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Manish Shrivastav
Iowa State University

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Using ArcGIS hydrologic modeling and LiDAR digital elevation data to evaluate surface runoff interception performance of riparian vegetative filter strip buffers in central Iowa

by

Manish Shrivastav

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Major: Agricultural and Biosystems Engineering

Program of Study Committee:
Steven Mickelson, Major Professor
Matt Helmers
Tom Isenhart

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DEDICATION

To my family and friends

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ABSTRACT

Vegetative Filter Strip (VFS) buffers have been used for over two decades to function as filters for surface runoff from agricultural land into streams and other water bodies. Many studies have revealed that the classic VFS design along the length of an agricultural field does not adequately address non-uniform flow through the buffer. New designs are being researched to increase the efficiency of the VFS, but in order to accurately implement new design strategies, researchers must be able to accurately model the runoff flowpaths through the agricultural field into the VFS. The common assumption about field runoff is that the runoff flows perpendicularly across VFS as sheet flow. But there is minimal research information available about the actual surface runoff flowpaths and the performance of VFS buffers. This research assesses the performance of existing established VFS by modeling and analyzing the flow accumulation from the field in the VFS, with the help of Geographic Information System (GIS) and Light Detection and Ranging (LiDAR) derived Digital Elevation Model (DEM) data and using new approach of Coefficient of Flow Interception (CFI) to assess the performance of VFS buffers. As spatially non-uniform runoff can reduce the efficiency of filter strips, this study will also prove to be helpful in identifying areas in the farmland where the flow is concentrated and help in designing more efficient filter strips to account for the concentrated runoff.

CHAPTER 1. INTRODUCTION

Water can be considered the “new gold” on earth because it is necessary for the survival of most living things and is important used for domestic, industrial and agricultural purposes by mankind. Today there is an enormous concern about the quantity and quality of fresh water because of its scarcity due to overuse and pollution. The issue of water quality is of greatest concern for the world at present as polluted water is causing alarming death rates for aquatic organisms, human health hazards, and the aesthetic qualities of many water bodies. Water pollution throughout the world is affecting food chains and food webs and is a growing problem in our environments. Due to the increasing hazardous consequences related to water quality, the awareness to conserve water resources is spreading globally. With respect to growing public concern and awareness to reduce water pollution, the U.S. Environmental Protection Agency (USEPA) enacted a law in the 1972 Clean Water Act (CWA), with a motive to protect and enhance the surface water quality in the U.S. As a requirement of CWA 303 (d), USEPA has identified more than 40,000 water bodies nationally that exceed the maximum pollutant limits of CWA water quality standards (USEPA 2013).

The two primary types of pollution that enter the water environment are point and non-point source pollution. A point source is a single, identifiable source of pollution such as pipe or drain. Point source pollution is often a factor of industrial plants that manufacture waste products that are not properly treated. Point source pollution waste products can easily be traced back to the facility that produced them. Non-point sources (NPS) of pollution is often termed ‘diffuse’ pollution as it comes from many diffuse sources. The presence of NPS pollution contributes more to the deterioration of surface water quality than point source since

NPS pollution is caused by water movement over and through the surface of land (Subra and Waters, 1996). When runoff occurs, it transports natural and human-made pollutants, and finally deposits them into water bodies like lakes, rivers, wetlands, coastal waters and groundwater. In order to minimize NPS pollution, the U.S. government has recommended the application of several measures towards addressing NPS pollution by means of employing best management practices (BMPs) such as terraces, vegetated waterways, and wetlands construction to help remove the pollutants from runoff.

Agricultural production and NPS pollution are very closely related. In farming areas, NPS pollution includes pesticides, fertilizers, animal manure, and soil washed into streams as rainfall-runoff. Where livestock animals are given access to stream banks, they also may foul the water and accelerate erosion. All of these various pollutants can degrade the surrounding environment, and controlling the loss of agrochemicals and soil sediments into receiving water bodies from farmland can be accomplished by planting tall, close-growing stiff grasses or other perennial vegetation in a linear area known as a vegetative filter strip (VFS) buffer. These VFS buffers are bands of planted or indigenous vegetation situated downslope of cropland or animal production facilities to prevent erosion, filter nutrients, sediments, and other pollutants from agricultural runoff before it can reach the nearby water sources (Dillaha et al., 1989). According to the Natural Resources Conservation Services (NRCS), VFS buffers are vegetated land areas of either planted or indigenous vegetation for minimizing the amount of sediments and contaminants entering a nearby water body carried by the runoff from agricultural land or animal production facilities. These BMPs are considered to be an effective measure in reducing the sediment delivery from overland flow by retarding the runoff velocity and filtering sediment (Van Dijk et al., 1996).

Many efforts have been made to minimize NPS pollution from cropland and to reduce off-site impacts by reducing erosion and surface runoff within fields. When flowing across the VFS, surface runoff undergoes changes in composition and volume, entering the watercourse relatively cleaner than when it left the field (Abu-Zreig et al. 2004). Agrochemicals are transported mostly with the runoff generated after a heavy rainfall. The VFS buffer acts as a barrier to the movement of the suspended particles and decreases the velocity of flow in the runoff which in turn promotes settling of the suspended particles. The sediment of sizes typically greater than 40 microns can be captured easily. However, the remaining small size aggregates are difficult to remove by filtering because there is still presence of some relatively low turbulent energy in water that is sufficient to keep the sediments in suspension (Gharabaghi et al. 2001). Another benefit of using grass in VFS buffers is that it covers the surface and protects it from splash erosion, raindrop impact, and helps combat pollution. Dosskey et al. (2002) concluded that efficiency of VFS reduces due to runoff concentration. Riparian VFS buffers are an accepted BMP for reducing runoff of pollutants from agricultural fields into streams. A VFS buffer is an efficient measure to reduce the amount of pollutants from runoff leaving the agricultural lands before the runoff reaches a nearby stream. But the disadvantage of using a VFS buffer is that it can remove a significant amount of land area that could have been used for agricultural production. This BMP also requires timely maintenance to maintain its effectiveness over time. Several studies have been conducted to assess the effectiveness of VFS buffers in reducing sediments and nutrients from runoff. The effectiveness of a VFS buffer depends on the width, types of vegetation, age, level of development, and most importantly, flow interception capacity of the VFS buffer. The quantification of a surface flow interception coefficient for a VFS buffer will help to quantify the amount of sediments and chemicals removed from runoff.

Literature Review

Hydrology and Characteristics of a VFS buffer

There are many studies which show that the effectiveness of VFS depends on the length, slope, and hydraulic characteristics. Some of the studies which are helpful in understanding these characteristics of VFS are discussed below.

Length

Gharabaghi et al. (2001) studied the variations in flowpath sediment removal efficiency of a VFS buffer. Effects of flow path length on performance of VFS buffers was studied by comparing the test results for 2.44 m, 4.88 m, 9.67 m and 19.52 m filter strips for 1.22 m wide field with slope of 5.1 % -7.2 %. From 58 runs of experiments and 348 runoff samples, they concluded that the first 5 m of VFS length played an important role in removing sediment from the runoff stream. Almost all of the easily removable aggregates larger than 40 µm were captured within the first 5 m of VFS buffer length. They also found that the performance of the VFS did not increase significantly when the flow path length was increased beyond 10 m. They found that even a low level of turbulence in the water can keep the finer particles in suspension which makes it difficult to remove them from runoff. However, the study concluded that infiltration is the only key mechanism that helps in removing the smaller size sediment particles.

Lee et al. (2003) conducted an experiment to study the effectiveness of a multi-species riparian buffer in removing the NPS pollutants from cropland runoff. The experiment involved installing three plots where each of the cropland source areas was matched with no buffer (control), a 7.1 m switchgrass buffer and 16.3 m switchgrass/woody plant buffer. Sediment removal efficiency of 95% and 97% were seen for switchgrass and switchgrass/woody plant buffers, respectively. The increased sediment removal efficiency of the switchgrass/woody plant buffer was due to added length that increases the infiltration. This study could be considered as an ideal example of functional differences between long and short buffers. The ratio of sediment transported through the control plot to sediment transported through the switchgrass buffer was 13:1. Particle size distribution in the surface runoff changed through the buffers as runoff passed through the VFS buffer. In this case, large particles were deposited prior to small particles, and more than 90% of the sediment in surface runoff from the buffered plots was in the < 0.05 mm size fraction. During the infiltration of nutrients, suspended fine particles with adsorbed chemicals also entered the profile, thus decreasing the surface runoff and sediment transport capacity. Lee et al. (2003) concluded that there were major functional differences between narrow grass filters and wider mixed grass and woody plant buffers. The selection of one over another is dependent on site-specific problems whether as to remove the sediments and sediment-bound nutrients (narrow grass filter) or also to remove soluble nutrients in all including the most intense storm events (> 75 mm hr^{-1}.).

Abu-Zreig et al. (2004) conducted field experiments to examine the efficiency of VFS buffers for sediment removal from cropland runoff. The experimentation included 20 filters with varying length, slope, and vegetated cover. Experiments were conducted with incoming sediment load of 2700 mg l^{-1} on filter lengths of 2 m, 5 m, 10m, and 15 m, with slopes of 2.3% and 5%, and three types of vegetation. It was concluded that length of the vegetative filter was the most important factor affecting the sediment trapping efficiency of the VFS. It was also observed that increasing the length of the VFS buffer greater than 10 m did not significantly increase sediment trapping efficiency. The rate of incoming runoff flow and percent vegetation cover have a secondary effect on sediment deposition in VFS buffers. Although percent vegetation cover has a secondary effect on sediment trapping efficiency, higher vegetation density helped reduce erosion and sediment transport capacity of the runoff, causing more sediments to settle. It was observed that when there was a decrease in runoff inflow rates and soil water content, sediment trapping efficiency of the VFS buffer increased due to enhanced infiltration.

Hydraulic characteristics

The principle mechanism that is responsible for trapping the suspended solids and applied chemicals carried by the runoff is infiltration. Infiltration is the process by which water on the surface enters the soil profile. According to Gharabaghi et al. (2001), infiltration is the sole mechanism that helps in removing the smaller-sized sediment particles. The vegetative cover impedes the flow velocity of the incoming runoff, increasing the residence time and enhancing the infiltration process. Due to a decline in runoff velocity, ponding may occur at the upstream end of the VFS buffer which can cause some of the sediments and suspended solids to get filtered out and settle on the top of the filter as water flows through the filter. Meyer et al. (1995) suggested that stem diameter, density, stiffness and hedge width can have a significant effect on ponding depth.

Ree (1949) observed a decrease in Manning’s roughness coefficient (n) as the submerged grass in the waterway started to bend in the flow direction due to high flow rates. When the grass stems bend, effects of turbulence and flow velocity decrease due to the stems’ blocking effect on the moving water column. However, in the case where grasses were not submerged, the grass stood erect and was more effective in reducing surface runoff flow. Ree

(1949) also indicated that the grass remained erect until submergence was complete. The study concluded that non-submerged vegetation is the ideal condition to maximize flow retardation and minimize sediment transport capacity.

Dickey and Vanderholm (1981) reported that vegetative filters reduced nutrients, solids, and oxygen- demanding materials from feedlot runoff by over 80% on a concentration basis and over 90% on a weight basis. The degree of pollutant removal was dependent on the type of flow (overland or channelized) and length of flow. The channelized flow type was less effective than the overland flow type, requiring greater flow lengths for similar degrees of treatment.

Van Dijk et al. (1996) identified that grass vegetation can be effectively used as grass strips, buffer zones and grass channels in reducing sediment transport to surface waters. The study concluded that infiltration and sedimentation were the common mechanisms for retention of water and sediment in each BMP. The primary objective of the experiment was to compare the results regarding the sediment trapping efficiency of grasses with two different ages and management practices. According to the experiment, older grass was much more effective in reducing erosion than the younger grass. This was because the younger grass received frequent mowing activities. The differences in water retention capacity of the two kinds of grass were due to differences in grass densities at the two locations. Sediment trapping efficiency of grass filters of length 1 m, 4 m – 5 m, and 10 m was recorded as 50-60%, 60-90%, and 90-99 %, respectively.

M. Abu Zreig (2001) studied the factors affecting VFS performance using the simulation model VFSMOD. He found the length of filter to be the most significant factor affecting sediment trapping in VFS followed by the grain size of incoming sediments.

Maintaining a good vegetation cover increased the Manning's roughness coefficient, resulting in greater contact time between the runoff and vegetation and less erosive power and transport capacity of the runoff. Trapping efficiency of 95% was observed for a filter length of 15 m. An increase in length from 1 m - 2 m resulted in an increase in trapping efficiency by 42%, whereas there was only a 2% increase in trapping efficiency when filter length was increased from 12 m - 15 m.

Sediment and nutrient removal

Young et al. (1980) conducted a two-year study to evaluate VFS buffers for their ability to reduce pollutants from feedlot runoff under simulated rainfall conditions. Tests were performed on six VFS buffer plots that were 41.15 m long by 4.06 m wide with slope of 4%. Out of the length of 41.15 m, 13.72 m of the VFS buffer plots were within the feedlot boundaries. Cropped fields of corn, orchardgrass, sorghum-sudangrass and oat plots were used in the study to reduce runoff, total solids, and nutrients. All of the cropping treatments helped in reducing the total solids and dissolved nitrogen (N) and phosphorus (P) nutrients in runoff. The results showed that total nitrogen (TN), total phosphorus (TP), ammonium-nitrogen (NH_4-N) and orthophosphorus (PO_4-P) in runoff were reduced by an average of 84 %, 63 %, 83% and 76% respectively. However, average nitrate-nitrogen (NO_3-N) values in runoff increased about 9%, due to the fact that some NO_3-N was picked up from the soughum-sudangrass and oat plots. There was 82%, 81%, 61% and 41% reduction in runoff on corn, orchardgrass, sorghum-sudangrass and oat plots, respectively. In case of the corn plots, the reduction in runoff, suspended sediments, and nutrients were appreciably higher in comparison to other fields. This was credited to planting crops across the slope. As the runoff passed through the VFS, there was a reduction in the number of indicator organisms like *E. coli* in the runoff. In this experiment, buffer lengths of 36 m appeared to be long enough to reduce the concentration of nutrients and microorganisms in feedlot runoff to within acceptable standards.

Magette et al. (1989) conducted an experiment to study the effectiveness of VFS buffers in removing sediments and nutrients by simulating rainfall on bare plots of 5.5 m wide by 22 m long. Liquid N as 30% urea-ammonium-nitrate (UAN) solution and chicken (broiler) litter were applied at 112 kg ha^{-1} and 8.9 wet metric tons ha^{-1} as nutrient sources in test plots. The VFS buffer lengths of 4.6 m and 9.2 m were used in each set of experiments. The field soil was rich in P and required no supplemental P application. This study assumed P movement was dependent on total soluble solids (TSS) transport, in which N would move in the soluble form. The results showed higher losses of P during UAN tests versus the broiler litter tests. This was attributed to the mulching effect of the litter, which eventually minimized the TSS losses. Losses of TN, TP and TSS were seen to reduce by 0%, 27% and 66%, respectively, with the use of a VFS. This clearly indicated that performance of a VFS buffer in reducing nutrient losses is highly variable but is more effective in removing suspended solids.

Concentrated flow

The performance of VFS buffers in removing pollutants from agricultural runoff also largely depends upon the type of flow that the VFS receives. Factors like a concentrated flow or non-uniform flow distribution limit the performance of a VFS. Some studies considering these factors are discussed in this section.

Meyer et al. (1995) performed an experiment where they planted strips of tall, stiff grasses across the slope to study sediment trapping efficiency. They observed that planting the grasses perpendicular to the slope helped achieve higher trapping efficiencies by retarding the flow concentration. Concentrated flows were seen to have an aggravating effect on filtering effectiveness of the VFS buffers. It was also observed that the grasses retarded the flow and resulted in a hydraulic jump several meters upslope in the field which led to the deposition of the incoming sediment. The formation of an upslope hydraulic jump and the resulting deposition of sediment further improved flow retardation and increased the ponded flow. Sediment trapping resulted mostly from the upslope ponding due to grass hedges versus the runoff-filtering action. The experiment concluded that the sediment trapping was most effective because of sufficient settling time in ponded flow. The effectiveness of stiff grasses for trapping sand-sized sediments were as high as 80%. This demonstrated that trapping efficiency was a function of the size distribution of sediments carried in the runoff, requiring longer path lengths for sediments of smaller sized particles such as silt and clay.

Dosskey et al. (2002) found that concentration of surface runoff from agricultural fields can greatly restrict the ability of riparian buffers to remove pollutants. When runoff contacted a small area of a riparian buffer, concentrated flow or non-uniform flow distribution occurred. Riparian buffer evaluation plots on four farms were used to study the influence of surface runoff flow on sediment trapping efficiency. A numerical model using a regression equation based on the proportion of buffer area to field runoff area was used for evaluating the sediment trapping efficiency. The sediment trapping efficiency was estimated to be 99%, 67%, 59%, and 41% based on ratio of gross buffer area to field runoff area in contrast to 43%, 15%, 23%, and 34%, respectively, when based on effective buffer area to field runoff area. It was concluded that the sediment retention capacity of riparian VFS buffers could be improved by avoiding concentrated flow and distributing the runoff evenly through existing buffer areas. Concentrated flow is generally caused by severe erosional downcutting, soil deposition, or uneven topography.

Dosskey et al. (2011) found that buffer area ratio (the ratio of filter strip area to upslope contributing area) plays a key role in improving the effectiveness of VFS buffer performance. They found that sediment and water trapping efficiencies of filter strips increased non-linearly as the buffer area ratio increases. They found that under uniform flow conditions for the same buffer area ratio, the trapping efficiency of filter strips is twice than under non-uniform conditions.

Pesticide Retention

Chemical pesticides are applied to agricultural cropland to protect crops from invasive pests like insects and weeds. There are various ways in which pesticides are applied such as spraying, injection into soils, and surface applications. Similarly, there are several pathways in which pesticides can be lost such as adsorption to soils, aerial drift, and decaying to simpler forms over time. The most concerning loss pathway of pesticides for environmentalists is loss as runoff to nearby surface water source or leaching down into the ground water. The pesticides that are highly soluble in water have a tendency to move down into the ground water profile, whereas, the ones which are highly volatile get vaporized during application. Fate and transport of pesticides depend on several factors which are described below:

Adsorption and solubility

Adsorption is a process by which a pesticide binds to soil particles. When a pesticide is applied to soil, some of it will attach to soil particles while some may mix with water present between soil particles. Some pesticides are strongly adsorbed to soils that are high in organic matter or clay. When the soil is in a saturated state, the adsorbed pesticides may get detached from soil through desorption. The highly soluble pesticides can move down to the groundwater through leaching or be transported by surface runoff. Some moderately adsorbed pesticides can be retained by buffer strips through infiltration (Arora et al., 1996).

Soil properties

Soil properties like texture, organic matter content, and hydraulic conductivity are some important factors that determine the fate and transport of pesticides. The hydraulic conductivity of coarse-grained soils is generally higher compared with fine grained soils. Consequently, the time taken by the dissolved (or soluble) pesticide to travel is shorter in coarse soil versus fine soil. This increases the chance for these pesticides to leach down in coarse soils. In the case of soils having a high clay and organic matter content, there is greater sorption that prevents pesticides from readily leaching down into the soil column.

Site Conditions

Site conditions play a key role in the performance of a VFS and should be considered when assessing a VFS. Gilliam et al. (1993) observed that pesticides are less adsorbed in the shallow vadose zone. The direction and rate of chemical movement is greatly dependent on whether the underlying layer is permeable or impermeable. If permeable, chemicals can flow in a vertical direction and leaching is easier, but if the layer is impermeable, that would contribute to the lateral flow of shallow ground water and hence will result in polluting the surface water.

Study Objectives

Midwest is very well known for farming. In fact, Iowa is no. 1 in corn and soybean production. As farmers use fertilizers and chemical pesticides to increase the productivity, this can adversely affect the soil and water health. Besides, Midwest farmers also rear cattle and these graze on pasture land. This might also lead to favorable condition for erosion.

The selected research site is of great importance as it drains into a recreational lake, the Rock Creek Lake. The sites chosen were the same sites studied by Bansal, 2006. In fact, this is the second busiest site for lakeside camping. This lake also provides habitat to many aquatic lives and provides many recreational activities like fishing, boating etc. to people. This lake was constructed in 1952 AD with a surface area of 641 acre and a maximum depth of 24 ft. But over the past 50 – 55 years the lake has lost 40% of its volume and 102 acres surface area due to erosion and deposition. According a study conducted by Iowa State University, the lake receives 25,000 tons of soil per year from an upland watershed area of 26,698 acres. According to the study about 89% of phosphorus deposited into the lake comes from the sediments from upland. The chemicals and sediments being deposited into the lake might create hypoxic conditions which might threaten the aquatic life of the lake and also may decrease the total volume of the lake due to sediment deposition.

One the Best Management Practices (BMPs) adopted by farmers to mitigate the problem of nutrients and sediments getting into nearby water bodies is by establishing Vegetative Filter Strips (VFSs) along the edge of the farm land. We need to verify and quantify the performance of VFS.

A VFS buffer is an effective practice in reducing the transport of sediments and other chemicals into streams and other water bodies. It is important to assess the effectiveness of a VFS and ensure that the VFS proves to be a useful, practical and an economical measure against polluting and deteriorating water quality. Most VFSs are installed along the margins of farmland to filter incoming runoff to improve the water quality before it enters receiving waters. A common assumption about field runoff is that the runoff flows perpendicularly across VFS as sheet flow. However, there is little documented information available about the flow path followed by the runoff and the performance of VFS. The primary objective of this project is to assess the performance of existing VFS buffers by modeling and analyzing the flow accumulation from the field in the VFS, with the help of Geographic Information System (GIS) and Light Detection and Ranging (LiDAR) derived Digital Elevation Model (DEM) data. As spatially non-uniform runoff can reduce the efficiency of filter strips, this study will help in identifying areas in the farm land where the flow is concentrated and assist in designing more efficient filter strips to account for the concentrated runoff.

The second objective of this study is to evaluate the accuracy of LiDAR. LiDAR is an improved method of collecting terrain data that eliminates the limitations of time-consuming data collection techniques such as ground-based data collection procedures. If LiDAR data proves to be accurate enough, it can be used as supplemental data to GPS ground collected data. Since LiDAR data has the potential to be collected in less than optimal conditions, this greatly enhances the data collection window. The study is of great importance in evaluating the effectiveness of an existing agricultural BMP which is critical to water quality and surface runoff improvement, and also in helping to realize the need of effective management practices.

Expected Benefits

This research is expected to help agencies in expediting the installation of new vegetative filter strips (VFS) buffers more accurately as well as study existing buffers by simulating runoff flow path from the agricultural field to ensure if they are intercepted by the existing buffers. Non-uniform runoff can reduce the effectiveness of the filter strips of constant width along the edge of field (Dosskey et al., 2011). This study will help identify the areas of critical runoff load variability so that the effectiveness of VFS buffers can be improved by placing these BMPs where runoff load can be more effectively intercepted and treated.

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CHAPTER 2. LIDAR AND GIS

New Data Acquisition Technology: LiDAR

There are currently several techniques to acquire terrain data. A significant disadvantage of current terrain data collection methods that include conventional surveying and GPS is that these techniques require a significant amount of time in the field. Post-processing field-collected data in the office such as DEM preparation and photogrammetry also is very time consuming. An emerging remote sensing technology that has shown promise for collecting terrain data at a greater speed than existing data collection methods is Light Detection and Ranging (LiDAR). Acquiring field data from agricultural land generally requires receiving permission from property owners, which can constrain the data acquisition process. Since LiDAR data can be collected by aerial vehicles, these data can generally be acquired without obtaining landowner permission or disturbing agricultural crops and other annual and perennial vegetation. The use of LiDAR has increased dramatically in recent years, primarily due to the higher quality results produced by the automated collection of elevation data point measurements that are sampled very densely. Consequently, LiDAR has been used in numerous mapping and research projects in areas such as agriculture, construction, forestry, archeology, geography, and oceanography.

LiDAR

The LiDAR active remote sensing system uses a laser beam as the sensing carrier (Wehr and Lohr, 1999). These laser scanners measure three-dimensional points distributed over the terrain surface and on objects rising from the ground such as trees or buildings. Elevations are derived by making distance measurements to and from the earth surface from the sensing platform. These points can then be used to obtain a DEM for use with a number of applications where further interpretation and qualification of the original data is required (Haala and Brenner 1999).

The use of early LiDAR systems was difficult and expensive due to the system size, weight and power demands. They also required large four-engine aircraft platforms for their operation (Shrestha et al. 2003). However, with the recent advances in LiDAR systems, these components are now smaller in size and weight and require less power. The accuracy of Global Positioning System (GPS) has also improved. One major drawback of switching to LiDAR-based technology is associated with increasing data volume and expansion of necessary processing capabilities. Today, advances in computer processing speeds and memory allow a vast quantity of data to be stored and processed more efficiently and quickly.

Description of Technology

The manner in which LiDAR works is similar to Sound Navigation and Ranging (SONAR) and Radio Detection and Ranging (RADAR), which uses sound and radio waves, respectively, to map surface and atmospheric features. Aircraft vehicles are employed as a platform for onboard laser ranging systems, using the laser to scan the earth from side to side as the plane flies. The LiDAR laser system uses either green (532 nm) or near infrared (1064 nm) light because these wavelengths are readily reflected off of vegetation surfaces. The next component of LiDAR is a GPS receiver that tracks the altitude (z) and planar (x, y) locations of the aircraft. The GPS component determines the point locations where LiDAR reflections are incident on the ground. The third component of LiDAR unit is the Inertial Measurement Unit (IMU). This system tracks the tilt of the aircraft in the sky as it flies which is essential for accurate elevation calculations. Finally, the LiDAR system includes a computer that records all important feature height information that the LiDAR unit collects as it scans the earth surface.

The LiDAR aerial platform is flown over the area in which data are to be collected while the laser emits up to 25,000 pulses per second during the scanning process. The travel time of the pulse is recorded as it goes from the platform to the ground and is reflected back to the platform (round trip), along with the position and orientation of the platform to calculate distance. Figure 1 illustrates the process of LiDAR data collection.

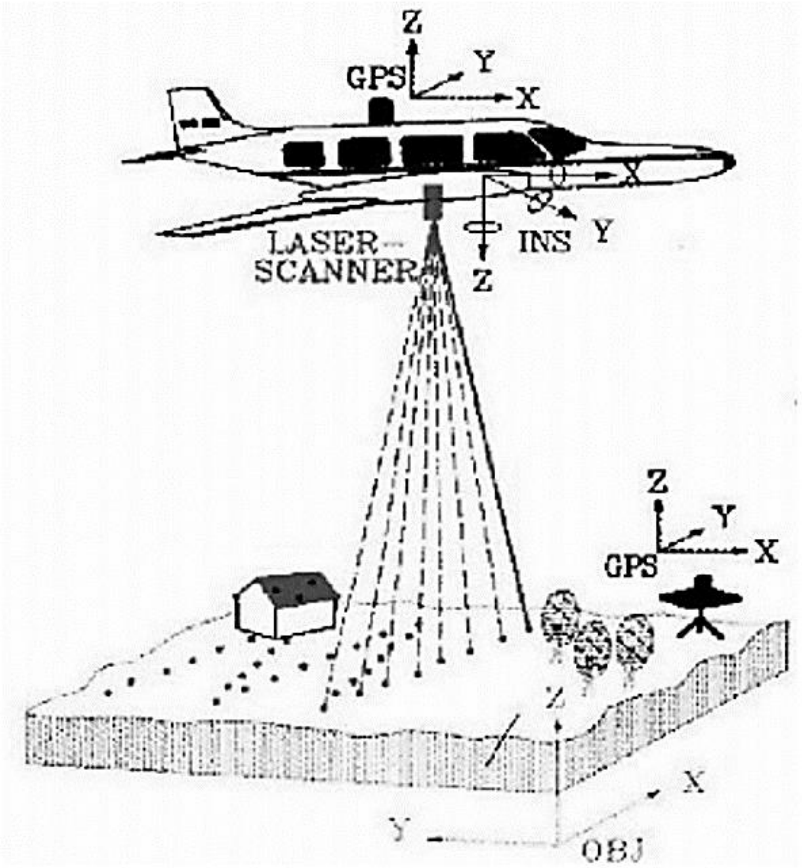

Figure 1. LiDAR Aerial Platform and Data Collection Process.

The distance between the plane and ground is calculated using the travel time and the known constant (c) for the velocity of light ($c = 3.0 \times 10^8$ m/s). The GPS receiver on the aircraft calculates the altitude of the aircraft and distance is subtracted from the altitude to equal the ground-point elevation. During the distance calculation, the tilt angle of the aircraft and laser light are both corrected to get accurate distance, allowing calculation of corrected surface coordinates X, Y, and Z. Further data processing can extract measurements of the bare ground (e.g., removal of vegetation and buildings), to create a DEM.

There are a series of steps involved in processing the LiDAR-collected data. The first step is the computation of points along the trajectory of the aircraft. Step two includes coordinate transformation and interpolation to determine the position and orientation of the sensor head at the precise time of each laser pulse. Finally, laser scanner angle and range values are used to compute vectors from the sensor to the reflective surface for each measurement and are combined with the sensor head position and orientation to obtain the coordinates of the surface points (Carter et al. 2001).

One of the primary uses of LiDAR data is to generate surface models of the earth's surface. This makes it possible to delineate physical features of the land surface on spatial scales as fine as few decimeters horizontally and a few centimeters vertically. As a result, scientists may now be able to answer important spatial questions such as the process of erosion and plate motion. This information could then be used to address various engineering issues such as mitigation of floods and landslides (Carter et al., 2001).

LiDAR Errors

The advent of LiDAR has provided a new and efficient system for producing high-resolution surface elevation data. Although LiDAR is a relatively new technology, it is not a problem-free technology. Huising and Pereira (1998) classified LiDAR errors into four broad categories including laser, GPS/Inertial Navigation System (INS), filtering induced errors, and errors caused by other problems. Laser-induced errors originate when height for the points on the surface changes at a narrow angle (ridges and ditches), and grain noise, which makes smooth surfaces like beaches appear rough (Huising and Pereira, 1998). Errors that include GPS/INS calculations occur when there is an error in equipment initialization and variances in measurements taken by the instruments. Filtering errors occur from incomplete and unwanted removal of features (e.g., vegetation and buildings), which may or may not be required in the final data. Incomplete coverage of the survey area from improper aerial flight paths and water bodies reflecting beams instead of absorbing them can produce false readings that could be the other sources of errors (Huising and Pereira, 1998)

LiDAR Accuracy

There are different methodologies available to compare accuracy between two elevation datasets. The majority of LiDAR data-collecting commercial organizations state that the vertical accuracy of their data is approximately on the order of 15 cm Root Mean Square Error (RMSE). Several studies have been conducted with varying results to examine the vertical accuracy of LiDAR data. Most of the studies on LiDAR data reported that the data were collected under leaf-off conditions (Huising and Pereira, 1998; Pereira and Wicherson, 1999; Pereira and Janssen, 1999; Shrestha et al., 2003). Past research has also studied the accuracy of LiDAR data under leaf-on conditions (Berg and Ferguson, 2001). Table 1 summarizes the results of past research on the accuracy of LiDAR data. The variations in accuracies of LiDAR data among the studies may be due to variations in laser systems employed to collect data, flight characteristics, and the terrain being surveyed. The accuracy ranged from 3 - 100 cm. In most of the studies, RMSE ranged from 7 - 22 cm.

Table 1. Comparison of LiDAR Accuracy from studies that included vegetation condition and Root Mean Square Error (RMSE) vertical accuracy values.

Study	**Condition**	**Vertical Accuracy (cm) (RMSE)**
Road Planning (Huising and Pereira, 1998)	Leaf-off	8 -15 cm (flat terrain) 25 - 38 (sloped terrain)
Highway Mapping (Shrestha et al., 2003)	Leaf-off	6 - 10 (roadway)
Flood Zone Management (Pereira and Wicherson, 1999)	Leaf-off	7 - 14 (Flat areas)
Highway Engineering (Berg and Ferguson, 2001)	Leaf-on	3 - 100 (Flat grass, ditches)

Accuracy Comparison Methodology

Direct Point Comparison

There are various methods available to compare the accuracy between two elevation datasets. Shrestha et al. (1999) employed a direct point comparison method, using a computer program to extract points from the LiDAR dataset that are within a specified tolerance of the reference points (within 1 m horizontal and 25 cm vertical). Elevation differences between the two reference points were calculated and then imported into a statistical program called SURFER to compute the accuracy statistics such as mean, standard deviation (SD), and RMSE. This method has the advantage of making a direct and exact comparison between the two datasets. The main disadvantage of this method is that the procedure is subjective regarding the tolerance around reference points from which points being compared are to be extracted and must be specified by the researcher. Specifying different tolerances may lead to greater or fewer points being identified and can produce different statistical accuracy results.

Point Interpolation

Many studies have made accuracy comparisons by interpolating LiDAR points bilinearly to photogrammetric points (or GPS points) (Huising and Pereira, 1998; Pereira and Wicherson, 1999; Pereira and Janssen, 1999). Only points on flat surfaces, such as roads, were used in order to minimize interpolation errors. The difference between the reference point and LiDAR point was used to calculate the RMSE. The main advantage of this method is that point comparisons can be made without specifying the tolerance for reference points and LiDAR points. The disadvantage is that only points from flat areas can be used for comparison. This inhibits determining the vertical accuracy of LiDAR on areas with variable slopes.

Grid Comparison

The elevation accuracy of an entire surface is very crucial for modeling surface terrain. Non-linear interpolation methods such as Inverse Distance Weighting and Spline gridding can be used for accuracy comparison in contrast to point interpolation method, where it requires an assumption of linearity. The non-linear interpolation method also assumes that points near to one another have more effect on each other than the distant points. It is possible to compare elevation between datasets throughout a study area by comparing grid cell values if grids of the same resolution can be produced for both datasets. This method makes it possible to determine the accuracy of the entire study area. The main disadvantage of this method is that it may produce a less accurate representation of surface for sparse datasets (e.g., photogrammetry); and for large LiDAR datasets, grid production can be a time-consuming process even for most advanced computers.

Statistical Test

The laser system, measurement process, and terrain can significantly affect the accuracy of LiDAR data (Pereira and Janssen, 1999). Accuracy is also affected by the acquisition and processing strategy of the vendor (Pereira and Janssen, 1999) The vertical accuracy of LiDAR data is also greatly influenced by the filtering procedures used, requiring a comparative analysis to evaluate the accuracy of a dataset. This can be done by comparing the coordinates of various points that can be located by looking at the attribute table of the dataset in ArcGIS in all of the datasets to an independent dataset of greater accuracy. In this research, LiDAR data were compared to data collected using GPS Real Time Kinematics (RTK) equipment separately. According to National Standards for Spatial Data Accuracy (NSSDA), points that represent right-angle intersection, such as roads, canals, fence lines, and curb intersections, are ideal for accuracy evaluations. However, because the LiDAR data are dense and randomly distributed, it is time-consuming, if not impossible, to identify points that correspond to such features. Instead, the point data were extracted from LiDAR-derived DEMs corresponding to RTK collected points using the “Add Surface Information” tool in ArcGIS and compared to each other to evaluate the accuracy.

National Standards for Spatial Data Accuracy

The NSSDA has outlined a statistical testing methodology for estimating the positional accuracy of digital geospatial data with respect to high accuracy georeferenced ground positions (TVA 1998). This test can be applied to any georeferenced spatial data that are derived from different sources such as ground surveys, aerial photographs, and satellite imagery. At least 20 points are required to conduct statistically significant accuracy test and is independent of the size of dataset or area of coverage (NSSDA, 1998) This number of data points allows for the computation of a 95% confidence interval, which indicates it is acceptable if one out of 20 points exceeds the computed accuracy (RMSE) value.

When certain situations dictate there are less than 20 test points available, there are three other alternatives available to determine positional accuracy (NSSDA, 1998). These include:

1) Deductive Estimates
2) Internal Evidence
3) Comparison to Source

For the accuracy comparison between LiDAR and GPS points, the NSSDA recommended methodology included the following five procedural steps:

1) Determined what accuracy (horizontal, vertical, or both) is to be tested. Vertical accuracy was tested in this research project.
2) The on-site collected GPS dataset was used as the high-accuracy independent dataset for the statistical analysis.
3) Surface information (elevation data) was extracted from LiDAR-derived DEM and appended to the GPS point dataset that already has its own elevation data (reference elevation data) collected on-site previously. The extraction was achieved using the "Add Surface Information" tool in ArcGIS.
4) ArcGIS online imagery in combination with GPS collected points were used to select manually points that fell in the grassed waterway, filter strips and bare field for comparison in ArcGIS working environment.
5) The RMSE test was used to calculate the positional accuracy statistic.

RMSE Test

As per the NSSDA guideline, the RMSE test was used to evaluate vertical accuracy. The RMSE test measures the differences between data values of higher accuracy and observed values of data to be tested and estimates a common value within group SD of the data. At least

20 or more test points are required in order to conduct a statistically significant evaluation despite the size of dataset or coverage area (NSSDA, 1998) The test statistic is calculated in equation (1):

$$\mathbf{RMSE_Z} = \sqrt{\frac{\sum_{i=1}^{n}(Z_{data\ i}-Z_{test\ i})^2}{n}} \quad \textbf{(Equation 1)}$$

Where,

$Z_{data\ i}$ = is the ground truth point of the i^{th} point in the dataset

$Z_{test\ i}$ = is the test point of the i^{th} point in the dataset

$\sum_{i=1}^{n}(Z_{data\ i}-Z_{test\ i})^2$ = is sum of squared differences between the ground-truthed data and test data

n= is the total number of points being checked

The NSSDA accuracy statistic was determined by multiplying the $RMSE_Z$ value derived from the above equation with a value that represents the mean at 95% confidence level (NSSDA, 1998) According to NSSDA, this value is 1.96. The NSSDA accuracy statistic was calculated using equation (2):

$$\text{NSSDA Accuracy}_Z = 1.96 * \text{RMSE}_Z \quad \textbf{(Equation 2)}$$

Results

The comparative analysis was conducted to determine the accuracy of LiDAR as it compared to GPS readings collected earlier in the study area. The RMSE is the most commonly used statistic to report accuracy, and will be the statistic used in the research to indicate the accuracy of the dataset. RMSE is a valuable index as it indicates the errors in the units (or squared units) of the constituent of interest which greatly helps in analysis of the result (Moriasi et al. 2007). Other statistics used in this study include the mean (the average difference of points) and the NSSDA statistic (the value that 5% of points may exceed). The accuracy test compared LiDAR points to GPS collected points and the elevations of GPS-collected points were used as controls and were compared to elevations from grids of 5m resolution LiDAR-derived DEM (Table 2). Overall, the computed RMSE value of LiDAR elevations were found to be close to the elevation of GPS control points. The accuracy value matches with the values of other previous studies as indicated in Table 1.

Table 2. Accuracy of LiDAR Compared to GPS Control.

Resolution	Dataset	Sample points	Mean Elevation Difference (cm)	RMSE (cm)	NSSDA (cm)
5-meter	LiDAR	12402	14	16	31

Geographic Information Systems

Maps and physical models have been used to study the earth's surface by scientists and engineers for many decades. However, throughout those years a need has arisen for the development of models beyond standard map data that provide an analysis tool. The Geographic Information System (GIS) is a sophisticated computer software system that is capable of querying and analyzing large quantities of geospatial data. The GIS capabilities include the following data analysis and management functions:

- Input data
- Visualize data
- Manage data
- Manipulate data
- Query and analyze data

The use of GIS can organize and present compelling ideas in developing effective solutions for different geospatial problems. A GIS is a powerful tool with capabilities to integrate various information that can be used for data analysis in areas such as natural resources, land use planning, transportation, real estate, property, and taxation. The GIS also stores information as a collection of data layers that can be linked together by a common locational component like latitude, longitude, and zip code. For example, a GIS includes world map data in distinct layers depicting oceans, continents, countries, states, and rivers. It is possible in a GIS to study the geography of the world and the chemical total maximum daily load (TMDL) of the rivers in USA separately, even though these data layers are in one geospatial dataset. The object that a particular layer depicts is called a feature that can have a set of attributes. All geographic information is managed and represented using three data structures: feature classes, attribute tables, and raster datasets. The geographic objects in GIS are represented as points, lines, and polygons. These are used to represent discrete or discontinuous features like roads, buildings, cities, and are called “vector” data. But there are other geographic phenomena such as temperature, elevation, and rainfall that are continuous in nature and “vector” data cannot effectively represent this phenomenon. These types of numerical information are referred to as “raster” data and represent geographic features by dividing the world into discrete square or rectangular cells laid out in the grid. Each cell has a value to represent some characteristics, such as temperature and elevation of that location. Data in raster form has numerical values rather than shapes, and these numeric values represent the intensity of that particular phenomena. Every point on a GIS map is referred to in the form of x, y coordinates, which is relative to an origin of that particular coordinate system. Four geographic properties are recorded for all datasets, and this information can be used to find the location of any particular cell:

- Coordinate system
- Reference coordinates or x, y location (usually the upper left or the lower left corner of the raster)
- Cell size
- Rows and columns configuration

GIS and Non-Point Source (NPS) Pollution

The section below discusses the literature reviewed to stress the importance of GIS in the field of environmental conservation, planning, and management and also to enhance the understanding of different GIS tools that can be used for watershed analysis.

Subra and Waters (1996) conducted a study using remotely sensed imagery and GIS modeling techniques to identify the areas that contributed to NPS pollution in a 32.19 km x 32.19 km section of the Calcasieu River Basin, Southwest Louisiana. The study also quantified and prioritized areas that were potentially contributing toward NPS pollution in the basin. The study used ERDAS Imagine Spatial Modeler in selecting and ranking the layers like land cover, soil type, slope, and distance that were important for the project. It was concluded that the primary source of pollution was industrial and commercial services. The results of this study recommended the use of GIS in determining appropriate locations for setting up industries and businesses and developing specific management measures to mitigate pollution.

Sieker and Klein (1998) studied the water quality of Rummelsberg Lake, Berlin, Germany, and found that effluent from the drainage systems of nearby Marzahn Hohenschonhauser – Grenzgraben (MHG) catchment (area 22 km^2) was causing deterioration of the lake water quality. The primary soil type in the MHG catchment generally had low infiltration capacity, with the exception of lesser soil types that had high infiltration capacity with high groundwater levels. Many pollution mitigation systems, like central/decentral stormwater treatment plants, were evaluated to indicate their pros and cons. A large scale model called KOSIM, a conceptual model initially developed for modeling combined sewer systems with overflows, was extended with modules to take the small size of the decentral storm water management into consideration. The KOSIM model was found to be the best in simulating the settling processes of pollution transport hydrology. They concluded that GIS spatial analysis software and techniques can be effective in simulating models of central and/or decentral stormwater management arrangements.

Dabrowski et al (2002) conducted a study over a three-year period that employed a GIS-based runoff model to validate the results of pesticides (azinphos-methyl, chlorpyrifos and endosulphan) contamination in the Lourens River watershed, South Africa. This watershed consisted of eight subwatersheds with an area of 44 km^2. The use of a GIS-based model enabled the researchers to predict the contamination considering the catchment variables, such as slope and soil type and pesticide properties such as adsorption and solubility, for each of the catchments. However, the mathematical-based model employed many variables concurrently and were found to be less accurate in their prediction. There was a positive correlation between the modeled and observed values. It was concluded that the primary reason for high pollution levels in the river was due to lack of BMPs in the watershed.

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CHAPTER 3: EVALUATING SURFACE RUNOFF FLOW INTERCEPTION EFFICIENCY OF VEGETATIVE BUFFERS IN ROCK CREEK WATERSHED USING LIDAR ELEVATION DATA

Introduction

Water can be considered the “new gold” on earth as it is essential for the survival of all living beings. It also is important for various domestic, industrial and agricultural activities. Currently, the quantity and quality of freshwater is of huge global concern due to overuse and water pollution. Consequently, there is increasing global awareness to conserve water resources. With respect to growing public concern and awareness to combat water pollution, the US Environmental Protection Agency (USEPA) legislated a law in the 1972 Clean Water Act (CWA) with a motive to conserve and enhance the surface water quality in the USA. The act made the EPA develop criteria for protecting and enhancing water quality using the latest scientific knowledge about the effects of pollutants on aquatic and human health. The act principally focused on combating point source pollution. Non-point source (NPS) pollution also defined as ‘diffuse’ pollution since it comes from many diffuse sources and is caused by water movement over and through the surface of land (Subra and Waters, 1996). A major contributor to deteriorating surface water quality is NPS pollution as it can carry a range of applied agrochemicals into surface water bodies. This has been a major environmental threat for several years.

Agricultural Best Management Practices (BMPs) include several vegetative buffers such as terraces, grass waterways, and constructed wetlands. These BMPs have been employed by the US government to mitigate the effects of pollution. One of the BMPs in use to help reduce the transportation of surface water carrying agrochemicals and sediments into water bodies is Vegetated Filter Strip (VFS) buffers. These VFS buffers generally include indigenous vegetation situated between a potential pollutant source area and a surface water body and are used to filter nutrients, sediments, pathogens, and pesticides from agricultural runoff before it reaches the water body (T.A. Dillaha et al., 1989). These vegetative buffer BMPs filter sediments by slowing down the runoff velocity and enhance settling of suspended particles such as soil and plant residue by providing an impediment to their movement. When flowing across the VFS buffer, surface runoff undergoes changes in composition and volume, entering the water bodies relatively cleaner than when it left the field (Abu-Zreig et al., 2004).

Literature Review

The effectiveness of a VFS is determined by several factors such as the VFS length, slope, and vegetation; species as well as the sediment size distribution and chemical concentration in the runoff. The length of the VFS is considered an important factor in many studies that affects the sediment removal efficiency. Several studies have shown that increasing the flow length beyond 10 m have very little effect in increasing the efficiency of a VFS (Gharabaghi et al., 2001; Lee et al., 2003; Abu-Zreig et al., 2004). A study conducted by Ree (1949) on grass filters of lengths 1, 4-5, and 10 m showed an filtering efficiency of 50-60%, 60-90%, and 90-99% respectively. Gharabaghi et al. (2001) studied the sediment removal efficiency of a VFS on varying lengths 2.44 m - 19.52 m for a 1.22 m wide field with a slope of 5.1% - 7.2 %, and concluded that the first 5 m were significant in removing suspended solids and aggregates greater than 40 μm in runoff. The experiment conducted by Abu-Zreig et al. (2004) in 20 fields with filter lengths of 2, 5, 10, and 15 m and slopes of 2.3% - 5 % concluded that there is no significant increase in sediment removal efficiency greater than a 10 m VFS length. The ratio of the cropland drainage area to VFS area (Area Ratio) is one of the important factor that affects the efficiency of VFS. Greater area ratio allow large volume of flow through smaller sections of VFS thus lowering the efficiency of VFS in filtering the pollutants and sediments from runoff. Past studies like Arora et al (2001), Leeds et al (1993) suggest that area ratio between 1:1 – 8:1 can achieve excellent sediment retention. According to Leeds et al (1993), area ratios should be maintained less than 50:1 for good sediment retention.

Many studies have suggested that infiltration is the primary mechanism responsible for trapping the suspended solids and applied chemicals (Ree, 1949; Meyer et al., 1995; Gharabaghi et al., 2001). The submergence of vegetation also can result in a decrease in Manning's coefficient (n), which in turn decreased the efficiency of a VFS greatly (Ree, 1949; Van Dijk et al., 1996). The flow retardation and infiltration were more efficient with older grass species (Van Dijk et al., 1996) since this denser vegetation provided more resistance to flow velocity, resulting in an increased contact duration between runoff and vegetation. Consequently, this lead to less erosive power and transport capacity of the runoff, resulting in an increased VFS sediment trapping efficiency.

Sediment size distribution is also an important factor that determines the efficiency of a VFS. Studies have concluded that smaller-sized sediments require a longer settling time, therefore requiring a longer vegetative filter length (Meyer et al., 1995; Gharabaghi et al., 2001). In a study conducted by Abu-Zreig (2001), trapping efficiencies of 0% and 47% were observed over filter lengths of 1 m and 15 m, respectively, for clay particles. Lee et al. (2003) conducted an experiment to study the effectiveness of a multi-species riparian vegetative buffer in removing NPS pollutants from cropland runoff. The experiment involved installing three plots where each of the cropland source areas was matched with no buffer (control), a 7.1 m switchgrass buffer and 16.3 m switchgrass/woody plant buffer. Sediment removal efficiency of 95% and 97% were observed for switchgrass and switchgrass/woody plant buffers, respectively. The increased sediment removal efficiency of the switchgrass/woody plant buffer was determined to be the additional vegetative buffer length that increased infiltration. The ratio of sediment transported through the “control” plot to sediment transported through the switchgrass buffer was 13:1. Particle size distribution in surface runoff changed as runoff passed through the VFS buffer. In this case, large particles were deposited prior to small particles, and more than 90% of the sediment in surface runoff from the buffered plots was in the <0.05 mm size fraction. During the infiltration of nutrients, suspended fine particles with adsorbed chemicals also entered the profile, thus decreasing the surface runoff and sediment transport capacity. It was concluded that there are major functional differences between narrow grass filters and wider mixed grass and woody plant buffers.

The performance of VFS buffers in removing pollutants from runoff also largely depends upon the type of flow. Factors like concentrated flow or a non-uniform distribution of flow limit the performance of a VFS. Generally, a uniform flow distribution (sheet flow) helps to achieve high pollutant removal efficiencies. Undulating surfaces and slopes >6% caused concentrated flow, erosion and decreased sediment removal efficiency of the VFS buffer. When flow is concentrated, the velocity of runoff becomes too high to be effectively treated by a VFS. Dosskey et al. (2002) found that concentration of surface runoff from agricultural fields can significantly restrict the efficacy of riparian buffers to remove pollutants. Riparian buffer evaluation plots on four farms were used to study the influence of surface runoff on sediment trapping efficiency. A numerical model using a regression equation based on the proportion of buffer area to contributing field runoff area (buffer area ratio) was used for evaluating the sediment trapping efficiency. The model yielded sediment trapping efficiencies of 99%, 67%, 59%, and 41% for uniform flow conditions and 43%, 15%, 23%, and 34% for non-uniform flow conditions for the four fields, respectively.

Another factor that largely determines the efficacy of a VFS buffer is the area ratio. It is the ratio of drainage area to buffer area. Greater amounts of flow are forced through a VFS buffer in the case of a larger area ratio which makes the VFS less effective during large rainfall events. This is because the effective area of a VFS buffer becomes substantially less than the gross area. Although studies have shown that higher area ratios tend to lower the sediment removal efficiency, there wasn’t a significant difference in the performance of the VFS buffer (Arora et al., 1996; Arora et al., 2003).

Objectives

- The primary objective of this project was to assess the performance of existing established VFS by modeling and analyzing the flow accumulation from the field in the VFS, with the help of GIS and LiDAR derived DEM by developing and using Coefficient of Flow Interception (CFI).
- The second objective of this study was to evaluate the accuracy of LiDAR generated DEM in comparison to on site collected, ground trothed elevation data.

Description of Study Area

This study focused on three agricultural sub-basin field sites located in Rock Creek watershed, Jasper County, Iowa, USA (41° 46.211’ N, 92° 50.330’ W). This watershed drains into Rock Creek Lake, which is a major recreational attraction for residents of central Iowa. The water quality of Rock Creek Lake is at risk due to incoming sediment and nutrient transport into the lake via contributing agricultural field surface runoff and stream channel flow. There has been a recent algal bloom in the lake due to erosion and chemical transport from the watershed, causing low oxygen levels and a deleterious effect to the aquatic life of the lake. These same three sub-basin field sites were also the subject of a previous MS thesis research project (Bansal, 2006) based on the established VFS buffers designed by the Natural Resources Conservation Service (NRCS). The VFS buffers in these sites have been established for over ten years, and will be identified as sites 1, 2, and 3.

Site 1 has a stream running through the center of the field and contributes to Rock Creek Lake. A VFS buffer at the downslope of the field of approximately 35 m wide has been established on both sides of the stream as per the Natural Resources Conservation Services (NRCS) design guidelines in the year 2000. The main purpose of these VFS is to help reduce the nutrient, agrochemicals and sediments transportation from the runoff. The field follows the traditional Iowa corn-soybean rotation. The major soil association at the research site is the Downs-Tama-Shelby association with silty, silty clay, and loamy soils formed in upland loess and glacial till. Dominant soils at the site are Tama silty clay loam, a fine-silty, mixed, mesic Typic Argiudolls and Ackmore silt loam, a fine-silty, mixed, nonacid, mesic Aeric Fluvaquents. Minor soils at the site include Colo, Ely, and Ackmore-Colo complex (Nestrud and Worster, 1979).

Table 3. Selected dominant soil type data, descriptive information, and physical properties at the Rock Creek Watershed research sub-basin field sites 1, 2, and 3 (Nestrud and Worster 1979).

Research Site Dominant Soil Type Data and Descriptive Information					
Research Site	Soil Series	Soil Description	Bulk Density $g\ cm^{-3}$	Clay %	Permeability $cm\ hr^{-1}$
1	Tama	Fine-silty, mixed, mesic Typic Argiudolls	1.40	18-26	1.5-5.1
2	Ackmore	Fine-silty, mixed, mesic Aeric Fluvaquents	1.35	28-32	1.5-5.1
3	Ackmore-Colo Complex	Fine-silty, mixed, mesic Aeric Fluvaquents; Fine-silty, mixed, mesic Cumulic Haplaquolls	1.35	20-26	1.5-5.1

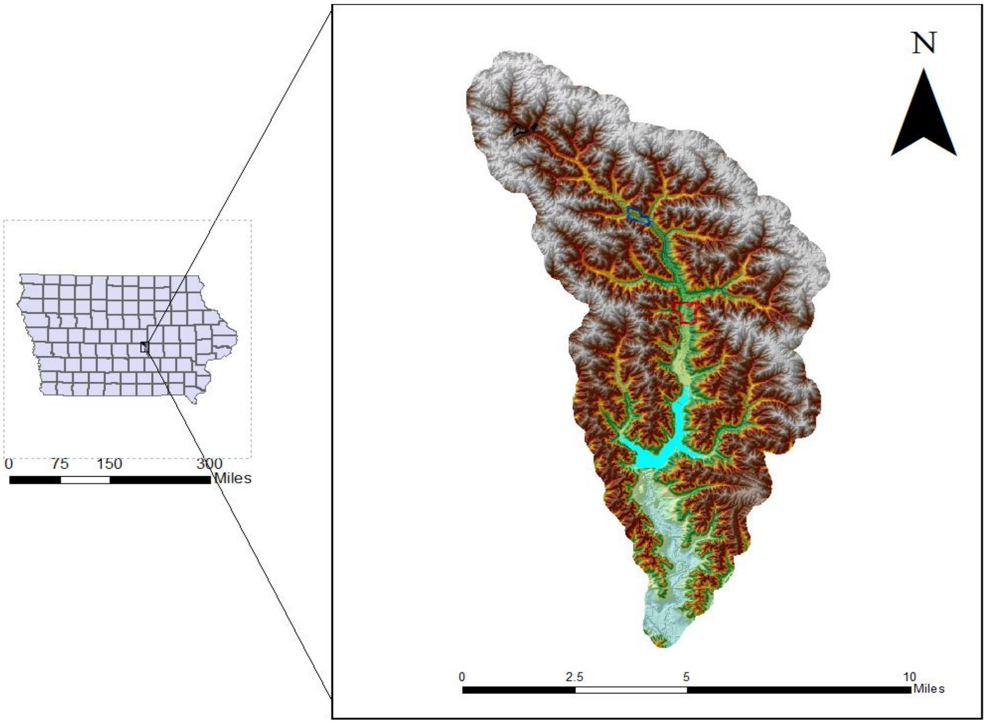

Figure 2: Location of Rock Creek Watershed and field research sites 1, 2, and 3 in northeast Jasper county, central Iowa USA.

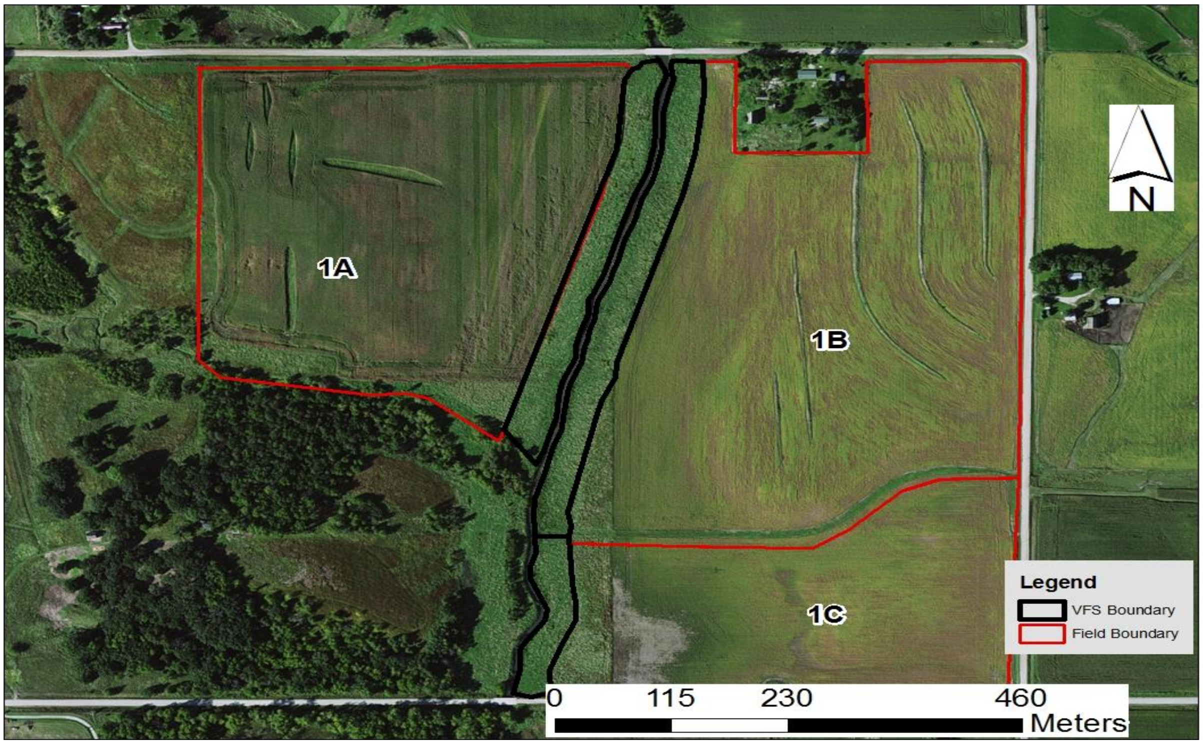

Figure 3: Field site 1 layout depicting sub-basin boundaries and drainage features

The infiltration rate for these soils ranges from 1.5-5.1 cm/hr (Nestrud and Worster, 1979). The farmer has adopted BMP techniques such as terraces and grassed waterways. The field has row cropping with corn – soybean rotation. The field is divided into three sub-watersheds 1A, 1B and 1C as shown in figure 3. The width of buffers ranges from 33 m – 35 m and the field hasslope between 3% - 7%.

During the visit to sub-basin field site 1A, there were some undulations observed in the field surface, and the flow was towards the south of the watershed instead of draining into the filter strips. From the site verification, some traces of sedimentation also were observed at the leading edge of the VFS buffer which would only be possible during a larger rainfall event as the topography of the field shouldn’t allow surface flow to be towards the VFS buffer.

The second field site “2” is located north of site “1” as shown in figure 4 below. It also has a stream running through the field and divides the field into two sub-basin fields, namely 2A and 2B. An approximately 18 m wide VFS was installed at the edge of the field on both sides of the stream. Shelby, Tama, Ely, Ackmore and Downs are the types of soil found on the field. The soils fall under the hydrologic group B. These soils mainly consist of silty clay loam, loam and silt loam. The farm is under row cropping with corn – soybean rotation. During the field visit, it was evident that surface flow entered through the VFS buffer. The average slope of the field is between 2% - 5%. The adjacent cropped fields used no-tillage practices.

Field site “3” is shown in figure 5 below and has approximately 30 m-wide VFS buffers on both sides of the stream. The field has grassed waterway of up to 18.3 m. The common soil types in the field are Tama, Shelby-Adair complex, and Ackmore-Colo complex. These soil types fall under hydrologic group B and C. The farm is under row cropping with corn – soybean rotation. This site consists of three sub-watersheds, with two sub-basins adjacent to each other while the other sub-basin is to the northwest. The average slope of the field is between 9% - 11%.

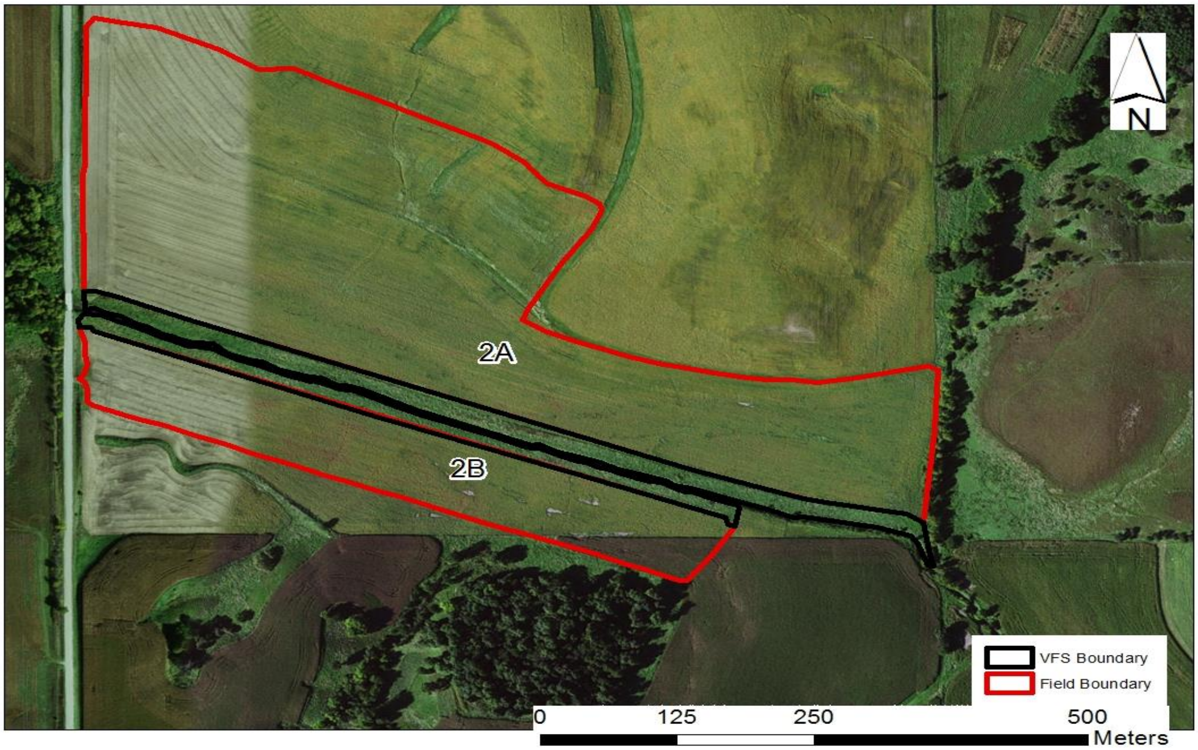

Figure 4: Field site 2 layout depicting sub-basin boundaries and drainage features

Methodology

Geographic Information System was used to validate spatially visual observations regarding surface flow and outlet points in field sites 1, 2, and 3. A Digital Elevation Model (DEM) of 5 × 5 m resolution, derived from LiDAR points, was used to model the topography of Rock Creek Watershed. Elevation data stored in the DEM also was used to determine flow routing in the fields using ArcGIS version 10.3 and validate the visual observation regarding surface flow interception of the VFS buffer, and later quantify VFS buffer interception efficacy using Coefficient of Flow Interception (CFI) in equation (3):

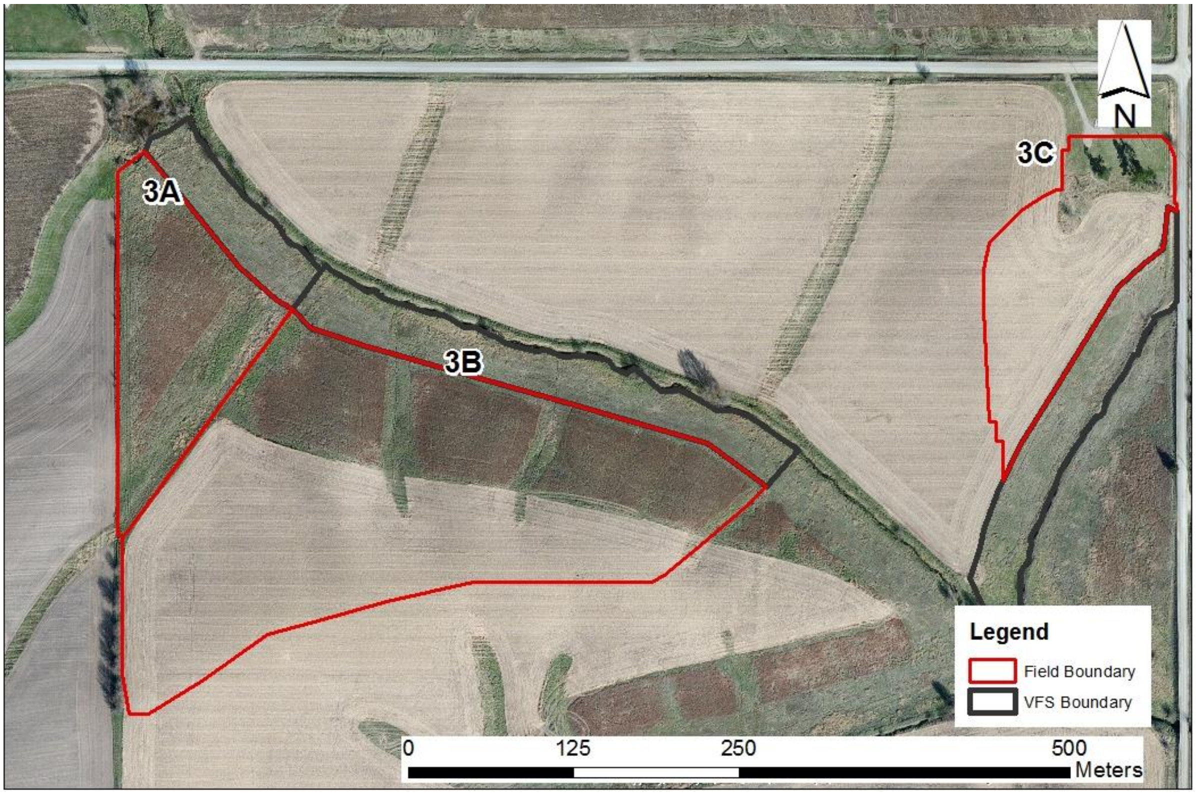

Figure 5: Field site 2 layout depicting sub-basin boundaries and drainage features

$$\textbf{CFI} = \frac{\textit{Total Area of VFS}\ (m^2)}{\textit{Drainage Area of Flowpaths intercepted}\ (m^2)}\ \textbf{(Equation 3)}$$

The contributing drainage area and total VFS area are calculated using ArcGIS tools and the CFI value could be between 0.0 – 1.0. The CFI can be calculated only for those contributing drainage areas whose flowpaths pass through the VFS buffer. To determine whether the flowpath is intercepted by the VFS, the flowpath obtained from the DEM is overlaid on ArcGIS online basemap for visual observation and also intersecting the flowpath with VFS boundary in ArcGIS.

The DEM was also used in identifying sinks in the topography and generate the flow accumulation and stream network/flowpaths in the watershed using the elevation data. The contributing runoff drainage area was determined by using the automatic delineation tool in

ArcGIS. The VFS area has been calculated by digitizing over a base map for each sites using ArcGIS online images in ArcGIS.

Area Ratio/CFI Calculation and Analysis Stepwise Procedure

Step 1. Area Ratio calculation

$$\textbf{AR} = \frac{\textit{Drainage Area of all Flowpaths}\ (m^2)}{\textit{Total Area of VFS}\ (m^2)} \qquad \textbf{(Equation 4)}$$

Step 2. Comparison of AR value to standard AR values (Bansal, 2006)

I. Excellent AR, 1:1 – 8:1
II. Good to Fair AR, 8:1 – 50:1
III. Poor AR, >50:1

Step 3. Calculation of CFI = 0.0-1.0 (equation 2) for vegetative buffer interception performance.

Sample Calculation for Site 2

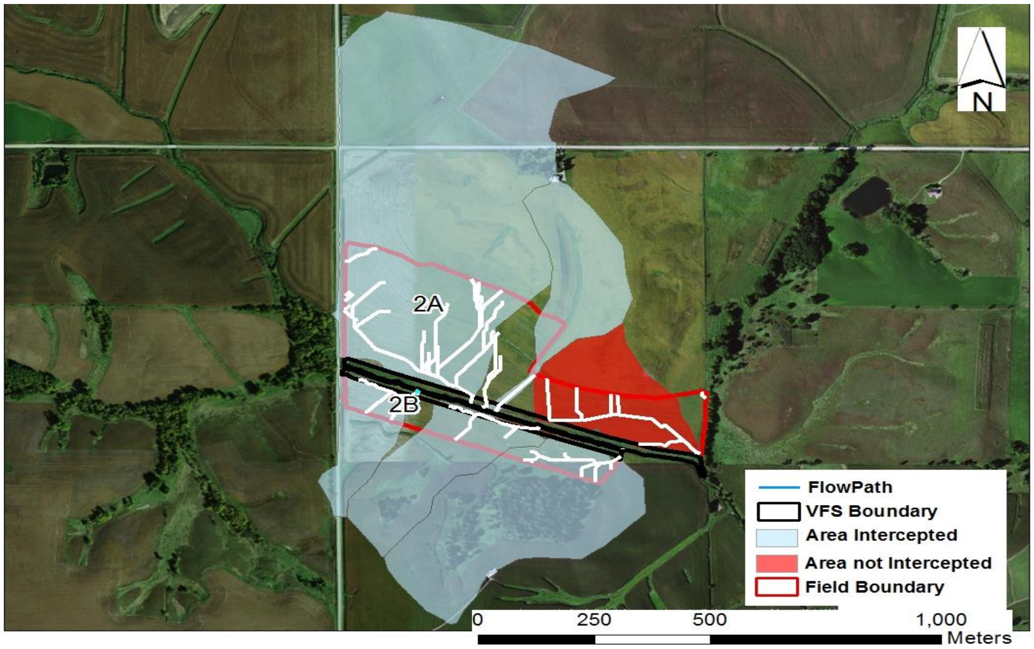

Figure 6: Site 2A and 2B with Watersheds

Here,

<u>For 2A</u>

Total drainage area = 463190 (area in light blue) + 69290 (area in red) = 532480 m^2

Effective Drainage area = Area intercepted (in light blue) = 463190 m^2

Total Area of VFS = 16975 m^2

CFI = 16975/463190 = 0.04

<u>For 2B</u>

Total drainage area = Effective drainage area = 248570 m^2

Total area of VFS = 9970 m^2

CFI = 9970/248570 = 0.04

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CHAPTER 4 RESULTS AND DISCUSSION

The average of the difference in elevation data between LiDAR generated DEM and DEM generated from onsite collected data was 14 cm with RMSE of 16 cm. The vertical accuracy of LiDAR generated DEM was found to be 31 cm using NSSDA method.

The site 1 research area is divided into three sub-basins 1A, 1B, and 1C. The flowpaths for the site were delineated to evaluate the effectiveness of a VFS buffer. The 5 x 5 m DEM-generated flowpaths were in correspondence with visual observations conducted during site visits in 2013 and 2014. Figure 6 indicates no simulated surface flow through the VFS. Due to the surface undulations present at the field site, flow was re-directed towards the south of the watershed instead of passing through the VFS. There were signs of some sedimentation at the leading edge of the VFS, which could be attributed to the runoff originating due to larger rainfall events.

During site verification for sub-basins 1B and 1C, it was observed that sedimentation occurred at the downslope end of the grassed waterway present between the two sub-basins. These results indicate that surface runoff was diverted to an alternate flowpath from the grassed waterway during high rainfall events. Figure 6 shows how surface runoff was diverted from the full length of the grassed waterway in sub-basin site 1C. This surface flow was also observed to become more concentrated as it approached the VFS.

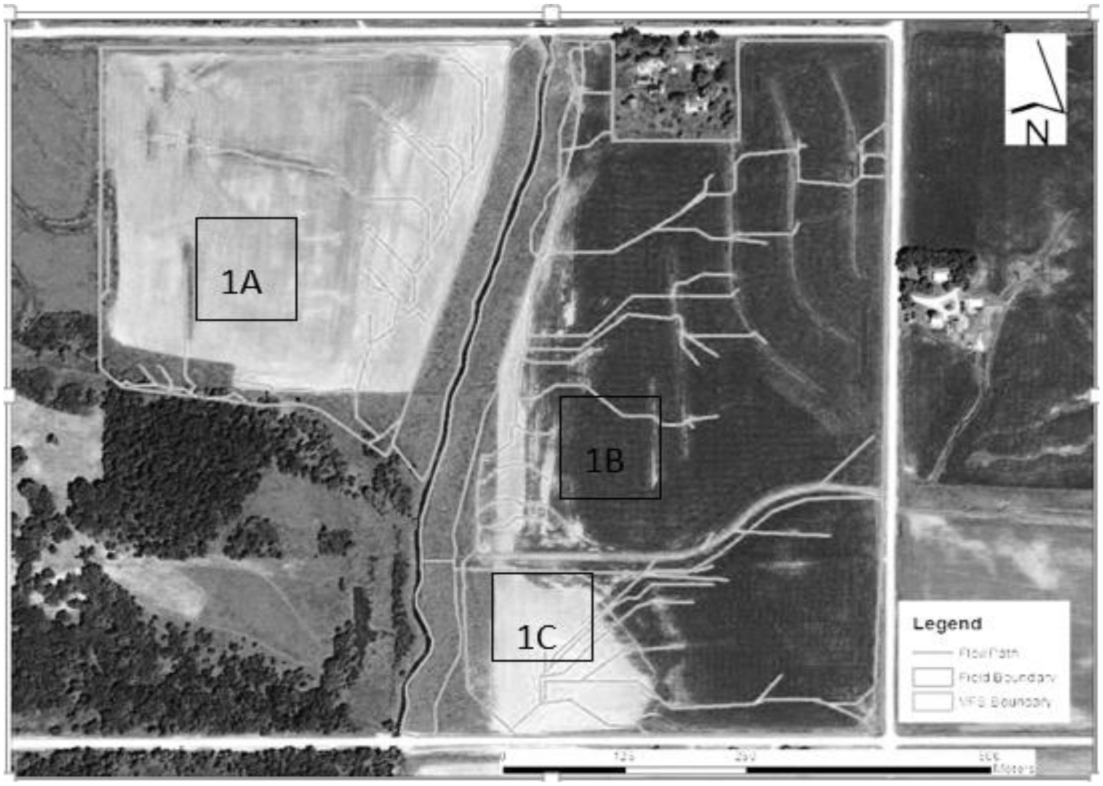

Figure 7: Rock Creek Watershed Site 1 surface flowpaths generated by 5 x 5 m DEM.

Site 2 was divided into two sub-basins 2A and 2B. The surface flowpaths modeled from the 5 x 5 m DEM indicated they passed through the VFS at many locations as shown in figure 7. This corresponded to visual observations made during the field site visits. The simulated surface flowpath pattern suggests that the flow in this site is more dispersed but does become more concentrated as the flowpath approaches the VFS buffer.

Site 3 consists of three sub-basins 3A, 3B, and 3C.Sub-basin sites 3A and 3B are adjacent to each other, with sub-basin 3C located in the northeast corner of the field site map as shown in figure 3. Note that all simulated surface flowpaths pass through the VFS buffer area. However, site observations for this field could not be conducted because permission could not be obtained from the landowner. When surface flowpaths are overlaid to the ArcGIS online imagery, the flowpaths tend to follow the grassed waterway drainage feature.

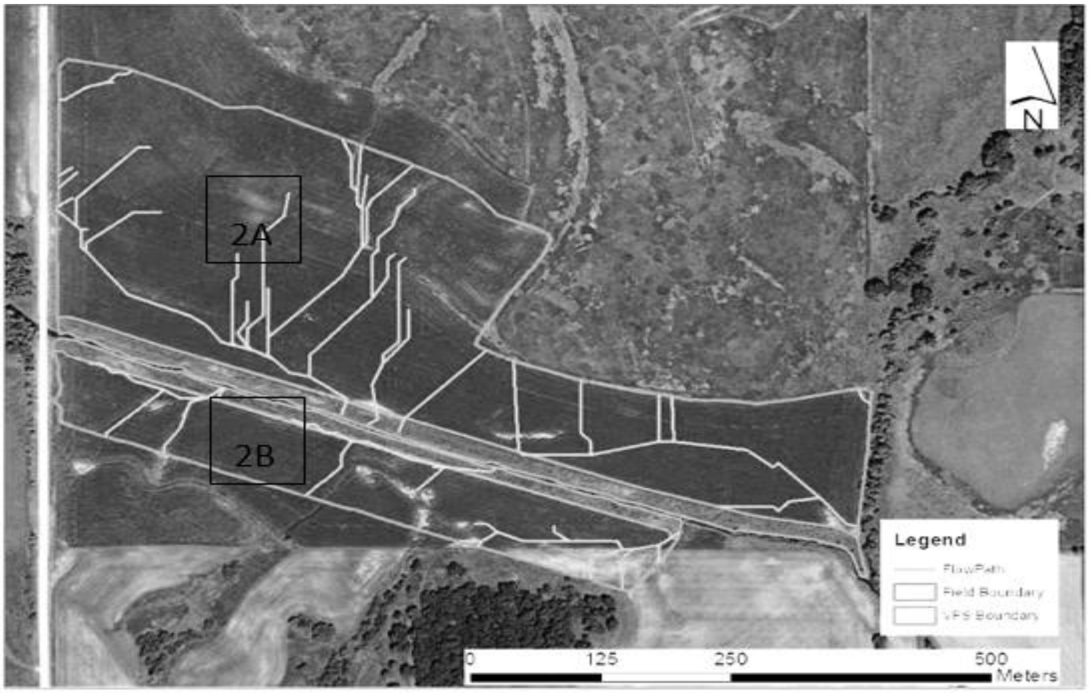

Figure 8: Rock Creek Watershed Site 2 surface flowpaths generated by 5 x 5 m DEM.

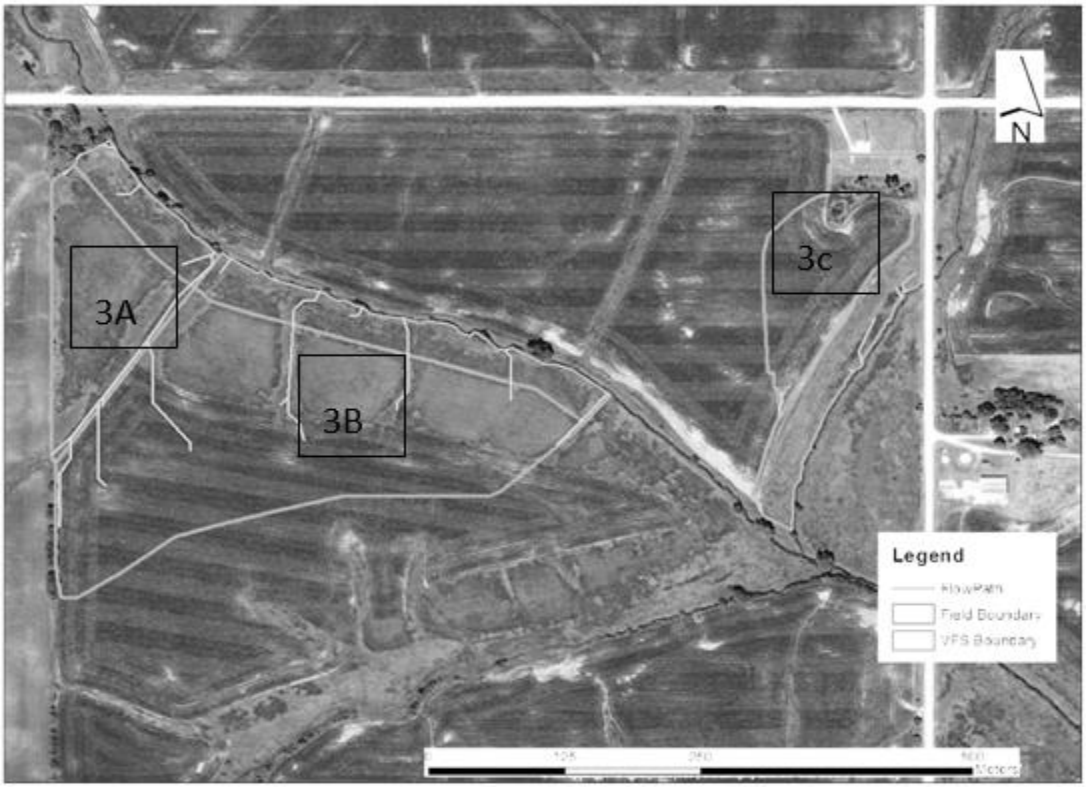

Figure 9: Rock Creek Watershed Site 3 surface flowpaths generated by 5 x 5 m DEM.

This indicates that the simulated flowpaths are generally representing the actual hydrologic landscape conditions at the research site. Some of these hydrologic conditions are quantified as Area Ratio (AR) and Coefficient of Flowpath Interception (CFI) values in table 4.

Table 4. Area Ratio (AR) and Coefficient of Flow Interception (CFI) value of the sites

Site	Sub-basin	Contributing Area of flowpath (m^2)		VFS Area (m^2)	AR	CFI	CFI Range	Efficiency
		Total	Effective					
1	A	203070	0	17595	11.54	No value	Excellent: 0.125 – 1.000 Good to Fair: 0.02 – 0.125 Poor < 0.02	Poor
	B and C	684110	0	27780	24.63	No value		Poor
2	A	532480	463190	16975	31.37	0.04		Lower range of good to fair
	B	248570	248570	9970	24.93	0.04		Lower range of good to fair
3	A and B	114010	114010	19860	5.741	0.17		Excellent
	C	12960	12960	11230	1.154	0.87		Excellent

Discussion

It is apparent from table 4 that some of the sites have Area Ratio that are fairly good but the CFI values are lower. In an ideal situation the CFI values must be equal to the reciprocal of AR values. Here in some situations the values of CFI are a bit higher than the reciprocal of their corresponding AR this is because the effective contributing drainage area of the flowpath intercepted by VFS is less than that the total contributing area. At sites where CFI values are greater than the reciprocal of AR, some of the flowpaths is not intercepted by the VFS and run-off takes some alternate route to reach the nearby water sources without getting filtered. When the LiDAR DEM derived flowpath were draped on the ArcGIS online basemap for site 1 sub-watershed 1A, it is quite obvious that none of the flowpath passed through the VFS. This is also validated during the site visit. At site 2 and 3 the flow is not as concentrated as site 1. Most of the flowpaths pass through the VFS. The contributing area of the flowpaths passing through the VFS is less than the total drainage area. From the study it is clear that the flow can get concentrated at some location other than VFS and not necessarily the flow gets all the way up to VFS.

The flowpath obtained using 5m resolution LiDAR generated DEM in this research is very much consistent with research conducted by Bansal (2006) where she used DEM generated from NRCS collected 5m × 5m data. The vertical accuracy of the LiDAR generated DEM data was found to be 31 cm which is very much similar to other studies.

Summary and Conclusion

The research work was performed using ArcGIS and LiDAR points generated DEM. The resolution of DEM used for the research is 5m × 5m. VFS buffers are key elements in reducing pollutants from runoff water and have been used for more than two decades. From the study, it can be concluded that the current classic design of VFS along the length of an agricultural field does not adequately address the non-uniform flow through the buffer. Out of 8 sub-watersheds only three have excellent CFI values. New technologies such as high-resolution DEM data and ArcGIS can be used to aid in better designing VFS buffers and finding the optimal location for VFS buffers. The research can be extended to other watersheds too. The research can be used for finding the optimal location for installing VFS buffers rather than just at the edge of the farm as is practiced nowadays.

The high-resolution LiDAR derived DEM data can be used to model better the flowpath generated due to runoff from agricultural land and determine whether the flow is intercepted by the vegetative filter strips (VFS). Using this proposed research approach, there is potential to improve the design and landscape placement of new and existing VFS buffers, allowing them to function more effectively in reducing sediment and nutrient transport from agricultural land into adjacent streams and water bodies.