fluvial and Aeolian processes are the dominant factors that move ^{137}Cs tagged soils with a watershed; chemical and biological processes have little effect on the movement of tagged soils (Ritchie, Nearing et al. 2005). Therefore, estimates of the erosion and deposition patterns can be measured based on the concentrations of ^{137}Cs found at the sample sites. Unlike other methods that estimates total soil loss, this technique measures net soil loss at each site and thus can be directly compared with sediment yield values estimated at the outlet of a large plot (Ritchie and McHenry 1990).

8.4 Appendix IV – WEPP Input Parameter Information

8.4.1 Soil Parameter - SoilsMcNeal-AZ0400 hc375.sol

Soil Texture	clay loam
Albedo	0.23
Initial Saturation Level (%)	30
Interrill Erodibility	4.55+e006 (KG*s/m**4)
Rill Erodibility	0.0046 (s/m)
Critical Shear	3.11 (Pa)
Effect HydroConductivity	3.749 (mm/h)

Layer	**Depth(mm)**	**Sand(%)**	**Clay(%)**	**Organic(%)**	**CEC(meq/100g)**	**Rock (%)**
1	50.8	60.4	15.3	0.800	10.5	25.3
2	127	45.7	23.5	0.300	14.1	11.4
3	787.4	44.8	30.0	0.100	18.0	14.6
4	1346	46.9	23.5	0.001	14.1	19.7
5	1524	84.0	9.0	0.001	5.4	5.5

8.4.2 Plant Parameter - Creosote and Whitethorn for Tombstone AZ.rot

Parameter	**Value**	**Unit**
Initial Plant	28% Shortgrass Prairie	
Bulk density after last tillage	1.3	(g/cub. cm)
Initial canopy cover (0-100%)	28	%
Days since last tillage	20000	Days
Days since last harvest	20000	Days
Initial frost depth	0	Inches
Initial interrill cover (0-100%)	28	%
Initial residue cropping system	Annual	
Cumulative rainfall since last tillage	393.7	Inches
Initial ridge height after last tillage	0.3937	Inches
Initial rill cover (0-100%)	28	%
Initial roughness after last tillage	0.3937	Inches
Rill spacing	0	Inches
Rill width type	Temporary	
Initial snow depth	0	Inches
Initial depth of thaw	0	Inches
Depth of secondary tillage layer	3.937	Inches
Depth of primary tillage layer	7.874	Inches
Initial rill width	0	Inches
Initial total dead root mass	1784	lbs/acre
Initial total submerged residue mass	0	lbs/acre

8.4.3 Climate Input Parameter – Small portion of LH Tombstone.cli

```
4.30
  1   0   0
  Station:  TOMBSTONE AZ                              CLIGEN VERSION 4.3
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated
   31.72  -110.07        1383          96           1          100
 Observed monthly ave max temperature (C)
 15.4  17.5  20.4  25.0  29.5  34.5  33.8  32.2  30.9  26.3  20.2  15.6
 Observed monthly ave min temperature (C)
  1.3   2.6   4.5   8.0  11.9  16.7  18.6  17.8  15.8  10.8   5.2   1.8
 Observed monthly ave solar radiation (Langleys/day)
 330.0 405.0 545.0 655.0 730.0 690.0 630.0 590.0 570.0 430.0 365.0 310.0
 Observed monthly ave precipitation (mm)
 19.9  17.9  16.4   6.5   4.6  12.6  88.2  80.4  38.3  19.2  15.0  20.5
```

day	mo	year	prcp (mm)	dur (h)	tp	ip	tmax (C)	tmin (C)	rad (l/d)	w-vl (m/s)	w-dir (Deg)	tdew (C)
1	1	1	7.9	2.42	0.02	5.81	13.7	0.9	143.	3.1	343.	6.2
2	1	1	0.0	0.00	0.00	0.00	9.9	-1.7	250.	4.1	308.	-0.3
3	1	1	0.0	0.00	0.00	0.00	11.5	-1.5	314.	3.1	141.	-10.7
4	1	1	0.0	0.00	0.00	0.00	21.9	-2.2	310.	0.0	0.	-10.2
5	1	1	0.0	0.00	0.00	0.00	15.1	5.3	236.	4.8	282.	1.7
6	1	1	0.0	0.00	0.00	0.00	20.4	10.3	218.	4.2	295.	2.6
7	1	1	0.0	0.00	0.00	0.00	11.7	6.9	274.	3.7	100.	-3.0
8	1	1	0.0	0.00	0.00	0.00	19.6	4.3	320.	2.1	186.	-2.0
9	1	1	3.5	1.64	0.08	6.93	15.5	5.1	321.	1.3	34.	0.0
10	1	1	0.0	0.00	0.00	0.00	17.4	-0.2	351.	0.0	0.	1.8
11	1	1	0.0	0.00	0.00	0.00	17.3	-1.6	324.	0.0	0.	-14.7
12	1	1	0.0	0.00	0.00	0.00	13.0	-0.9	326.	0.0	0.	1.9
13	1	1	0.0	0.00	0.00	0.00	11.2	4.3	317.	0.0	0.	6.3
14	1	1	0.0	0.00	0.00	0.00	9.0	0.2	223.	5.3	263.	-5.7
15	1	1	0.0	0.00	0.00	0.00	10.4	0.9	258.	0.0	0.	-11.8
16	1	1	0.0	0.00	0.00	0.00	11.8	-0.9	268.	2.3	119.	-7.3
17	1	1	0.0	0.00	0.00	0.00	14.9	3.4	320.	2.1	307.	-5.9
18	1	1	0.0	0.00	0.00	0.00	16.0	-2.5	284.	0.0	0.	-7.2
19	1	1	0.0	0.00	0.00	0.00	18.6	-2.9	245.	5.1	194.	-1.6
20	1	1	0.0	0.00	0.00	0.00	6.1	-0.2	291.	3.7	326.	-11.6
21	1	1	0.0	0.00	0.00	0.00	20.0	-1.8	222.	2.4	117.	2.9
22	1	1	0.0	0.00	0.00	0.00	13.7	3.9	227.	0.0	0.	-1.7
23	1	1	0.0	0.00	0.00	0.00	18.0	7.6	240.	3.4	196.	0.1
24	1	1	0.0	0.00	0.00	0.00	12.8	2.4	388.	1.9	217.	-13.3
25	1	1	0.0	0.00	0.00	0.00	18.8	-0.3	369.	6.6	107.	6.7
26	1	1	0.0	0.00	0.00	0.00	19.9	4.5	356.	3.2	345.	11.9
27	1	1	0.0	0.00	0.00	0.00	12.9	0.7	347.	0.4	224.	1.5
28	1	1	0.0	0.00	0.00	0.00	20.4	5.9	312.	3.3	270.	-8.4
29	1	1	19.9	0.86	0.82	4.80	26.0	5.5	403.	1.6	232.	-0.8
30	1	1	0.0	0.00	0.00	0.00	16.3	-0.5	338.	2.4	179.	-7.7
31	1	1	0.0	0.00	0.00	0.00	23.7	0.0	324.	2.2	242.	8.0

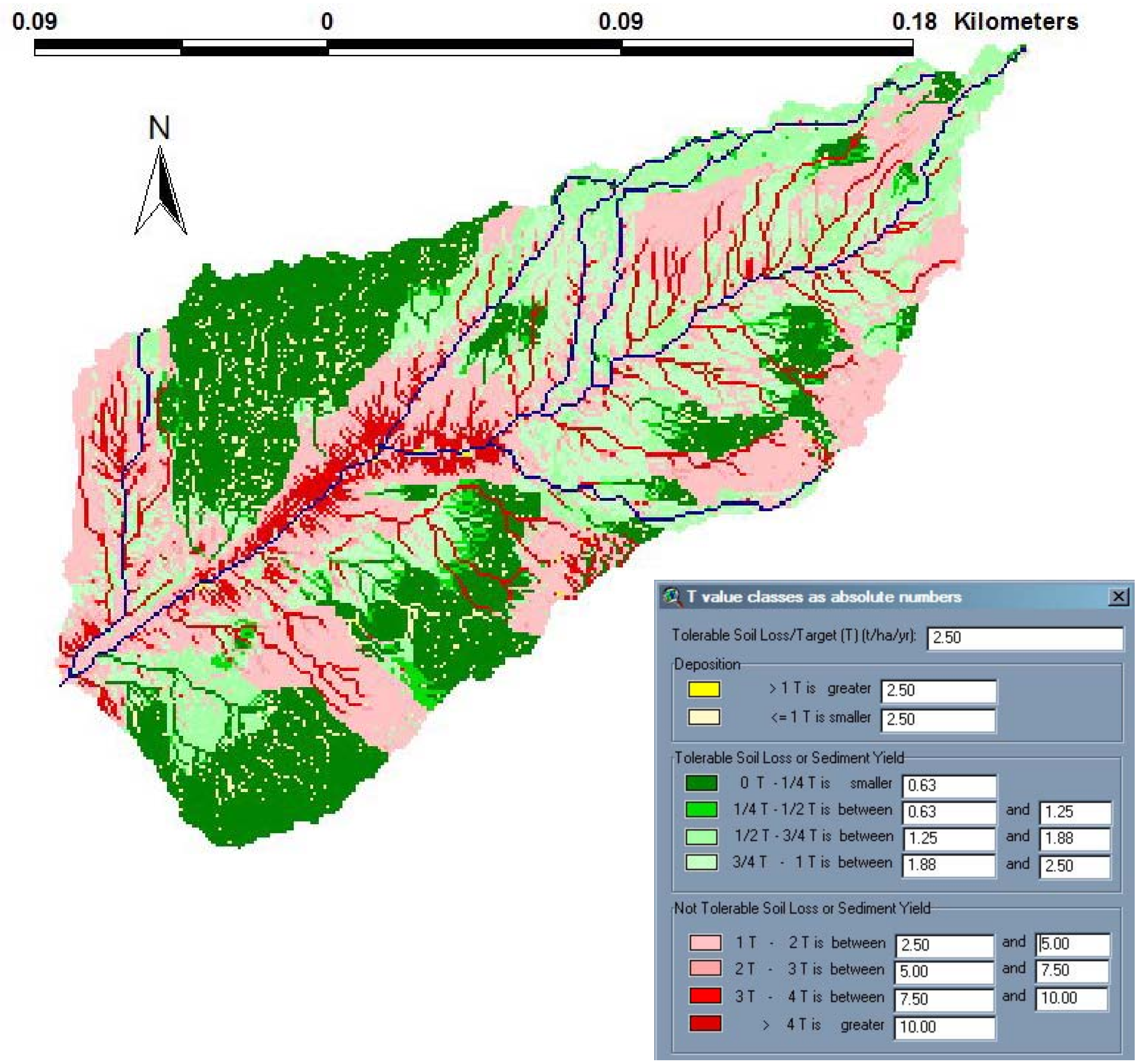
8.4.4 Elevation Input Parameters – Lucky Hills LIDAR DEM Metadata

Horizontal coordinate system
- Projected coordinate system name: NAD_1983_UTM_Zone_12N
- Geographic coordinate system name: GCS_North_American_1983

Details
- Grid Coordinate System Name: Universal Transverse Mercator
  - UTM Zone Number: 12
- Transverse Mercator Projection
  - Scale Factor at Central Meridian: 0.999600
  - Longitude of Central Meridian: -111.000000
  - Latitude of Projection Origin: 0.000000
  - False Easting: 500000.000000
  - False Northing: 0.000000
- Planar Coordinate Information
  - Planar Distance Units: meters
  - Coordinate Encoding Method: row and column
- Coordinate Representation
  - Abscissa Resolution: 1.000000
  - Ordinate Resolution: 1.000000
- Geodetic Model
  - Horizontal Datum Name: North American Datum of 1983
  - Ellipsoid Name: Geodetic Reference System 80
  - Semi-major Axis: 6378137.000000
  - Denominator of Flattening Ratio: 298.257222
- Bounding coordinates
  - Horizontal
    - In decimal degrees
      - West: -110.054698
      - East: -110.051061
      - North: 31.745414
      - South: 31.742762
    - In projected or local coordinates
      - Left: 589539.000000
      - Right: 589881.000000
      - Top: 3512606.000000
      - Bottom: 3512315.000000
- Spatial data description
  - Raster dataset information
    - Raster format: ESRI GRID
    - SDTS raster type: Grid Cell
    - Number of raster bands: 1
    - Raster properties
      - Origin location: Upper Left
      - Has pyramids: FALSE
      - Has colormap: FALSE
      - Data compression type: Default
      - Display type: matrix values
    - Cell information
      - Number of cells on x-axis: 342
      - Number of cells on y-axis: 291
      - Number of cells on z-axis: 1
      - Number of bits per cell: 32
  - Cell Size
    - X distance: 1.000000
    - Y distance: 1.000000

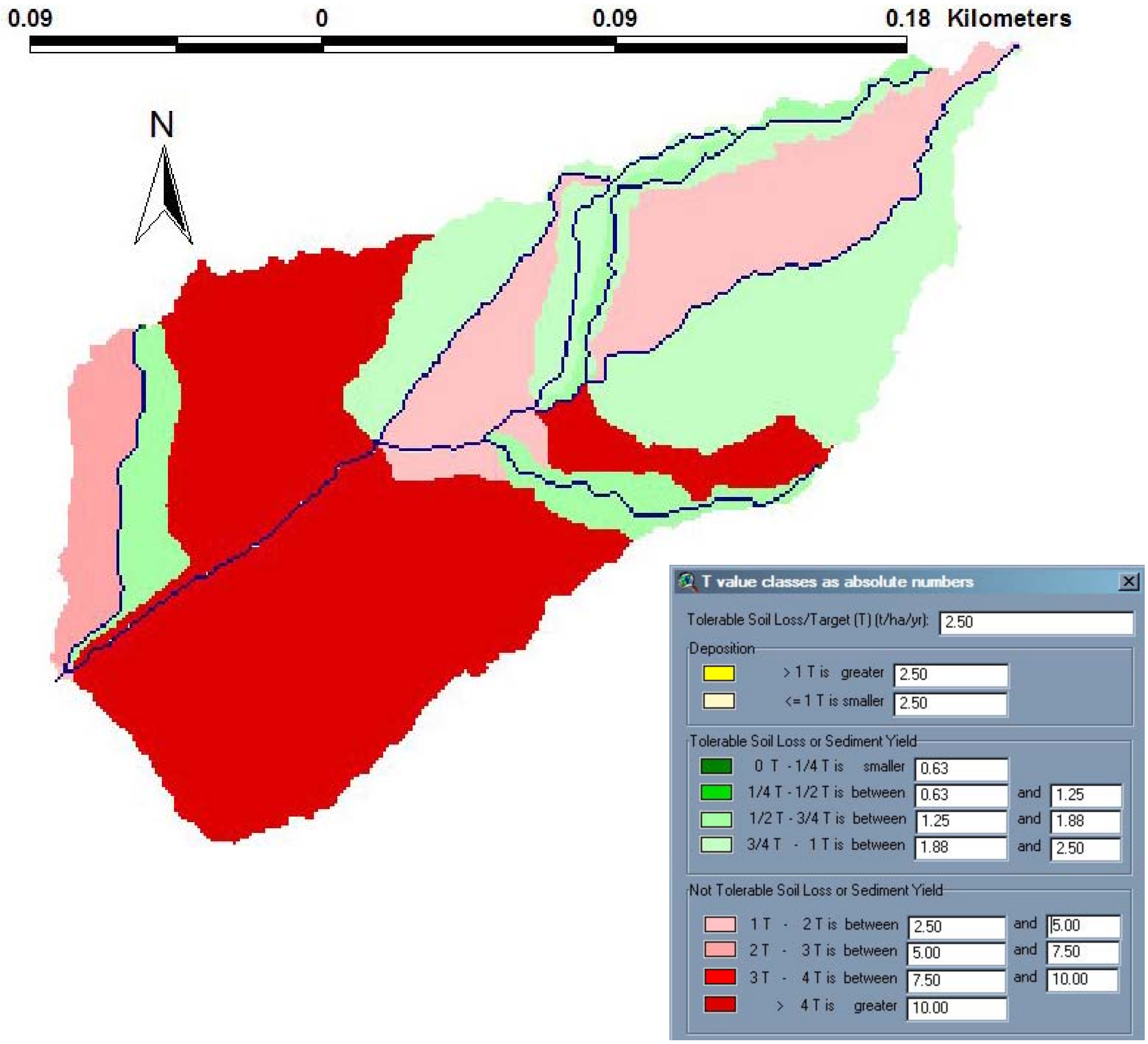
8.5 Appendix V – GeoWEPP and VBFlow Simulation Outputs

8.5.1 GeoWEPP Onsite Erosion Results (50 year simulation)

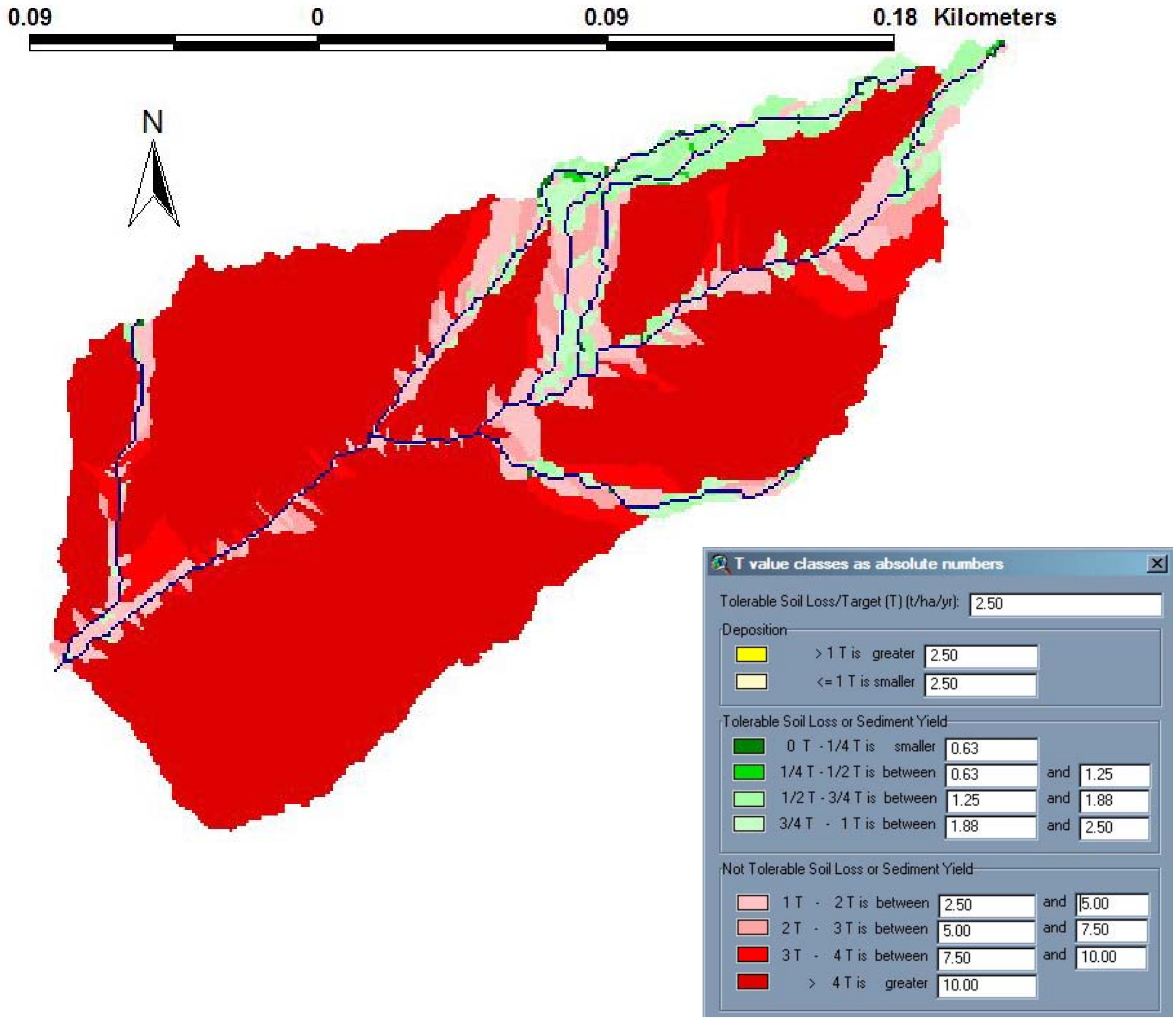


The onsite assessment

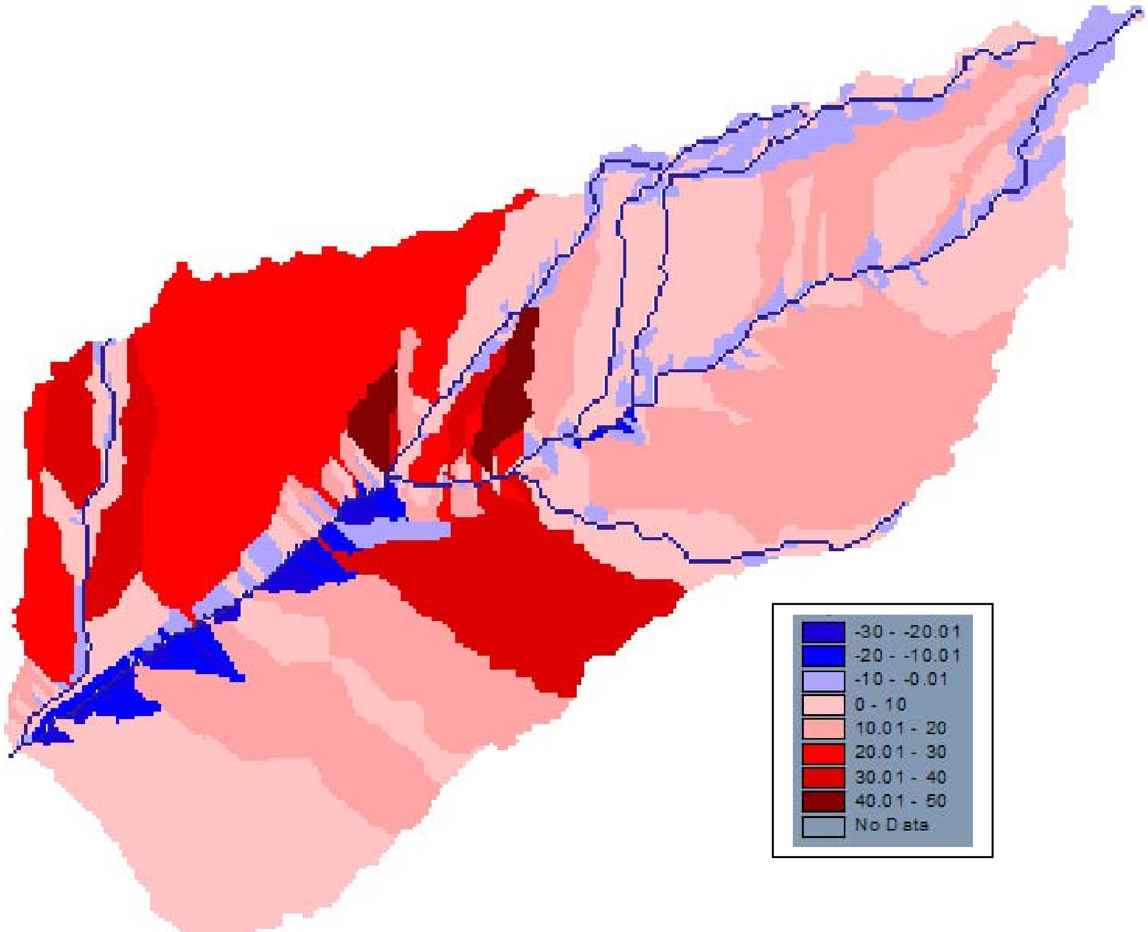
8.5.2 GeoWEPP Offsite Sediment Yield (50 year simulation)



8.5.3 VBFlow Sediment Yield (50 year simulation)



8.5.4 Sediment Yield Prediction Differences between VBFlow and GeoWEPP



This image represents the differences reported during the long-term assessment simulations between VBFlow and GeoWEPP. Red regions indicate a higher VBFlow prediction, while the blue regions are a lower sediment yield prediction compared to GeoWEPP.

Sediment yield measurements are made in t ha^{-1} yr^{-1}.