NON POINT SOURCE POLLUTION WITH SPECIFIC REFERENCE TO THE MKABELA CATCHMENT

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DISCLAIMER

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from January 2005 to December 2007, under the supervision of Professor S.A.Lorentz.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others it is duly acknowledged in the text.

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ABSTRACT

Non point source pollution (NPS) has long been the negated form of pollution within our natural systems. With an increase in the demand for quality crops and staple foods, there have been added pressures on water systems to cope with increasing NPS pollution (NPS-P).

The effect and importance of scale on the assessment of NPS pollution has been identified as a pivotal component in the assessment of such pollutants, in particular the translation of processes from a field to a catchment scale. It has therefore become important to further investigate and research the processes involved in transporting and retaining pollutants at each measurement scale.

A number of models have been developed for simulation catchments, however none of the suitably address the issue of NPS pollution and the translation of processes from the field through to the catchment scale. Each model researched fails to effectively address processes over varying scales, and tend to concentrate on a particular scale of observation. There is a distinct lack of a capable mechanism that assesses NPS pollution across varying scales within a catchment.

The *Water Research Commission (WRC) NPS-P* project aims at eventually developing a successful model that addresses the issue of assessing NPS pollution across a number of different scales. This study aimed at assessing the loads of sediments and nutrients at different scales and included the establishment of a research catchment in the Mkabela Catchment outside Wartburg in KwaZulu-Natal, and the collection and interpretation of rainfall, runoff and nitrate data for a full year of sampling. The sampling provided valuable data for the calculation of pollutant masses and concentrations within the Mkabela Catchment. Non Point Sources are generally more dilute with suspended solids and nitrate in particular tending to have a high transport dependence upon summer events with a high intensity and low duration.

A varying degree of scales were monitored during this study, ranging from plot to catchment scale in order to assess the varying influences on NPS Pollution (Nitrate and Suspended Solids). Monitoring was conducted through research mechanisms ranging from runoff plots at the plot scale to catchment scale flumes.

It was found that scale has a varying influence on NPS pollution, with pollutant concentrations measured to be at a maximum at the field scale, with a value of 13.54mg/l of nitrate measured within the cane fields from event 3. Suspended solid values taken from within the water samples were most apparent at the plot scale, within the runoff plots, with a maximum of 2866.7mg/l measured during event 3 as well. It was evident from measurements and results obtained for each of the 10 sampled events that the main influencing factor of the nitrate concentrations and suspended solid values was the nature of the event. Summer rainfall events (high intensity and short duration) provided large overland flow volume that contributed largely towards the high concentrations of both nitrate and suspended solids, whereas the winter rainfall event (low intensity and long duration) contributed little to the concentrations of nitrate and suspended solids.

In contrast to nitrate concentration, the largest nitrate loads by mass were measured during event 1 at the large catchment scale (Bridge 2), with a total cumulative load of 74.17kg nitrate estimated to have been yielded at the catchment outlet. The majority of nitrate are yielded from the agricultural lands where farming practices lead to the application of chemicals pre-planting and post emergence. Suspended solids displayed a similar trend to that of nitrate, with an increasing cumulative yield measured throughout the catchment, resulting in a total 13414kg of sediment being measured at Bridge 2. It is interesting that Event 1 measured the largest cumulative loads for both nitrate and suspended solids; however it was recorded as an average intensity event (19.1mm/h) in comparison to the largest sampled intensity event of 165.9mm/h (Event 4) during the study. This may be attributed to the fact that the event coincided with the planting schedule of the sugarcane crops, and so the bare nature of the agricultural fields resulted in increased overland flow, and hence nitrate and suspended solid transportation.

Data collected during all the events clearly show that the impoundment (a farm dam) acts as a water quality filter by retaining many of the nitrate pollutants when they enter the dam as channel flow.

In summary, the controlling processes governing NPS-P movement varied through the differing scales, with crop size, artificial chemical application, nature of the event and timing during the year all contributing in varying manners at the differing scales.

Future research within the *WRC-NPS-P* project should continue with sampling from the designated research points and add several more seasons of data to the already comprehensive first season of sampling. In addition, once a reasonable number of seasons have been sampled and analysed within the Mkabela Catchment, the initiation and development of an effective, representative scaled NPS-P model that addresses the movement and retardation of pollutants is necessary to be able to successfully model and predict the movement of NPS-P through catchment systems. In particular the effects of the controls afforded by such features as road crossings, wetlands and farm dams should be taken into account in the modelling of sediment and nutrient movement from field to catchment scale.

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1. INTRODUCTION

Non-point source (NPS) pollution has long been disregarded and underestimated as a substantial contributor to water quality (Pegram and Gorgens, 2001). Water quality has primarily been concerned with immediate, direct impacts such as point source pollution, and has thus largely ignored the effects of NPS pollution which is a less direct, less immediate source of pollution, yet may be just as degrading on the water resource. The latter half of the 20th Century has seen farming transformed quite considerably. Production rates have increased largely to meet the demands of a growing population throughout the world. Deforestation and soil erosion have increased as a result of changes in land use and large-scale irrigation and, as a result, traditional farming practices have often been replaced by intensive monoculture. The modern changes in agriculture have thus resulted in increases in NPS pollution from monoculture (and hence an increased reliance on chemical fertilizers and pesticides). This, coupled with an increase in the number and concentration of livestock (resulting in animal wastes becoming a problem rather than a resource), have lead to such increases in NPS pollution. Although agro-industrial practices are continually being rethought, with sustainability now a key concept, agricultural NPS pollution needs to be addressed as a priority.

There has recently been a greater understanding and acceptance of the importance that NPS pollution plays in the overall study of water quality (as opposed to point source pollution), and so an increase in time and effort has been placed upon the quantification of the sources of NPS pollution. Such pollutants include sediments, pathogens, nutrients (leading to eutrophication), salinity and pesticides and the sources include fertilizer application, erosion and animal waste. All of these sources are common to agriculture, and hence agricultural practices need to be further understood through the consideration of processes such as pesticide and nutrient application, local scale runoff characteristics and the movement of nutrients and pollutants through the soil profile. Scale is particularly relevant in such studies. In order to effectively assess the translation of processes from one scale to the next, the mechanisms at each scale need to be addressed. Local scales generally define a point, and have strong relations with the field scale. Within the field scale, hillslope processes and lateral movement mechanisms are vital in order to define hillslope scale relationships. Furthermore, small and large catchment scales combine several processes that control the smaller scales. The key to modelling such larger scales is the ability to accurately translate processes from a smaller scale to a larger scale. In doing so, we may be able to better understand and predict the effects of NPS pollution on water quality and related issues, such as the ability to locate the local source of NPS pollution based on observed poor water quality at the catchment scale.

Issues of scale are of particularly relevance to modern science and problem solving. Problems are often scale specific, and so an understanding of dominant processes at different scales is vital. In order to identify sources of NPS pollution at a catchment scale, it is important to understand and be able to quantify the transfer mechanisms that occur when translating from field to receiving stream to large-scale catchment. It has therefore become particularly important to be able to not only better understand the effects of NPS pollution, but to understand particularly smaller field scale effects and impacts. Several catchment and field scale models exist. These models generally provide users with representative mechanisms through which specified catchment processes may be modelled on a catchment scale. A notable absence in current modelling packages is the lack of understanding regarding the translation of processes from one scale to the next. Lorentz (2005) suggests that there are several excellent profile (local) scale models, as well as good field and catchment scale models. However, their integration and the translation of mechanisms between these scales is an issue that requires greater attention. This translation is a vital component of NPS pollution if one wants to identify and assess the impact of sources on streamflows and the effect of remedial measures.

The key question involved in such a study relates to the translation of processes and mechanisms from one scale to the next. Catchment models have been favoured over field scale models. These models are based on field data that are translated and lumped to represent catchment characteristics, and hence a catchment model is produced. This has been widely accepted as a method through which catchment scale models have been developed.

Water quality is seldom assessed on a field scale. Generally speaking, measurements are made in major river basins at the catchment scale, and assumed to be representative of that whole catchment. This method is acceptable, provided that the catchment is the scale at which results are being utilized. It is, however, unacceptable to assume that such results are evenly distributed over the entire catchment. Catchment modelling relies largely on the relationship between surface and subsurface processes and that is, therefore, key to defining the hydrological processes that may regulate the movement of NPS pollution. It therefore becomes vital to be able to identify, quantify and model such processes in order to more fully understand the paths that NPS pollution takes from the crop (field scale) through to the main river channel (catchment scale) and within the river channel.

A current NPS pollution study at the University of KwaZulu-Natal aims at investigating the translation relationships that exist between processes and mechanisms at different scales from field to catchment. It is funded primarily by the Water Research Commission (WRC) and is being conducted under the supervision of Ninham Shand Incorporated and academics from institutions across South Africa. The initial hypothesis for the project is that sediment, nutrient and pesticide transport (NPS pollution) is largely event-based (Lorentz, 2005).

This study aims to investigate, define and describe the issues related to NPS pollution and associated scaling issues. Scaling and the translation of processes from one scale to the next forms the crux of the overall NPS-P study as well as this literature review. Additional issues addressed through this document will concentrate on a review of four water quality and touch partially on NPS pollution models, namely CREAMS, SWRRB, BASINS and SWAT. These reviews concentrate on the respective models’ strengths and weaknesses in performing NPS-P modelling for specified scales, and their strengths in translating processes from one scale to the next.

2. WHAT IS NON-POINT SOURCE POLLUTION (NPS-P)?

This section defines the concept of Non-Point Source Pollution and reviews the factors affecting NPS-P as well as methods for assessing and remediating NPS-P.

2.1 Origin and Definition

To effectively define NPS pollution, one needs to consider the National Water Act (Act 36 of 1998: 1xv), which defines pollution as:

"alteration of the physical, chemical or biological properties of a water resource so as to make it:

- *less fit for any beneficial purpose for which it may reasonably be expected to be used, or*
- *harmful or potentially harmful*
    - *to the welfare, health or safety of human beings;*
    - *to any aquatic or non-aquatic organism;*
    - *to the resource quality; or*
    - *to property."*

For the purpose of this study, NPS-P will be considered as anything that changes the quality of the water within the Mkabela Catchment whether it be physical, chemical or biological, with specific reference to differing scales that apply within the catchment and their varying effects on NPS-P.

The exact pathways that NPS pollution follow are somewhat vague, although it is generally believed and assumed that it results from atmospheric deposition, precipitation, surface runoff, interflow, drainage, seepage, groundwater flow or river course modification (Pegram and Gorgens, 2001). Simply defining NPS pollution as all sources not classified as point sources is inadequate, as there is no real definition of point sources within the National Water Act either. Pegram and Gorgens (2001) therefore offer their own definition of point sources as "*discernable and confined sources of pollution that discharge from a single (point) conveyance, such as a pipe, pitch, channel, tunnel or conduit.*" Furthermore, NPS may be diffuse/intermittent or concentrated. Diffuse NPS pollution contributes to the contamination of water resources over a large area, and derives largely from agricultural runoff. Concentrated NPS-P, according to Pegram and Gorgens (2001), is largely associated with localised activities such as mining, feedlots, landfills and industrial sites, however for the purpose of this study, these sources are not considered to be NPS-P generators. Impacts in terms of NPS pollution are varied. Surface and near surface runoff sources (i.e. streamflow) are relatively immediate, whereas impacts originating from groundwater discharge are often delayed as a result of to the time taken for contaminants to move through the soil and geology.

2.2 Factors Affecting NPS-P Monitoring and Assessment

2.2.1 Water quality

Pegram and Gorgens (2001) identify four elements of water quality pollution that they believe form the backbone for water quality monitoring and assessment. These elements cover the mobilisation (i.e. movement), impacts and effects of contaminants.

- **Production**: refers to the production of the pollutant, usually at the source, and includes generation, deposition, application and the natural availability of pollutants. Such processes therefore include variables such as mobilisation and attenuation.
- **Delivery**: refers to the movement of the pollutant from the source to the surface water environment, involving such processes as surface washoff, interflow and groundwater flow.
- **Transport**: refers to the movement through the surface water environment, involving advection, dispersion and diffusion.
- **Use**: refers to the way in which, and by whom, the resource is utilised, either directly, or via abstraction.

The assessment of NPS pollution is generally only in response to a water quality concern. Domestic, agricultural or industrial sectors/users become affected, and so the need to conduct a water quality assessment becomes evident. Water quality, as described by Pegram and Gorgens (2001), is the term used to describe how well the physical, chemical and biological character of water matches the requirements of the aquatic environment and human uses.

2.2.2 Assessment of NPS pollution sources

Analysis of such pollution requires different methods to be implemented according to whether the problems are acute (short term), transient or event driven. Sub-catchment analysis allows for finer spatial and temporal details to be explored, and hence site specific results may be deduced. Non-point sources occur in differing forms, and hence have differing water quality effects. Impacts of various sources are related to factors such as climate, natural features (such as soils and topography) and human activities (such as agriculture), all collectively or individually involved in the production and delivery of contaminants within an area. The assessment of non-point sources is highlighted by Pegram and Gorgens (2001) as a vital component that adds to the understanding and study of NPS pollution. These authors highlight the following points upon which NPS assessments should be based:

- the combination of hydro meteorological and natural conditions, as well as the land use in the area, and
- the transition from one land use to another, frequently as a progression from undisturbed land, through agricultural activities, to urbanised areas.

Agricultural sources are the major source of diffuse pollution that this project aims to address. The exact area that contributes diffuse pollutants is defined by Heathwaite *et al.,* (2000) as depending on the coincidence of source (soil, crop and management) and transport (runoff, erosion and channel processes) factors. Furthermore, the authors suggest that the "biochemical reactivity and mobility of different nutrients determines the spatial extent of the contributing area and the degree of environmental risk."

2.2.3 Environmental factors

Land use, soils, geology, slope and climate are vital components of the study, as they govern the transport properties, both surface and subsurface, of sediments, nutrients and toxic compounds. Several factors therefore either enhance or reduce the rate of transport. The following have particular importance in governing transport properties:

- **Climatic and hydrological factors:** Higher intensity rainfall results in greater erosivity potential, and hence a greater chance of surface runoff potential. Interflow and groundwater discharge on the other hand, deliver dissolved contaminants that have infiltrated and leached from the land. The differences in seasonal rainfall have a controlling effect on whether nutrients are transported above the surface of sub surface, having a marked effect on the translation of processes from a small to a large catchment scale.

- **Natural features:** Soil permeability affects the rate of infiltration, and hence the ratios that exist between surface and subsurface water. Geology governs deep percolation and groundwater discharge, while topography influences stormflow and peak discharge and hence the delivery of particulate matter.
- **Agricultural activities:**
    - Grazing by livestock may contribute to sediment yield through overgrazing, while defecations from livestock add pathogens to the soils and, eventually, the receiving stream.
    - Croplands, especially if managed poorly, are prominent suppliers of sediments associated with high surface runoff. Nutrients (fertilizers) and pesticides are often washed away and removed from fields via surface runoff.
    - Irrigation of crops can increase salinity levels of waters, especially those associated with high concentrations of return flow from field to stream.

Accumulated nutrients, metals, pesticides and sediments tend to settle and accumulate in rivers at low flow or in impoundments such as dams. These constituents may be re-mobilised under certain high flow conditions, acidity or dissolved oxygen (anaerobic) regimes.

Heathwaite *et al.,* (1989, 1990) believe that land management practices damage the soil surface (through deep compaction and soil degradation) and hence serve as significant sources of polluting flow. The frequencies of runoff and erosion events are thought to be spatially limited and may be confined to higher rainfall events (Heathwaite and Dils, 2000). When these higher rainfall events do occur, nutrient enriched topsoil is mobilised (including manure and plant residues), hence serving as a diffuse pollution pathway.

2.3 Sediments

Sediments can be made up of minerals and organic matter. High intensity storms dislodge surface particles, and transport them in suspension into main channels. Sediments are minerals and organic matter. Wind erosion of soil particles have also bee observed. Sediment is the most widespread pollutant of surface waters. Heathwaite *et al.,* (1989, 1990) believe that erosion and sedimentation are two vital processes in the understanding of NPS-P. Erosion refers to processes that dislodge and transport sediment over the land, whereas sedimentation refers to the similar processes that occur within streams. Turbid water resulting from sedimentation affect the productivity and functioning of the aquatic environment as it decreases light penetration, thereby stressing the importance of so-called filter feeders and aquatic plants. Furthermore, with high sediment loads, storage space (volume of dams) is decreased, thereby increasing the possibility of flooding. Sediments absorb pathogens, heavy metals and toxic substances (such as pesticides) and transport them into the aquatic system, creating possible toxic compounds that pollute and degrade. It is important for researchers to understand erosion and surface runoff to be able to accurately understand and predict NPS pollution.

2.4 Nutrients

Nutrients, mainly nitrate and phosphates, may be absorbed by sediments and thus degrade water resources. Excess concentration levels of phosphates and nitrate may lead to the process of eutrophication, i.e. the situation where there is an excessive algae infestation within an aquatic system. Such infestation can result in cloudy, discoloured waters with strong odours and a lack of dissolved oxygen as a result of the decay of algae and plant material. Again, surface runoff (as with sediments) is the main cause of NPS pollution in terms of nutrients. Nutrients are generally yielded from agricultural fields onto which fertilizers are applied. A major gap in the identification of activities leading to diffuse pollution is how nutrients are retained within landscapes and released into river systems or subsurface flow paths. There are multiple pathways for nutrients to travel from fields. Unpredictable reactions and attenuations of nutrients, as well as eroded soils, can occur well beyond the area of nutrient application, and hence “the mobilisation and fate of pollutants and fate of pollutants within and from agricultural fields is a major challenge to research on nutrient pollution” (Heathwaite *et al.*, 2003).

2.5 Pesticides

Pesticides are widely used for agriculture, domestic and industrial application. Certain pesticides may be strongly absorbed by organic matter and, once again, can be transported via surface runoff to the main river channels.

2.6 Scale of Assessment and Monitoring

Scale is a vital issue regarding NPS-P assessment.. The scale at which measuring and modeling takes place is influenced by the range and diversity of non-point sources within the area of interest, together with the aims and goals of the study. Spatial representation generally concerns itself with two vital issues, namely the scope (spatial extent) and resolution (spatial disaggregation) required for the analysis (Lovell *et al.*, 2002).

3. SCALING OF NPS-P

Many disciplines, including Hydrology, gather information at the small scale (e.g. runoff, interception and infiltration). This information is then used to build models at different scales to that at which the information was gathered (e.g. catchments). This often assumes that information properties remain the same over a change in scale, an assumption that is now being questioned from several scientific corners. The sections below discuss the problems involved in such assumptions, and try to create a clearer picture as to why such assumptions are no longer justifiable. Schulze (2000) suggests that such assumptions lead to the issue of '*scaling problems*'. The author suggests that the so-called '*scaling problem'* is two fold, namely;

- what model, or set of assumptions, is appropriate to apply to a problem at a particular scale of space and time
- being able to apply a set of concepts that will allow for information gathered, or a model developed at a particular scale, to be used in making similar predictions at other scales (whether they be larger or smaller scales).

These two problems form the basis upon which the NPS/WRC project is based upon.

3.1 Process Scaling

Catchments are complex natural systems that display multiscale dynamics where multiple processes operate concurrently, and hence water management issues (such as water quality) are challenging. The process scale is defined by Jewitt and Gorgens (1995) as the scale that natural phenomena exhibit. This scale is said to be out of our control and not fixed, as it depends on the varying processes involved. Processes operating over smaller scales tend to occur more frequently than processes operating over larger scales, while smaller scale events have been noted to show more variability (Jewitt and Gorgens, 1995). Water resources management involves an integrated approach that considers physical, chemical, biological, ecological and socio-economic processes that operate over differing spatial and temporal scales. Scale is defined by Lovell *et al.*, (2002) as "*relative size or extent*", and scaling simply means transferring processes (in this case) from one scale to another. It is widely accepted that environmental issues cannot be scaled up directly (Beven, 1989). The kind of measurements that characterise a point sample (1 m^2) may well differ from those taken at hillslope scales (1 km^2). Bloschl and Sivapalan (1995) suggest that scale should be considered from one of two perspectives, namely process scale (the scale that natural phenomena are observed at) and observation scale (determined through the method of measuring the phenomena). Management, the ultimate goal of water resource studies, relies solely on the acquisition of efficient, effective information. The analysis of management strategies are at best as accurate as the information upon which they are based. The scale at which the data are obtained therefore becomes important. This however, still leaves a gap in the translation of NPS pollution from one scale to another.

The issue of integration has become important to not only hydrology, but most of the natural sciences, with a global move towards multivariable assessment of the natural world. Integration, in some cases, offers a solution to scale issues, and a GIS/modeling system is such a tool that aids this process. The main noticeable problem, as discussed by Saracino *et al.*, (2004), is that the model "*must represent the hydrological processes in the manner that is most consistent with the observations, while staying physically realistic and computationally practical*". It becomes important that while we strive to accomplish shortfalls within scale issues, we do not jeopardise the accurate and realistic modelling of processes. Data, as previously stated, are collected and recorded at varying scales, and so true management plans and suggestions therefore need to be effective at scaling such data sources; to be able to take mechanisms and responses at one scale and translate them to another scale is a skill that needs to be mastered.

3.2 Observation Scale

This is the scale at which humans choose to study natural phenomena, and is dependent upon the choice of the observer. Technological and logistical constraints generally define the scale at which observation is conducted, and so the observer is limited to a "*low-dimensional slice through a high-dimensional cake*" (Levin, 1992). An observation scale may be defined by several characteristics, namely the spatial/temporal extent of a dataset, the resolution of data samples and the grain (i.e. the area of and time taken to attain each sample). These three classifications are called the "*scale triplet*" (Levin, 1992) suggests that in an ideal study, the largest extent with high resolution (i.e. a high sampling frequency) should be employed as far as possible.

3.3 Operational Scale

The nature of the study at hand generally defines the operational scale at which it is sampled. The operational scale is defined by Jewitt and Gorgens (1995) as the scale at which the study or management actions focus, and may also be referred to as the working scale. Should the goal of a study be the runoff relationships that exist between different crops at the hillslope scale, then the hillslope will act as the operational scale.

3.4 Scale Problems

Harvey (1997) and Bugmann (1997) identify six scaling challenges that exist with regards to hydrological responses:

- **Spatial heterogeneity in surface processes**. Natural landscapes display heterogeneity which influences different processes in different ways. Such processes are spatial and temporally variable dependant upon topography, soils, rainfall, evaporation and land use and can vary markedly based on the relevant influences of these factors.
- **Non-linearity in response**. Vertical and horizontal variances in processes (such as soil permeability, through flow and overland flow) occur in the hydrological system. Differences in responses of processes are made between hillslope and channel processes for example. Nature operates non-linear, and so it is important that it is not assumed to be linear.
- **Processes require threshold scales to occur**. Processes, such as interflow, have threshold values, above which they occur and become dominant processes. Threshold values for interflow may be different on a gentle slope next to a river than on a steep slope further away.
- **Dominant processes change with scale**. Certain processes, which may be dominant at the hillslope scale, may be insignificant at the catchment scale, and vise versa.
- **Development of emerging properties**. For example, the enhancement of evaporation at the edge of a well-irrigated field surrounded by a dry environment while evaporation over the irrigated field would be suppressed by a vapour blanket of air with a reduced vapour pressure deficit (also known as the “oasis effect”).

- **Disturbance regimes**. Scaling issues arise as a result of changes such as the building of dams or land use changes and urbanisation.

3.5 Upscaling and Downscaling

Upscaling and downscaling are the two methods through which data scales are altered to formulate more effective, relevant strategies and understand the influence of varying processes at different scales. Upscaling involves taking data which describe processes from small scale studies and using it to predict similar processes/phenomena at larger scales, with the assumption that they operate similarly on both scales. Downscaling is generally accepted as an easier process, as it largely consists of assemblies of smaller scales, and so may easily be broken down into such smaller scales or original research(Saracino *et al.*, 2004). Renard and de Marsily (1997) suggest that progress in terms of upscaling has been observed in the study of subsurface hydrological processes. This shows an initiative to further understand and attempt to enhance the process of upscaling. Simple aggregation of data/information in an attempt to upscale may not be sufficiently accurate. Band (1997) suggests that such assumptions of uniformity for the area where the data is simple aggregated, is only true where uniform wet or uniform dry conditions over a large area or catchment exist. Variations in such conditions lead to inaccurate conclusions due to the varying degrees of influence that dry and wet areas have on a catchments response, and hence poses a problem to the issue fo scaling in research. These kind of uniform catchment conditions are rarely present which poses an issue of accuracy.

Surface processes have not yet shared the same progressions in terms of understanding and upscaling efficiency. Furthermore, Saracino *et al.,* (2004) acknowledge that one of the major contributions within natural sciences was the general acknowledgement of the existence of naturally defined scales at which processes, both physical and ecological, occur. Processes within systems generally occur within a naturally defined unit or scale. Renard and de Marsily (1997) suggest that, when considering the upscaling of surface hydrology processes, it may often require that data be downscaled first (into these naturally defined scales/units), and only then be re-aggregated or upscaled. Simply utilising data at the scale of measurement is no longer necessarily applicable due to the varying influences that influence, either more or less, the behaviour of processes within a catchment at varying scales. This may be particularly relevant when considering the translation of processes. Breaking processes down into their naturally defined units may provide an avenue through which effective process translation may be achieved.

3.6 Scaling Tools and Modelling

Quinn *et al.*, (2004) consider hydrological integrated management (rivers or catchments) to be a vital component of scaling issues. They suggest that support tools, the crux to integrated hydrological management, are central to scale issues, in particular the choice of tool to be used. Engineering is suggested to have dominated catchment management for several decades. However, the engineering approach has recently been identified as a potential problem as it no longer adequately provides required management results for catchment management, largely due to the changes that have been observed in land use.

Different tools translate processes in different ways, and so the choice of tool is vital to the translation process. Quinn *et al.*, (2004) suggest that physically based models be used to generate information on a small catchment scale which, by upscaling, provides information on the hydrology of the catchment as a whole. Catchment scale meta-models are then used to mimic the dynamics of physically based models, usually used in conjunction with a GIS. Natural conditions are however somewhat different and, unless flow routing is performed, this would perform as a linear model. GIS models have, more recently, become a popular basis upon which decision support systems may be based. Such approaches have largely been utilised to assess large scale catchment nutrient processes (Viney *et al.*, 2000; Cassell *et al.*, 2001). These have, however, not been widely used at the field to hillslope scale, which is the scale at which agricultural land management decisions need to be made, and the scale at which this project aims to investigate.

The power of models in the upscaling and translation process cannot be ignored. Hydrological processes are complex, and models provide an easy and effective means through which upscaling and the translation of processes may be done accurately (Cassell *et al.*, 2001). This statement has however been widely questioned, as detailed by Quinn *et al.* (2004), the more that science has managed to understand processes themselves and the varying influences they have on scaling, and so models have become a less accurate manner through which to achieve upscaling success. Any form of management is based on a need for information, or a need to improve whatever is being managed, such as the environment.

Hence, certain information needs to determine the scale at which a study may be conducted, or at which processes may be quantified. The scale upon which most studies are conducted is generally the catchment scale. Management programmes are designed especially within Africa, to benefit as many stakeholders as possible, and so the smaller scales (plot and field) are often sacrificed to satisfy the majority stakeholder (such as government or a regional body), or as many stakeholders as possible.

Quinn *et al.,* (2004) suggest four different scales that exist within a river basin network, and offer recommendations as to which models would be best suited to modeling at the respective scales.

- The point scale is the smallest of all. A 1-dimensional physically based model with boundary conditions and physical properties in each layer is suggested for modelling purposes at this scale.
- The next scale up (the plot) would be adequately described by a 3-dimensional physically based model similar to that of the point scale.
- The hillslope and catchment scale, probably the most widely used scale of modelling, is suggested to be most effectively modeled through the use of a quasi-physical distribution function model, with functions covering variables such as topography and soils.
- The largest scale, the regional or basin, is comprehensively modelled using MIR (Minimum Information Requirement) models based on statistical distributions for each of the constituent subcatchments. MIR models generally consist of scaled up physically based models, and are the simplest of all, while still maintaining the significance of the physically based parameters of the model.

3.7 NPS-P Models

Several pollution based models exist, both Non-Point Source and Point Source. Of particular importance for this study are the processes that each model identifies and incorporates within the respective models. Several relevant NPS models have been identified and are briefly described below, with the view of gaining a better insight into the processes and mechanisms involved in NPS pollution at different scales

3.7.1 CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) Model

CREAMS (Knisel, 1980) is a field scale model developed with the aim of predicting runoff, erosion and chemical transport from agricultural management systems. Key to this model is the scale at which it operates, namely the field scale. The model defines a field as having the following criteria:

- a single land use,
- relatively homogeneous soils,
- spatially uniform rainfall and a
- single management practice, such as conservation tillage or terraces.

For the proposed study hypothesis (that sediment and nutrient transport are largely event-based), this model would be ideally suited as a test model, as it operates on individual storms. However, it may also be used to predict long term averages for up to 50 years (Foster *et al.*, 1980).

3.7.2 SWRRB (Simulator for Water Resources in Rural Basins) Model

The *SWRRB* model (Williams, *et al.*, 1985) is a distributed version of the *CREAMS* model that was developed as a simulator of hydrological, sedimentation and nutrient transport in large, complex rural catchments. It is a continuous time-scale model that allows for sub-catchment delineation, hence accounts for regional differences in soils, land use, topography and climate (Arnold and Williams, 1995).

The *SWRRB* model is divided into five major components, namely weather, hydrology, sedimentation, nutrients and pesticides, and involves processes such as surface runoff, return flows, percolation, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation and crop growth.

3.7.3 BASINS (Better Assessment Science Integrating Point and Non-point Sources) Model

BASINS, Better Assessment Science Integrating Point and Nonpoint Sources (EPA, 2001) is one of the most widely used point and non-point source models around the world. Coupled with the *SWAT* (Neitsch *et al.*, 2001) model, *BASINS* provides opportunities for complex modeling that assess mechanisms related to point and NPS pollution.

BASINS is a model developed by the US Environmental Protection Agency (EPA), and is a multipurpose environmental analysis system that aims to aid in the assessment of watershed and water quality based studies (BASINS User Manual, EPA, 2001). The modelling system is designed to be flexible, with the catchment scale being the main scale of operation. It can however, support analysis at a variety of scales using tools that range from simple to more sophisticate.

3.7.4 SWAT (Soil Water Assessment Tool) Model

SWAT (Neitsch *et al.*, 2001) is the most comprehensive and complex of all the models discussed in this document. *SWAT* is largely designed for large catchment and basin scale modelling. It is a physically-based model that assesses nutrients (namely nitrogen and phosphorous) in detail, as well as the fate and transport of pesticides both in stream and through/over the soil profile. Although addressing the major issues required within this study, *SWAT*'s scale of operation ignores the small scale intricacies observed within the upper Mkabela Catchment.

3.7.5 Summary of Models

The abovementioned models, namely *CREAMS* (Knisel, 1980), *BASINS* (EPA, 2001) and *SWAT* (Neitsch *et. al.*, 2001) are relevant and operate well at the scales for which they are designed. The *BASINS* and *SWAT* models operate at a catchment scale, whereas the *CREAMS* model identifies processes at the smaller, field scale. The requirements for the WRC-NPS project focus on the field/plot scale, and the relationship that exists between the translation of processes at such a scale through to larger catchment scales. *CREAMS* would therefore be considered an ideal model for the field/plot scale and the investigation of dominant processes at this scale. When translation issues regarding upscaling of processes are considered, then it would be relevant to use *BASINS* to assess the manner in which processes are upscaled. Having analyzed these, it is clear that no existing model truly plies to the current hypothesis of this study and project, in particular the assessment and inclusion of scaling issues.

3.8 Lumping of Processes and Hydrological Frameworks in Scaling

The concept of lumping, a common method of area-averaging, is coming under increasing pressure as scientists begin to question the science behind lumping and the lack of attention given towards important processes at smaller scales. It has been suggested in several texts (e.g. Quinn *et al.,* 2004, Bloschl & Sivapalan 1995,Saracino *et al*., 2004) that the hydrological world is in great need of a multi-scaling hydrological framework. This need stems from the uncertainty that exists within the hydrological fraternity as to how measurements should be done, how to build and run models, how to aggregate processes and how to inform policy makers for decision making, largely based on the multi-scale nature of hydrology. It is by no means a foregone conclusion that all measurements are scale-specific. Certain mechanisms and processes, such as the water balance or the nitrate cycles, are applicable at all scales, and so Beven (1989) suggests that such variables need to form the basis of a combined monitoring and modelling strategy for addressing scaling issues.

3.9 Errors in Scaling

Various types of errors may be experienced through scaling issues, largely due to spatial irregularities and generalisations across spatial scales. Haufler *et al.,* (1997) suggests that scale related errors may be classified into one of two types of errors;

- Errors of commission.
- Errors of omission.

An error of commission (Haufler *et al.,* 1997) refers to the occurrence of a process in an area where it is in fact realistically not present. Such an error is a common occurrence when attempting to solve a problem or investigate a hypothesis on a scale that is too small. Assumptions regarding what is perceived to be the appropriate scale of assessment have been shown to be misleading in terms of appropriate scale selection.

An errors of omission (Haufler *et al.*, 1997) refers to one that fails to predict the occurrence of a process that is actually present within an area. This type of error is generally common at a single (as opposed to varying) scale that commonly ignores processes that only become evident at larger scales.

3.10 NPS-P Scale Issues

Direct reference to scale issues in assessing non-point source (NPS) pollution is made in Schreier and Brown. Soil erosion and excess nutrients are considered the two most prominent and important non-point sources that originate from agricultural activities. The scales upon which they are observed vary from plot to fields, to small and large catchments, to entire river basins. Schreier and Brown's 2004 work quantifies excess nutrient applications through the use of a nutrient mass balance model that is linked to a GIS. Their results showed that while farm based budgets helped the farmer with his/her personal planning and management, the results could not easily be scaled up, largely due to very large spatial uncertainties.

Schreider and Brown (2004), in their study of two separate catchments in Nepal and Canada, suggest that a multi-scale approach, rather than a scaling up approach, is required to address the problem of identifying NPS pollution. Sources of NPS-P problems may be identified and monitored spatially using a GIS, by overlaying several different aerial images that allow for the observation and quantification of changes in land types and uses. Nutrient inputs and infiltration rates, for example, are altered by management practices and cannot be assessed as in the previous examples in Nepal/Canada. In such cases (where management practices alter conditions and processes), field surveys and/or modelling need to be implemented. Erosion, on the other hand, is a little more difficult to quantify. Changes are largely visible from aerial images and are poorly observed spatially due to the episodic nature of the processes involved. Schreier and Brown (2004) found that through their studies of the Nepalese catchment sediment budgets remained relatively similar between the plot and mini catchment scales, with greater uncertainty existing at the plot scale due to the ever changing conditions that occur. The plot scale is more susceptible to changes because of the small scale upon which it operates, and hence natural process thresholds are easily overcome. Furthermore, they suggest that "*estimating erosion rates and sediment budgets over different scales requires a combination of approaches that includes the use of models based on topography, site* *conditions and land use, and the determination of sediment yields using sediment rating curves, hence an assessment at different scales is required.*”

Scaling certainly does have its uncertainties. It is clearly highlighted by Schreier and Brown (2004), Quinn *et al.*, (2004), Bloschl & Sivapalan (1995) and Saracino *et al*., (2004), that gaps exist in the understanding of processes between different scales. Aggregating data is assumed to effectively represent processes at a larger scale. This assumption has long formed the basis of catchment scale models; however the need to improve management practices at the smaller scales (such as fields and plots) has questioned the accuracy behind aggregation. It is therefore important that we attempt to better understand the translation of processes from one scale to the next as opposed to assuming linear behaviour, and so the understanding of influencing processes and their degree of influences over varying scales becomes vitally important

3.11 Resolving scale issues in South Africa

Jewitt and Gorgens (2000) offer several examples of scale issues in South Africa. Jewitt and Gorgens (1995), in their study of the rivers of the Kruger National Park, recognise the fact that the scales at which the different disciplines (namely ecology, geology and hydrology) operate would not be easily matched, and that disparities were evident. Hydrological research and models generally operate at a catchment or sub-catchment scale over a daily time step. Geological models focus on channels with measurements covering the seasonal time step, whereas ecological models tend to consider data gathered at the biotope scale (using varying scales of vegetation occurrence as the determining scaling factor) with point measurements being the dominant source of information. The challenge was clearly to merge these disciplines into a single scale of operation to be able to effectively model the rivers of the Kruger National Park.

4. MKABELA CATCHMENT AND FIELD INSTRUMENTATION

4.1 Overview

The Mkabela Catchment (a subsidiary of the Mgeni Catchment) is located in the sugar belt of the KwaZulu-Natal midlands, one kilometer east of the town of Wartburg (30.68 DD East, 29.37 DD West). The Mkabela catchment covers an area of approximately 36.8km^2 (Figure 4.1) with a headwater sub-catchment (that has detailed instrumentation), covering an approximate area of 2.8km^2.

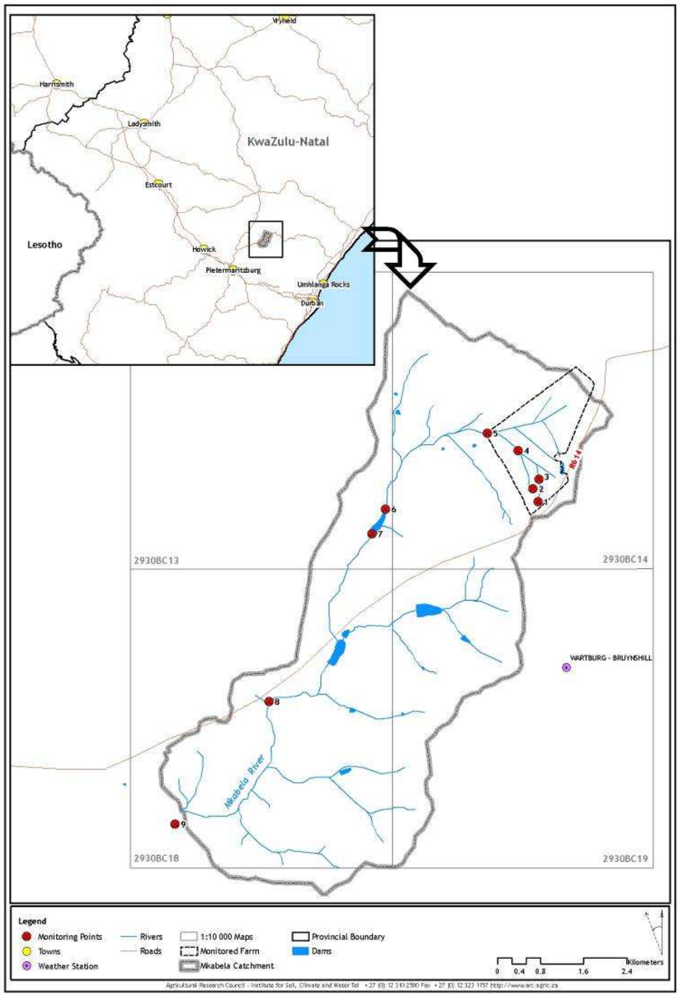

Figure 4.1 Mkabela Catchment location within KwaZulu-Natal (Germishuyse and le Roux, 2006)

The Mkabela Catchment was selected as the research catchment of choice as it provided logical, accessible sampling points with generally uniform and homogeneous fields of crops, thereby decreasing the number of additional crop specific factors that may contribute further to NPS-P, and further complicate the analysis thereof. Sampling points a various nested scales are shown in Figure 4.2.

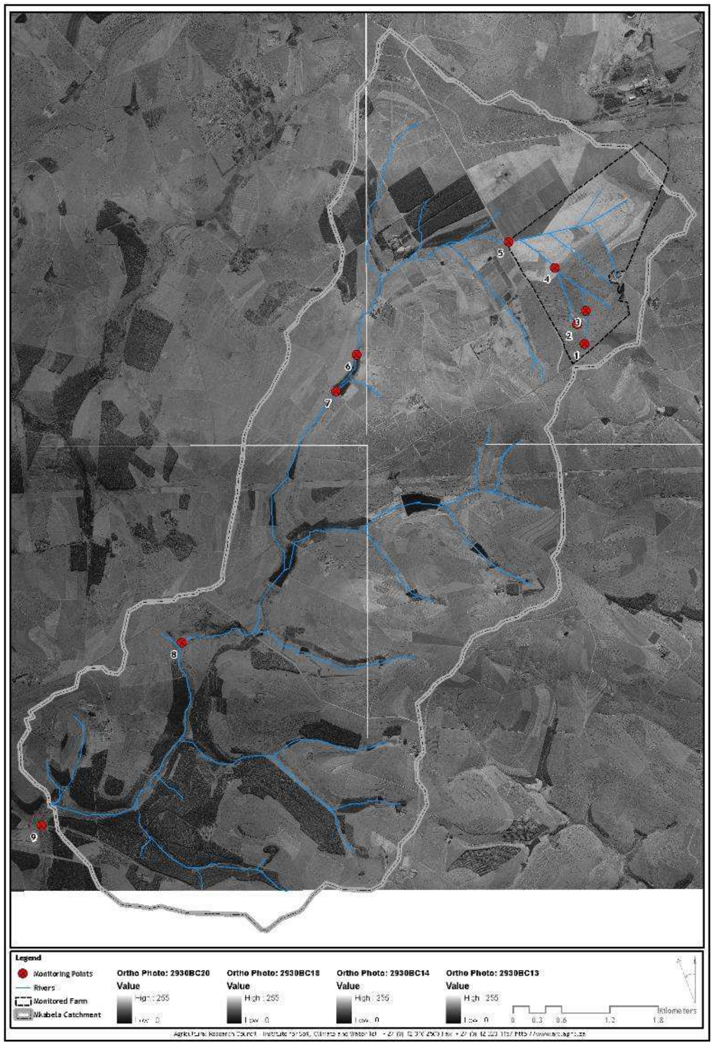

Figure 4.2 Sampling points within the Mkabela Catchment (Germishuyse and le Roux, 2006)

The Mkabela Catchment has been instrumented at differing scales so as to assess the effects of NPS-P on waterway pollution in relation to the point of application. Nine monitoring points were pre-determined within the catchment at strategic locations as per the listings below:

- Monitoring Point 1 - Runoff Plot 1
- Monitoring Point 2 - Runoff Plot 2

- Monitoring Point 3 - Flume 1
- Monitoring Point 4 - Flume 2
- Monitoring Point 5 - Dirt Road
- Monitoring Point 6 - Dam Entry
- Monitoring Point 7 - Dam Exit
- Monitoring Point 8 - Bridge 1
- Monitoring Point 9 - Bridge 2

Table 4.1: Sampling Method Summary

Sampling Point	Name	Automatic Sampling?	Grab Samples?	Scale
1	RP1	Y - Tipping Bucket	N	Field
2	RP2	Y - Tipping Bucket	N	Field
3	Flume 1	Y - ISCO/Datalogger	N	Small Catchment
4	Flume 2	Y - ISCO/Datalogger	N	Medium Catchment
5	Dirt Road	N	Y - Manual	Medium Catchment
6	Dam In	N	Y - Manual	Medium Catchment
7	Dam Out	N	Y - Manual	Medium Catchment
8	Bridge 1	N	Y - Manual	Large Catchment
9	Bridge 2	N	Y - Manual	Large Catchment

The Soil Science department at the University of KwaZulu-Natal Pietermaritzburg has the instrumentation and knowledge to be able to access and analyse water samples taken from the field for the presence of nitrate. The department is equipped with a continuous flow analyser for the detection of such nitrate. A filtered sample is passed through a column containing granulated copper-cadmium to reduce nitrate to nitrite. The nitrite (that originally present plus reduced nitrate) is determined by diazotizing with sulfanilamide and coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a highly colored azo dye which is measured colorimetrically. A sample of 10-100ml is needed to be able to effectively perform both tests. It has been suggested that there is a possible bias of approximately 0.01mg/l.

Furthermore, suspended solids (SS) are determined from the same samples. Suspended solids were tested at the University of KwaZulu Natal’s soil moisture laboratory by technician John Ngeleka. A 200ml sample was taken from the catchment sample and placed in a beaker. 5ml of Hydrochloric Acid was added to the sample to help settle the sediment. Once the sediment had settled, the water was taken out of the beaker, and the remaining sample was left to dry, ensuring that all moisture was drawn out of the sediment sample. The dry product is then weighed and the weight of the beaker subtracted from this value to determine the amount of suspended solids present in each of the samples.

Each of the ten events was sampled and monitored thoroughly enough to have gained valuable datasets for all measurables in order to effectively assess the movement of pollutants such as nitrate through the catchment system from a small to a large scale of observation.

4.2 Topography and Catchment Discretisation

The topography of the Mkabela Catchment is a major determinant in the movement and behaviour of NPS pollution. A digital elevation model (DEM) allows for watershed delineation, and was generated for the Mkabela Catchment using pixel sizes of approximately 21m x 21m from 5m contour intervals obtained from 1:10000 maps purchased through the Surveyor General (Germishuyse and le Roux, 2006) as shown in Figure 4.3.

The DEM of the Mkabela Catchment enables the determination of flow directions based on altitudinal differences and slope.

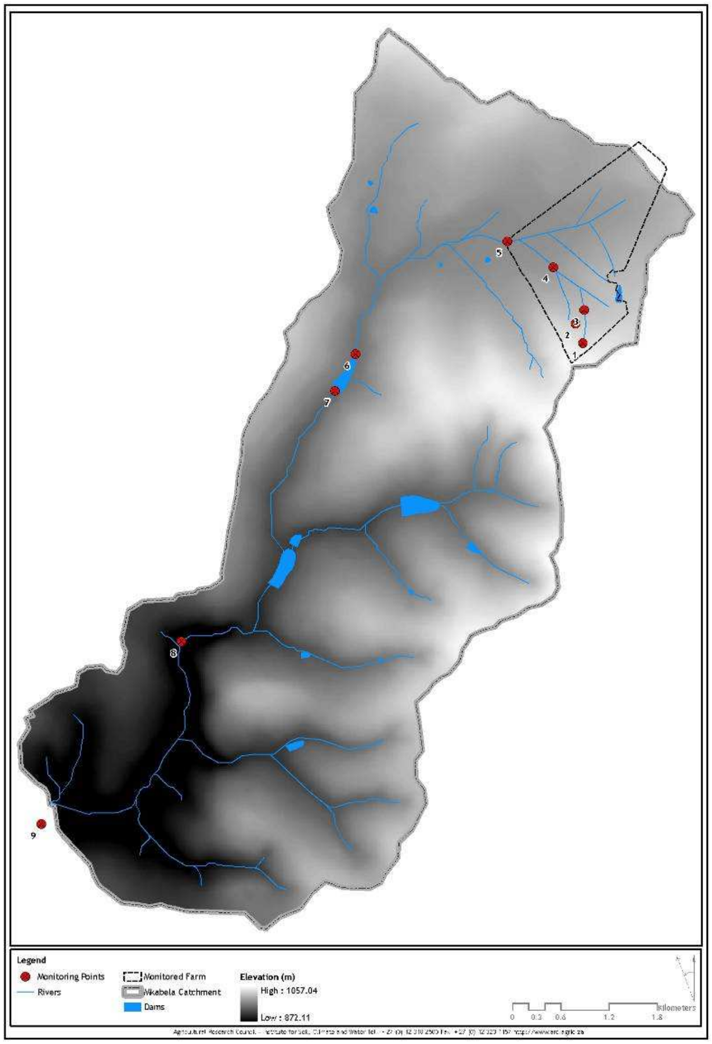

Figure 4.3 Digital elevation model of the Mkabela Catchment (Germishuyse and le Roux, 2006)

Drainage networks describing the process of gravity acting on slopes, the associated channel links and catchments are fundamental concepts in hydrology which describe the transport of water and associated material out of a local region (O'Callaghan and Mark, 1984).

These flow directions are important when considering NPS-P and its movement through a catchment, and were produced using the SWAT model (Arnold *et al.,* 1994) and are shown in Figure 4.4. If the source is identified, then the pollutants movement can be tracked through the catchment based on the flow directions detailed below, and hence preventative measures can be implemented and predictive models can be developed.

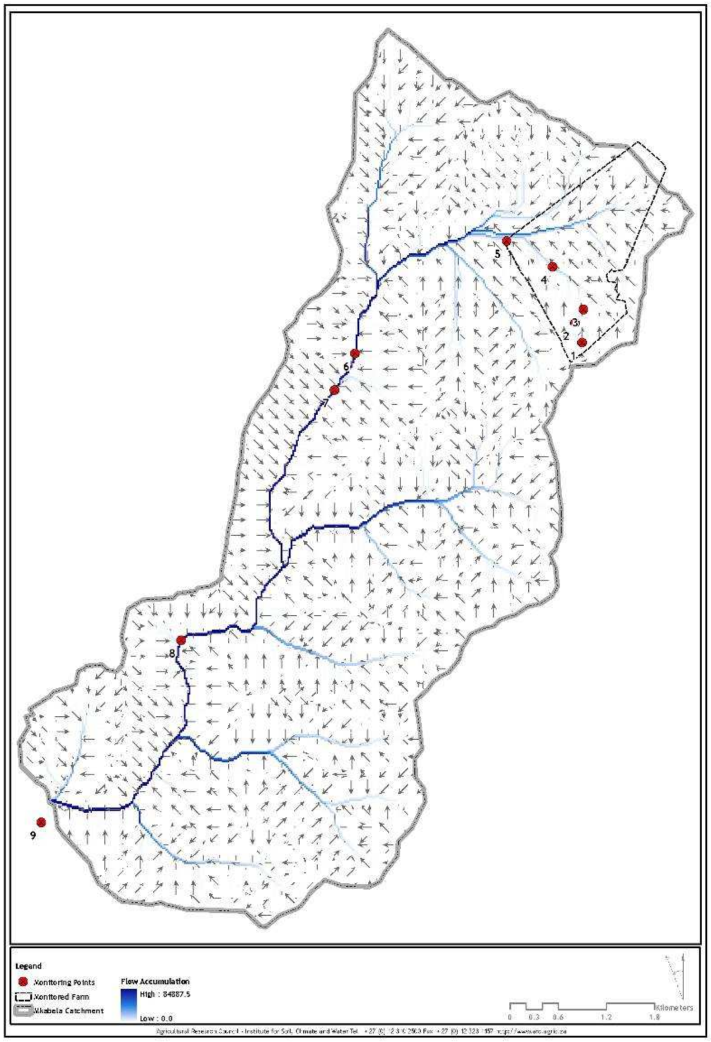

Figure 4.4 Flow Directions of the Mkabela Catchment Modelled using SWAT (Germishuyse and le Roux, 2006)

Burns *et al.*, (2004) suggest that the biggest complication associated with automatic channel extraction and flow directions lies with the appropriate drainage density that one should utilise. If catchment structural information is used to drive hydrological models, the consistency of the derived stream network and scaling behaviour needs to be addressed. SWAT allows the user to be able to specify the size (an area/percentage) of the catchment's watersheds.

The DEM of the Mkabela Catchment was then used to delineate watersheds for *SWAT*. *SWAT* discretisizes watersheds in different manners. Figure 4.5 indicates the catchment delineation performed by *SWAT*.

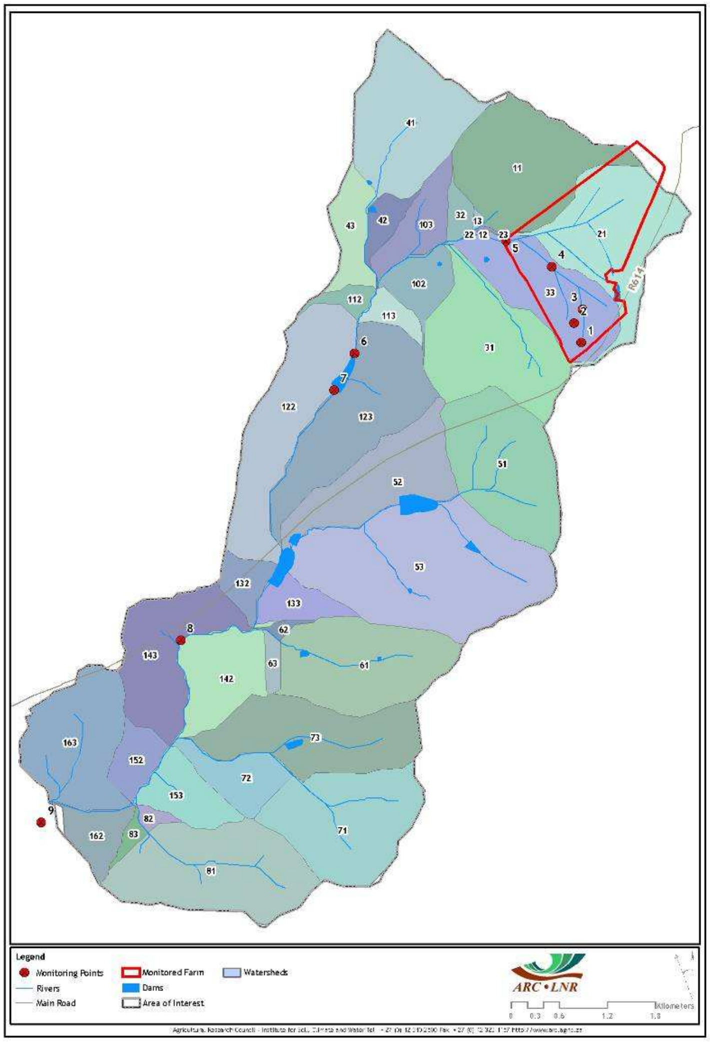

Figure 4.5 Watershed delineation of the Mkabela Catchment as modelled by SWAT (Germishuyse and le Roux, 2006)

When assessing the needs of this study, the larger catchment sizes produced by the *SWAT* model are sufficient for the nature of this study. This appropriate scale is further substantiated by Goodrich *et al.*, (2000) who proposed that a drainage density of approximately 0.65 to 1.52 x 10^{-3} m for catchments greater than 1 ha was adequate for kinematic runoff modelling in semi-arid regions.

4.3 Land Use

The land uses of the Mkabela Catchment are dominated by sugar cane as shown in Figure 4.6. (Germishuyse and le Roux, 2006). The upper catchment contains small areas of vegetable cropping and forestry, while the lower reaches are planted to pine, wattle and poplars.

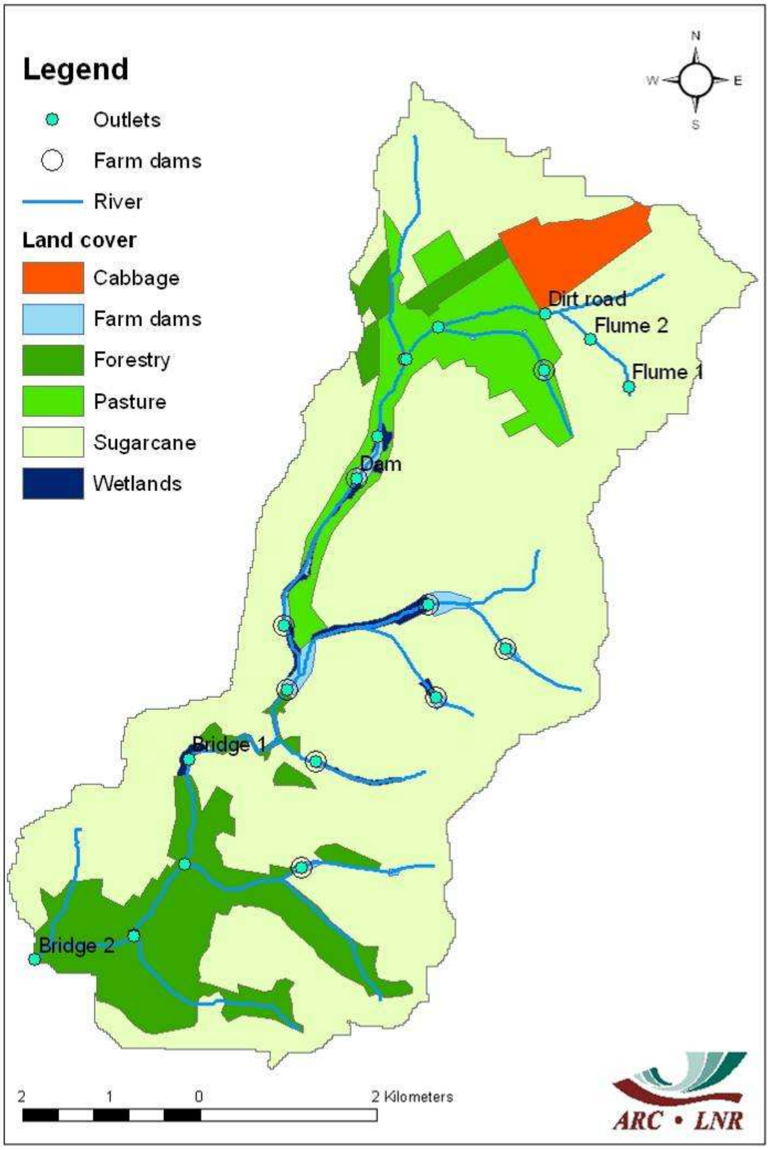

Figure 4.6 Land Use of the Mkabela Catchment (Germishuyse and le Roux, 2006)

4.4 Soil Survey

A soil survey of the Mkabela Catchment was conducted by Le Roux *et al.*, (2006) from the Department of Soil, Crop and Climate Sciences at the University of the Freestate (Figure 4.7). The survey was completed to support the hydrological and soil science research as part of the WRC’s NPS-P project.

Varying scales of survey intensity were carried out within the Mkabela Catchment, with the area draining through to flume 1 being surveyed at the most intensive scale (using a hand auger on a 50m grid) and the area draining through to flume 2 being surveyed on a 100m grid. The balance of the Mkabela Catchment was derived by transferring soil survey information from existing soil maps.

Homogeneous sequences of soil distribution (from crest to the drainage line of the topography) are classified as hillslopes. Le Roux *et al.*, have classified the Mkabela study catchment into nine hillslopes, with greatest variations observed in the upper catchment, largely due to the detail of survey conducted. Figure 4.7 indicates the hillslope classification of the Mkabela Catchment at a scale of 1:100 000.

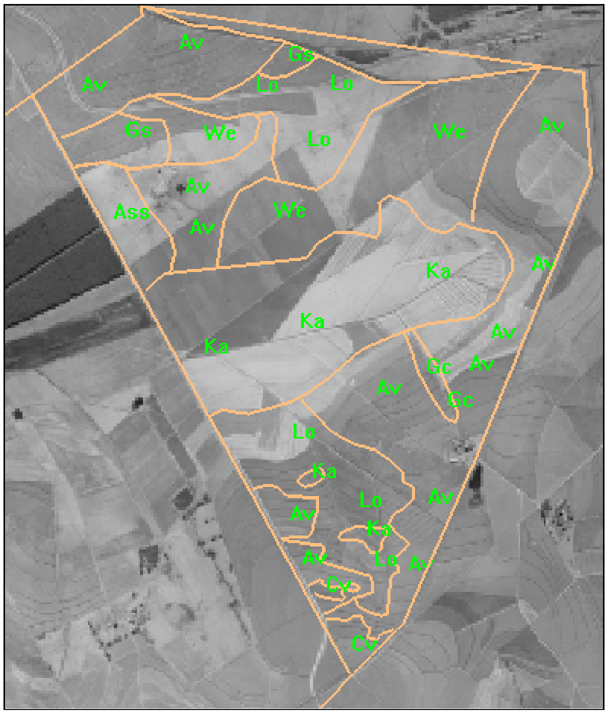

Figure 4.7 Hillslope Classification of the Upper Mkabela Catchment (le Roux *et al.*, 2006)

Table 4.2 Soil form Key

Soil Key	Soil Type
We	Westleigh
Av	Avalon
Gc	Glencoe
Lo	Longlands
Ka	Katspruit
Gs	Glenrosa
Cv	Clovelly
Ass	Ass. Of Wasbank, Avalon and Bainsvlei Soils

Varying types of soils were found through the survey from well drained soils dominated by Hutton and Clovelly (with occurrences of Griffin, Shortlands, Inanda, Magwa, Kranskop, Nomanci and Oakleaf being observed) to moderately drained soils of Avalon, Glencoe, Longlands, Westleigh, Cartref and Tukulu. Krronstad and Katspruit forms (poorly drained soils) were also observed.

The upper catchment is dominated by two Westleigh form hillslopes (Figure 4.8), containing poorly drained soils that are dominated by clays with evident mottling, possibly due to vegetables having been planted on these soils within the catchment. The morphology of the soils suggests that the underlying material could well be impermeable, thereby creating saturated conditions experienced during high rainfall periods. Le Roux *et al.*, suggest that a water table probably develops a month after the rains have begun, and lasts for another 4 or so months, varying in its distance from the soil surface.

Figure 4.8 Photographic Representation of In field and Furrow Adjacent Profiles

The Avalon hillslopes are characterised by well developed soft and hard plinthic horizons, connected through soil macro-pores that enhance permeability between the layers, hence anability for NPS-P to infiltrate these soils. These are typical of the furrows and areas around the furrows in which the flumes have been constructed. The water table in this plinthic layer is located within and below this layer, with the hard layer being semi-permeable. The Avalon hillslopes are generally higher in relief than the Westleigh hillslopes, and the underlying material was observed to be Ecca sedimentary rocks of the Natal Group sandstone. Morphological observations of the hillslopes indicate that the underlying material is impermeable, as water tables form in the subsoil, and so drainage is largely dependant on lateral movement. The Avalon hillslope is expected to gather water during the rainy season, with lateral drainage being the primary means of water movement. The water table is present for shorter periods of time than the Westleigh form, largely due to the lateral drainage and slope characteristics of the Avalon form. The Avalon form is particularly good in retaining water and holding large volumes of soil water, thereby aiding the growth of sugarcane. Being further up the topographical slopes of the upper catchment, the water draining from the Avalon forms contribute to the lower lying Westleigh forms.

The Longlands hillslope makes up the remaining forms of the upper Mkabela Catchment. This form is common throughout the greater Mkabela Catchment, however, are most concentrated in the upper north eastern corner. Clovelly soils dominate the crest of this form, Wasbank soils the midslope and Kroonstad soils the bottom of the form. Longlands forms are generally sandier than the Avalon, with steeper slopes and a sandy parent material being the major contributors. The sandier nature of this form results in quicker drainage and poorer water holding capabilities than the Avalon.

The middle sections of the Mkabela Catchment, on the North West slopes (facing south east), are dominated by Glencoe hillslopes. Glencoe forms are dominated by a hard plinthic subsoil on steepish slopes, with underlying Natal Group sandstone, giving this form similar water holding characteristics as the Avalon hillslope, except for the effect of steeper slope and higher relief (hence much shallower and poorer water holding capabilities).

The Cartref hillslopes occur in the middle of the catchment, and on the opposite side of the Glencoe hillslopes (facing North West). Natal Group sandstone again dominates the underlying material. However, the soils are quite shallow and sandy, and so the water holding capabilities of this form is poor.

The Hutton hillslope occurs towards the end of the catchment in an area that is characterised by steep slopes and gorge incisions into the topography. Shallow Glenrosa soils dominate the steeper slopes, while well drained deep Hutton soils occur on the flatter slopes of the crest and lowlands. The underlying material is once again Natal Group sandstone. Being a shallow soil, the Glencoe has very poor water holding capabilities, while the Hutton may be classified as having moderate water holding capabilities (unless a sandy component exists).

4.5 Catchment Monitoring and Data Collection

Nine monitoring points have been identified within the Mkabela Catchment for monitoring. Four of these points, namely runoff plot 1 (RP1), runoff plot 2 (RP2), flume 1 (F1) and flume 2 (F2), have been instrumented with permanent monitoring structures. The remaining five sampling points, namely Dirt Road, Dam Entry, Dam Exit, Bridge 1 and Bridge 2 have, for the purpose of this study, served only as grab sample points. However permanent monitoring structures will be constructed at these locations within the near future.

Table 4.3 Sampling Point Details

Sampling Point #	**Description**	**Scale:**
1	Runoff Plot 1	Plot
2	Runoff Plot 2	Plot
3	Flume 1	Field
4	Flume 2	Field
5	Dirt Road	Small Catchment
6	Dam Entry	Medium Catchment
7	Dam Exit	Medium Catchment
8	Bridge 1	Large Catchment
9	Bridge 2	Large Catchment

4.5.1 Runoff Plots

Two runoff plots (sampling points 1 and 2) have been constructed and installed in two separate sugarcane fields of the upper Mkabela Catchment (Figure 4.9). Both runoff plots were installed in sugarcane fields of differing growth stages with the aim of assessing the runoff characteristics of the different stages of sugarcane for the same event (i.e. equal rainfall, intensity and storm characteristics).

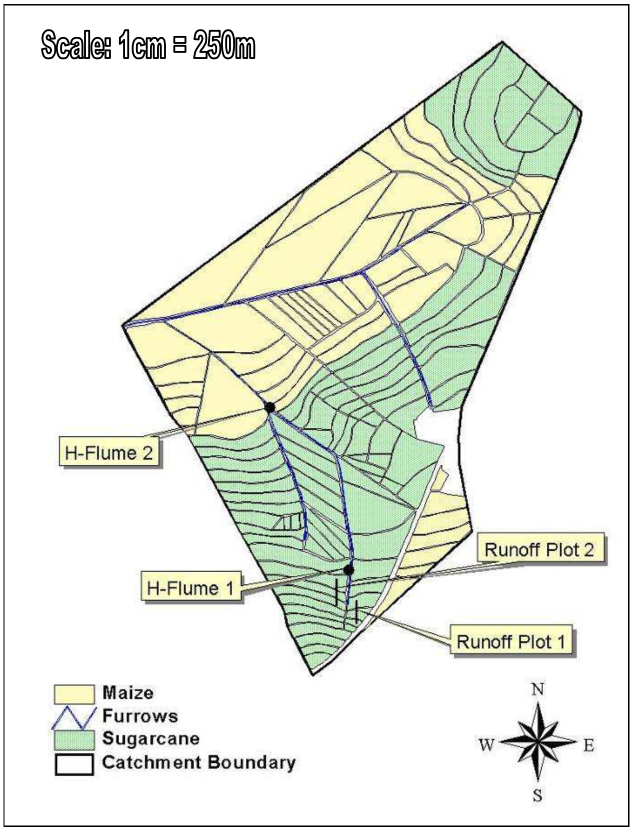

Figure 4.9 Locations of RP1, RP2, F1, and F2 within the Upper Mkabela Catchment

The runoff plot consists of a 22m x 2.5m plot that feeds into a collection trough at the bottom of the plot. The trough channels the runoff water into a pipe that feeds a tipping bucket system installed further down the plot at a level below that of the trough level, thereby creating a gravity gradient that ensures that the runoff water flows through the pipe and into the tipping bucket system. The tipping bucket system consists of a bucket with a capacity of two liters of runoff water. Each tip equates to 0.3mm of rain. As the bucket reaches it's two litres capacity it tips, and in doing so logs the tip on the mechanical and Hobo logging devices attached to the system.

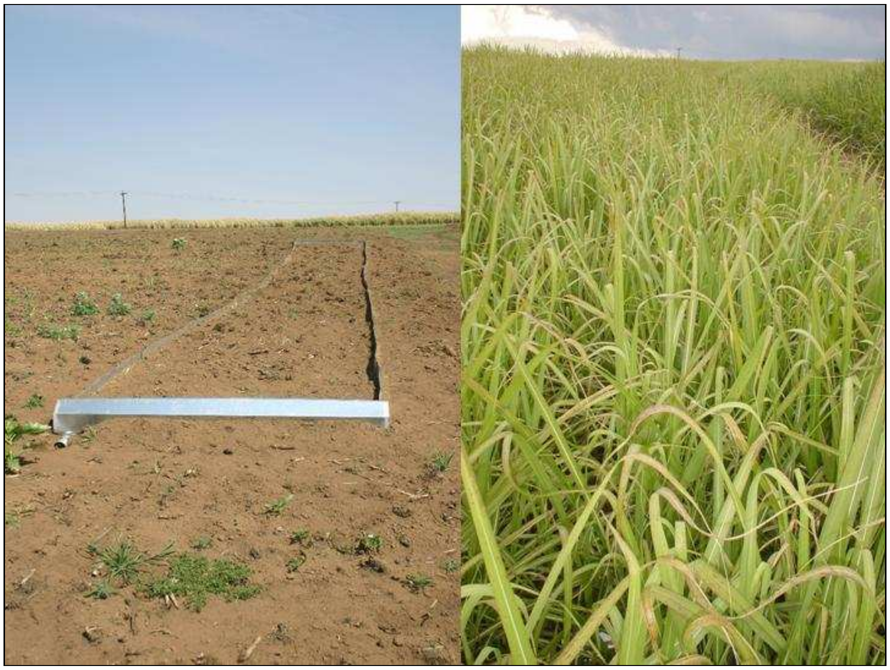

Figure 4.10 Differing stages of cane growth within RP1 between September 2005 (left) and May 2006 (right)

The tipping bucket system (Figure 4.11), once the two litre capacity has been reached, tips the runoff volume into a splitter system that has five exit pipes. One of these five pipes channels the runoff water into a collection bucket from which water samples were taken for nitrate and suspended solid testing, the other four allowing the runoff water to exit the system. The data collection process for the runoff plots is a three step, in field process, and two step laboratory process.

In field data collection process:

- Download Hobo logger using the Hobo download shuttle;
- Record and reset the mechanical logger;
- Take a water sample from the collection drum and empty drum before next event.

Laboratory process:

- Download Hobo data onto computer and verify recorded tips with mechanical logger reading;
- Perform nitrate and suspended solid tests on the water samples.

Figure 4.11 Tipping Bucket System (left) and Collection Bucket (right)

Data obtained from the runoff plots, in conjunction with meteorological data specific to the particular event that occurred, gives clear indications as to the runoff properties of the Mkabela Catchment, the soils in the upper catchment and the influence that different stages of sugarcane have on runoff properties.

4.5.2 Flow gauging H-Flumes

Two H-Flumes (sampling points 3 and 4) were constructed within the upper Mkabela Catchment. The two flumes, based on similar previous designs were constructed during the latter stages of 2006 by a local bricklayer.

The process of constructing the H-Flumes was made easier by the relatively high level of the bedrock within the upper catchment, eliminating the need to construct deep foundations. The dimensions of the two flumes were based on estimates of peak flow obtained by applying the SCS-SA model to the two proposed H-Flume sites. A summary of the SCS-SA output estimates for the two proposed sites are detailed in Appendix A.

Initial designs for the H-Flume (taken from an existing UKZN sampling project elsewhere) to be located at site 2 needed to be modified to account for the large storm flow estimates obtained through the SCS-SA model runs, and so the flume dimensions were adjusted accordingly. Housing for the instrumentation was constructed next to each flume, and the relevant instrumentation installed (Figure 4.12). The housing holds the ISCO sampler and MC logger apparatus. The ISCO sampler is connected, via a black PVC pipe, to the stilling well at the bottom of the flume. The ISCO sampler is connected to the MC logger which monitors the flow rate passing through the H-Flume. When the flow rate changes significantly (a predetermined value programmed into the MC logger), a signal is sent to the ISCO sampler that triggers the pump to take a water sample. The time, date and flow rate at which the sample is taken is recorded by the memory module within the MC logger.

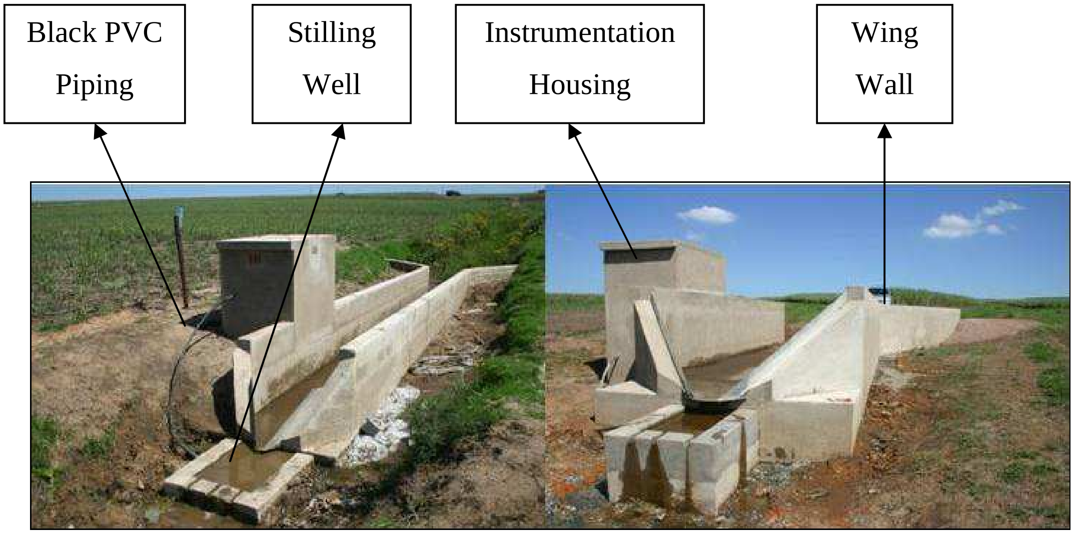

Figure 4.12 Flume 1 (left) and Flume 2 (right) of the Mkabela Catchment

After observing several early season events, Flume 2 was found to have been under designed for the given catchment size. The wing walls and the flume side walls were therefore increased in size and length to ensure that the generated flow rates from the catchment could be accommodated. As the design was based on the SCS-SA Model, it is suggested that the input data was possibly too vague, and that a better understanding of exact processes controlling this small catchment would have led to a sound initial design.

4.5.3 Additional sampling and monitoring points

Representative event grab samples (taken during events to ensure full sets of scaled data were obtained for as many events as possible) were taken as and when the storm hydrograph rose, peaked and dissipated. Water samples were taken and depth of flow estimates recorded for each event. Water samples were taken to the laboratory for nitrate and suspended solid testing. Channel morphology at each of the ungauged sampling points has been measured, and rating curves have been produced for each of these locations. The rating curves provide a means through which an estimate of flow rates during an event can be made for each of the sampling points.

4.5.4 Meteorological Station

A Campbell Scientific Automatic Weather Station (AWS) has been installed within the catchment. The purpose of installing the AWS is to accurately measure catchment specific variables such as rainfall (both volume and timing of rainfall events), wind speed and direction, radiation, and temperature. Such measurements provide more accurate data than having to rely on the closest South African Weather Bureau (SAWB) station which is located some 3 kilometres west of the Mkabela Catchment.

5. PLOT TO CATCHMENT SCALE SAMPLING RESULTS AND DISCUSSION

Ten events with full data sets from the nine sampling points have been observed through the catchment monitoring period (6/11/2005 to 28/4/2006). Additional events have been observed and recorded. However due to sampling inaccuracies, such as faulty MC loggers, flat batteries and broken ISCO samplers, full sets of data representative of all the observation scales were not always obtained.

5.1 Sampling points

Scaling is seen as fundamental to the understanding of NPS pollution and its movement through a catchment, and so it was decided that only full sets of data representing all nine sampling points (and therefore varying scales) would be considered for analysis within this study. Table 5.1 details the nature of the ten events sampled and analysed.

Table 5.1 Rainfall and Intensity Values for the Ten Sampled Events

Event	Date	Rainfall (mm)	Intensity (mm/hr)
1	2005/11/06	22	19.1
2	2005/11/18	18	7.2
3	2005/12/10	30	24
4	2006/01/01	47	166
5	2006/01/18	29	145
6	2006/02/06	13	12.8
7	2006/03/03	17	11
8	2006/03/12	18	6.1
9	2006/03/28	16	4.1
10	2006/04/28	11	3.8

Full sets of data include water samples and associated nitrate and suspended solid data for all nine sampling points, (initial soil water content data were not used).

Water samples collected at each of the nine stations during the course of rainfall events were analysed for nitrate and suspended solids concentrations. These analyses, when combined with the discharge, allowed for estimation of nitrate and suspended solids loads.

When referring to the catchment scale, the findings are based on the sampling point catchment drainage areas as detailed in Table 5.2.

Table 5.2: Catchment Drainage Areas

Sampling Point	Catchment Drainage Area (ha)
Runoff Plot 1	0.015
Runoff Plot 2	0.02
Flume 1	17
Flume 2	58
Dirt Road	330
Dam In	888
Dam Out	132
Bridge 1	1500
Bridge 2	1310

The events were sampled automatically at the runoff plots and flumes and manually at the “grab sample” stations. The results are discussed separately for the automatic and manual sampling and observed trends highlighted.

5.2 Gauged Sampling Points

Sampling points comprised automatic gauged sampling stations (Runoff plots and flumes) as well as stations along the stream network which were periodically hand sampled.

5.2.1 Runoff Plots and Flume Data

This section below identifies the trends measured at the plots and flumes. Dominant processes at each of the scales are identified, as well as the trends shown between different events and their season of occurrence. The runoff volumes measured at the plot scale, in combination with the nitrate and suspended solid concentrations and loads measured, are compared with each other and between similar data measured for Flumes 1 and 2.

5.2.2 Observed Overland Flow Characteristics

Ten events were sampled and measured during this study, and the runoff data is shown in Table 5.3.

Table 5.3 Runoff Characteristics: Events 1-10

		Nitrate (mg/l)	**SS (mg/l)**	**% Diff**	**I (mm/hr)**	**Runoff Volume (L)**	**Runoff (mm)**	**% Diff**	**Nitrate Load (kg)**	**Nitrate Load (Kg/ha)**
E 1	**RP1**	12.1	1800		19.1	184	3.485		2.226	421.7
	RP2	11.9	2133	16	19.1	138	2.614	25	1.646	311.8
E 2	**RP1**	6.5	800		7.2	44	0.833		0.284	53.8
	RP2	7.3	733	-9	7.2	20	0.379	55	0.146	27.7
E 3	**RP1**	11.4	2067		24	202	3.826		2.309	437.3
	RP2	10.7	1467	-41	24	100	1.894	50	1.071	202.8
E 4	**RP1**	12.9	2867		165.9	300	5.682		3.861	731.3
	RP2	12.5	2333	-23	165.9	146	2.765	51	1.831	346.8
E 5	**RP1**	6.5	2467		145	124	2.348		0.811	153.6
	RP2	7.3	1800	-37	145	24	0.455	81	0.176	33.3
E 6	**RP1**	9.4	733		12.8	142	2.689		1.331	252.1
	RP2	0.83	267	-175	12.8	48	0.909	66	0.4	75.7
E 7	**RP1**	3.5	800		11	22	0.417		0.076	14.4
	RP2	4.2	600	-33	11	36	0.682	-64	0.152	28.7
E 8	**RP1**	0.2	533		6.1	46	0.871	0.008	1.6	0
	RP2	0.2	467	-14	6.1	38	0.720	0.006	1.1	0
E 9	**RP1**	0	0		3.1	0	0.000	0	0	0
E 10	**RP2**	0	0		2.9	0	0.000	0	0	0

Table 5.3 shows that overland flow was recorded for events 1 to 8, and that nothing was measured for event 9 and 10. The rainfall intensities that were recorded during this period were too small to generate any overland flow.

Nitrate concentrations were measured for Events 1 to 8 for both runoff plots. Measured concentrations between the two plots showed a very small percentage difference, except for event 6. Event 6, when compared to the three previous events, yielded an unusually high number of runoff plot tips when considering the intensity of the event. This may be attributed to the antecedent soil moisture conditions created by the three previous high intensity storms. The relatively low intensity event of 12.8mm/h therefore resulted in much higher than expected overland flow measurements due to the already saturated conditions of the soil. In addition, the field that runoff plot 1 was constructed in may well have been top dresses with a very small amount of fertilizer. This top dressing would have been completed by the farmer in response to the growth stage of the younger sugarcane. A similar process was done on runoff plot 2 at an earlier stage in the study, just before event 2, and the increase in nitrate concentration within plot 2 can be seen in Table 5.3.

Nitrate concentrations may have some correlation to the suspended solid concentrations in that nitrate have been observed to show a similar event response trend (increase and decrease) during each event,. The transport of particulate Nitrate is not uncommon and has been recorded in many case studies to date (Kjerfve, 1973). The largest effect on the suspended solid yields is the vegetation itself. Plot 1, as previously discussed, has younger sugarcane than that of plot 2, and so effects such as vegetation cover and root depth influence the amount of overland flow generated form plot 2. These factors will be discussed at greater length later in this section.

The general trend is that plot 1 yielded greater nitrate loads than plot 2, except for Event 7. The yield measured from runoff plot 1 during event 4 shows both the highest nitrate concentration and load readings for all events sampled. When comparing the nitrate loads between the two plots, runoff plot 1 yields much more than that of runoff plot 2 (with both plots having exactly the same soils). It may be concluded that the effect of the younger sugarcane in runoff plot 1 is more marked when considering loads as opposed to concentrations. These trends are also displayed when assessing the suspended solid loads, and hence the younger sugarcane in runoff plot 1 having a more marked effect on loads is also true when considering suspended solids.

Antecedent soil moisture conditions, while not measured directly during this study, need to be taken into account. Event 4 has the highest intensity event, and also measured the highest nitrate and suspended solid concentrations and loads, as well as the largest volume of runoff from the plots. This event was preceded by the second largest intensity event of the study, only 3 days before, and so the water table and soil moisture conditions within the soil profiles were already saturated. This resulted in an increase in overland flow and hence yields from the plots. Antecedent soil moisture conditions also have a similar effect on smaller intensity events, with event 6 resulting in larger than expected runoff volumes and hence nitrate and suspended solid loads due to the existence of a high water table and catchment soil moisture conditions that showed signs of saturation.

In the runoff results detailed in table 5.3, it is clear that RP1, the plot with the younger sugarcane, yields greater runoff than that of RP2 for all events except Event 7 and 8, the only two winter rainfall events that yielded overland flow. It is clear that overland flow is more prevalent from sugarcane fields with less vegetation cover and hence shallow root systems. This trend was most evident during summer events.

The lower the percentage vegetation cover, the less interception loss occurs, thereby adding to the overland flow volume. Vegetation cover also decreases raindrop impact, and hence enhances infiltration rates, thereby decreasing the amount of overland flow occurring. Root depth is also a contributor towards overland flow characteristics. A more developed crop will have a more developed root network, hence stabilizing the soil surface and subsurface. This soil stability leads to an increase in infiltration capability, and hence a decrease in overland flow volume. Soil type is consistent across both runoff plots, and so differences in soil type response did not need to be considered.

5.2.3 Observed Flume Characteristics

Flumes provided valuable data that allowed for the comparison of catchment responses between both flumes and the runoff plots. This comparison allowed for the assessment of dominant processes that contributed to the movement of nitrate and suspended solids through the upper catchment, from the field through to the small catchment scale.

A detailed discussion of the observed responses to 4 follows. This is typical of the general method of analysis for each of the 10 events.

General trends show a lag between the two flumes (Figure 5.1). Flume 1 generally has a very sharp rising limb compared to that of Flume 2. This may be attributed to the location of the flumes and the drainage areas. In addition, the response of the flumes, as well as the plots, is closely influenced by the nature and season of the events.

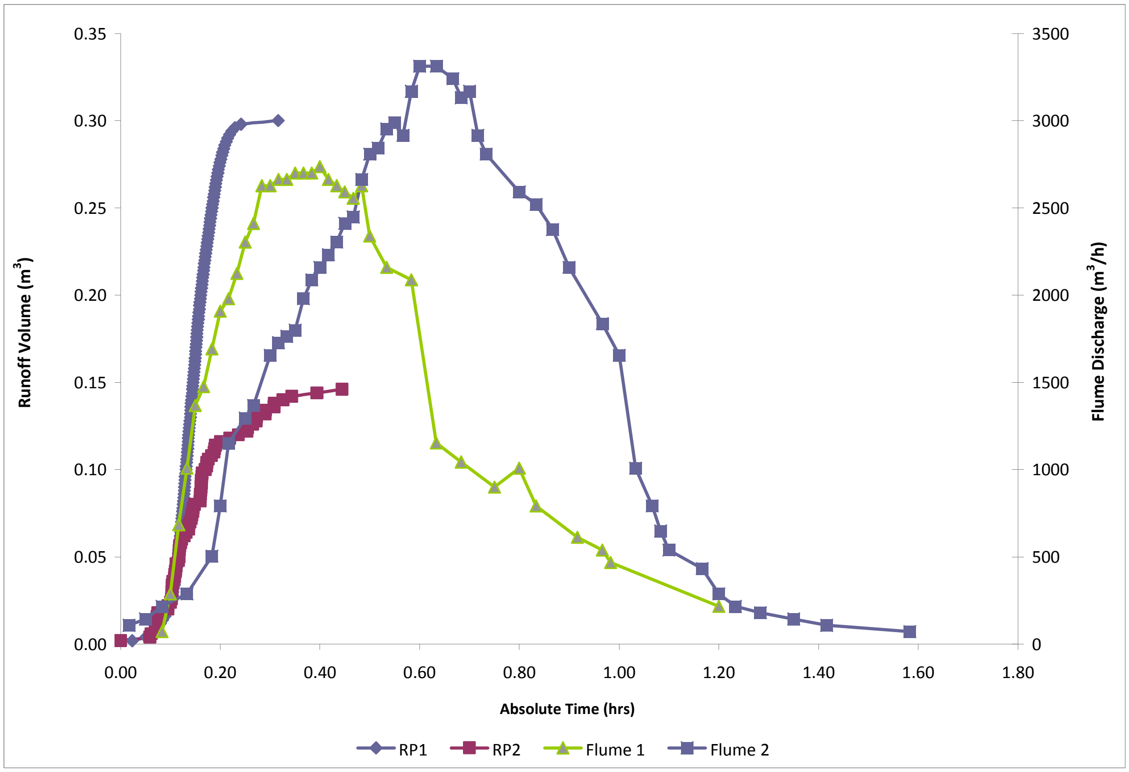

Figure 5.1 Observed Overland Flow and Flume Discharge (Event 4)

Table 5.3 shows measurement trends and correlations between the overland flow at plot and flume scales for the summer Event 4. RP 1 has three month old cane at an average height of 500mm, whereas RP 2 has four month old cane at an average height of 1.1m (measured as the smallest and largest visible plant average). The effect of the difference in growth stage is clearly evident in Table 5.3. RP 2 was observed to have yielded almost half the volume of runoff (0.146mm) than that of runoff plot 1 (0.3mm). Table 5.3 shows that the rate of overland flow measured at both plots displays similar initial surface runoff characteristics (both curves follow a similar rising pattern), after which the effects of better infiltration, vegetation cover and root depth take effect and decrease the amount of surface runoff measured by plot 2.

There is a clear lag in runoff/streamflow generation between the observed datasets of the runoff plots and the flumes. This can be expected, as the flumes are located further down the catchment, and tend to respond slightly slower than a runoff plot due to the fact that larger flows are measured at a larger scale of observation. The travel time is greater (due to distance) and flumes also include a certain portion of flow from subsurface contributions. It may be proposed that where the two flume hydrographs meet on the falling limb, that this contribution is made up largely of subsurface flow. These trends are evident throughout most measured datasets for Events 1 to 10 (Appendix B).

Event 4 is the highest intensity event of the 10 sampled events and shows the general trends measured at the runoff plot scale and flume scale for the summer rainfall events. When assessing events that occur further on in the season such as frontal systems (Event 5, 7 and 8 for example) where the nature of the rainfall is characterised by a lower intensity, long duration event, this lag is more marked (Appendix B). It is also evident that subsurface contributions become more prominent during winter events because of the decrease in surface runoff during these events. Figures B7 and B8 in Appendix B show such trends. There is also a lag between observed flow response at Flume 1, and that observed at Flume 2 (Figures B4 and B5 in Appendix B), which may be attributed to the location of Flume 2 within the catchment, being situated at a larger scale to that of flume 1 as the channel flow and storm contribution take longer to reach and contribute to flume 2 than they do flume 1 (Figure 5.1). Intensities have been calculated for measured flows passing through each of the flumes. When considering event 4 for example (the highest intensity rainfall event), Flume 1 reaches a maximum intensity of 16.09mm/h after 24 minutes, whereas Flume 2 reaches a maximum intensity of 5.71mm/h after 36 minutes. The runoff plots reach a maximum intensity of 30mm/hr and 13mm/hr respectively for plots 1 and 2, indicating a decrease in flow intensity as overland flow moves into the channel system. This would suggest that as overland flow moves through the system, it’s velocity is decreased due to surface friction and obstructions, the gradient changes in places to become more gentle, and some of the overland flow infiltrates as it moves through the system. This indicates that the smaller the catchment area, the faster the time to peak flow. These calculated intensities indicate that the upper catchment responds that much quicker to stormflow than that of the lower catchment, and this is substantiated by the respective hydrographs in Figure 6.7, where Flume 1 displays a more rapid rising and falling limb, and a quicker peak than that of Flume 2. The two hydrographs then meet again and continue on a similar falling pattern. This may be seen as the subsurface contribution to the hydrograph, and the approach to the base flow level of the catchment.

Measured overland flow values also display similarly consistent trends for events 1 to 6 during the summer rainfall months. However, Event 1 displays a much larger volume of runoff and sediment yield to that of similar intensity events observed (Figure 5.2). Event 1 is a standard event in terms of intensity for the wet season (of the study area) of 2006 however, a large volume of runoff (0.184mm) was observed from the runoff plots in comparison to rainfall measured. Figure 5.2 gives a graphical representation of the event from the field scale, with both runoff plot 1 and 2 graphed against the event's hydrograph obtained from Flume 1 (overland flow data discussed in section 6.1.1). It is clear from Table 5.3 that the timing of an event plays a vital role in the movement of nitrate and suspended solids through the system, with particular reference to the planting season of the crop in question. A bare field with no crop, or a young crop, is expected to contribute more towards overland flow, suspended solid and nitrate values, as well as increase the respective nitrate and suspended solid loads yielded.

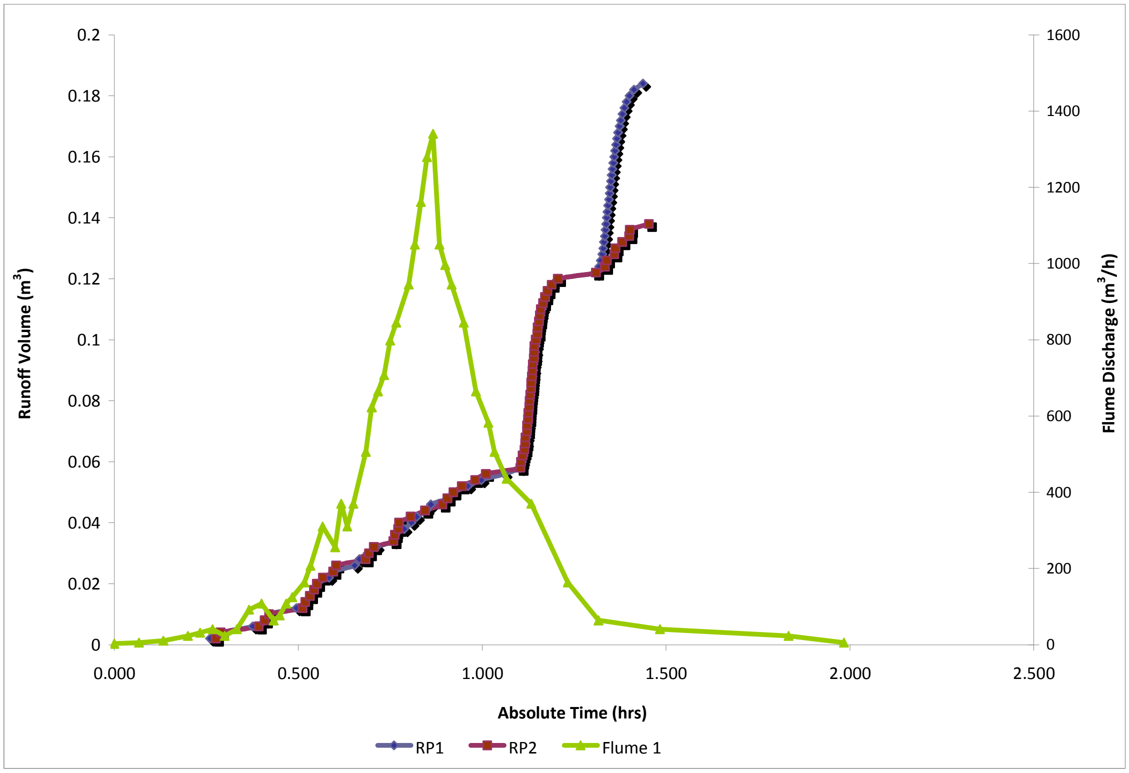

Figure 5.2 Observed Overland Flow and Flume 1 Discharge (Event 1)

Tillage and ploughing practices at the beginning of the planting season break up surface soil and loosen the top soil. This aids the planting process and initial growth stages of the seed, but makes the soil more vulnerable to wet season events of high intensity and low duration. The first event of noticeable intensity therefore dislodges a larger proportion of topsoil than an event occurring at the end of the wet summer months, and so suspended solid readings are that much more noticeable during events at the start of the summer months as opposed to the beginning of the winter months when soils are much more stable and root networks have developed and added more structure to the soil profiles.

In general, it has been observed and measured that the flumes in the upper catchment display different characteristics between summer and winter months due to a change in rainfall structure. In summer, a large volume of water passes through the flume in a short time, resulting in high flow intensities and large loads of nitrate and suspended solids and. It is evident from the results that overland flow is the greatest contributor to the rising and initial falling limbs of the respective event hydrographs, after which subsurface flows contribute largely. The antecedent soil moisture conditions during summer months contribute largely to the hydrograph dominance of processes such as overland flow. During winter months, antecedent soil moisture conditions are much lower, and combined with the low intensity, long duration nature of the events during this season, very little overland flow is observed and so rainfall contributes directly to subsurface processes. The observed flows and intensities at Flume 1 and 2 during these winter events are largely due to subsurface contributions and not overland flow contributions.

The timing of the overland flow yielded in relation to the hydrograph of Flume 1 is consistent. Overland flow from a runoff plot compared to that of the flumes increases proportionally as the rising limb of the hydrograph increases, with a slight lag in time. This lag in time may be attributed to the time it takes for the rainfall portion to travel over the surface of the field/plot and move through the runoff plot system to the logging system of both the plots and the Flumes.

As a general observation (Appendix B), as the falling limb develops, the frequency of runoff yield decreases more markedly from RP2 than from RP1. This may be attributed once again to the difference in sugarcane growth stages between RP1 and RP2. It is at this stage of the event that the difference in runoff characteristics between the two plots becomes evident. As the falling limb of the flume hydrograph develops, RP1 clearly yields additional overland flow volumes than that of RP2. Events 2 through to 8 show similar trends, with measured overland flow similar for both plots at the beginning of the event, with differentiation between the plots becoming more evident as the flume hydrograph develops (refer to appendix B).

Further explanation of these general runoff trends may be offered by considering the saturation capabilities of the soils, in particular antecedent soil moisture conditions. Having already mentioned factors such as vegetation cover, root depth and raindrop effect, the saturation properties of the soils contained within the two runoff plots will certainly vary (based on these factors). RP1 is therefore more likely to reach saturation quicker than RP2 because of vegetation cover, root depth and raindrop influences. The two overland flow plots deviate at specific points throughout the 10 events. This specific point may be attributed as the stage at which the soils in RP1 become saturated. Once the soils are saturated, a sudden increase/peak in overland flow is evident for RP1, while RP 2 continues at the normal non saturated rate of overland flow generation.

Runoff characteristics are more easily identifiable when events such as thunderstorms occur (in this study, the summer months are typically characterised by thunderstorm events, whereas the winter months are generally characterised by frontal systems). It is evident from the data gathered (Appendix B) that the larger events with a shorter duration display easily recognizable and clearly identifiable runoff characteristics. Events 1 to 6 are all summer rainfall events, and evidence of the nature of their plots can be seen in Appendix B.

The winter rainfall events are that much harder to confidently assess as there is no real pattern or trend that is clearly evident. Characteristics of runoff properties are less easily identifiable when an event has a low intensity and longer duration, such as Event 7.

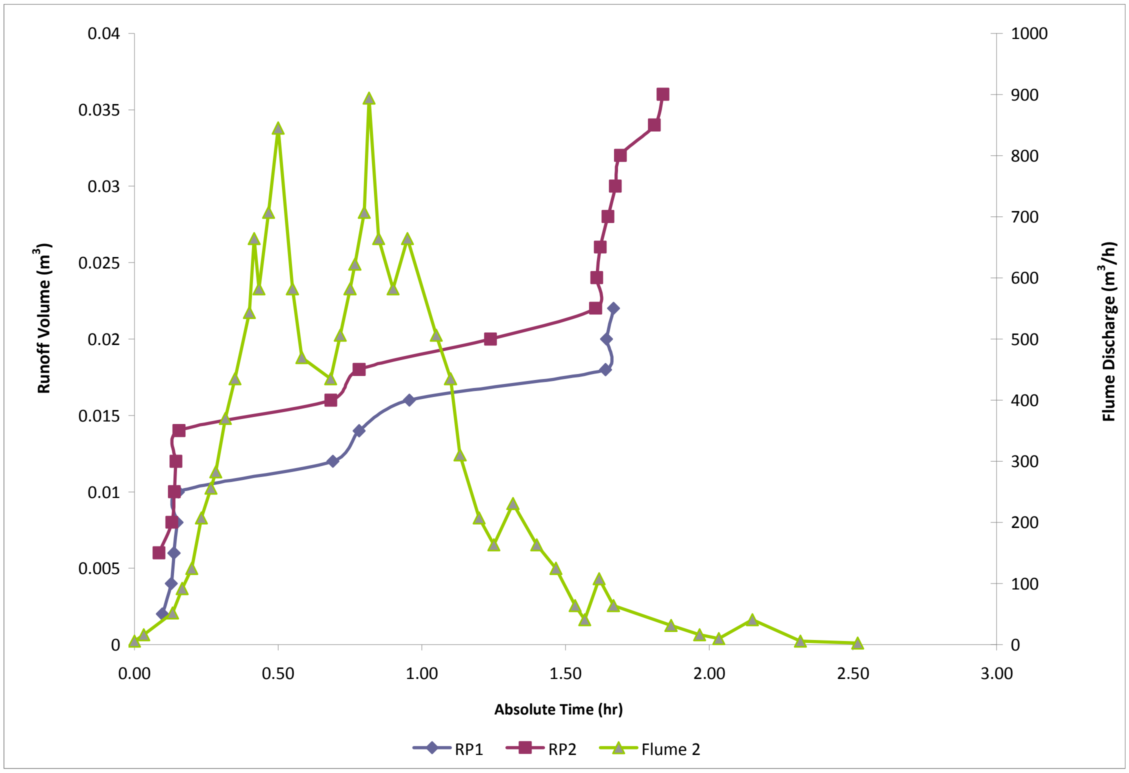

Figure 5.3 Observed Overland Flow and Flume 2 Discharge (Event 7)

While the general trends described above are still evident, it is that much harder to identify and confidently propose these trends as representative for these types of events (winter rainfall). With such a small volume of surface runoff being generated, a more erratic hydrograph and runoff response is observed (Figure 5.3). Winter events show several peaks in the hydrographs for events 7 through to 10 (such as Figure 5.3), whereas summer events show a single rise, peak and fall in the hydrographs for Events 1 to 6 (such as Figure 5.2). These hydrograph characteristics are consistent and expected.

5.2.4 Flume Concentrations

Water samples were gathered throughout the Mkabela Catchment for the ten events selected for analysis. The installed ISCO sampler gathered samples during events at each of the Flumes, and analyzed for suspended solids and nitrate. Nitrate concentrations were measured and graphed for all sampled events. Concentrations were further represented as loads to enable comparisons between concentration and load values for the catchment. The general trend is evident when assessing Appendix C. Summer events show a clear trend difference to that of the winter events. All summer events (Events 1 to 6) show a nitrate concentration peak occurring before the hydrograph peak, whereas the winter rainfall events (Events 7 to 10) show a much more erratic behaviour, with nitrate concentration peaking after the hydrograph peak. It has previously been identified that overland flow dominates the hydrograph during the summer months. The nitrate concentration figures contained in Appendix C would substantiate this conclusion, as the nitrate peaks occur during the rising limb of the event hydrograph. As the catchment produces overland flow, it transports nitrate in solution with the initial volume of flow through to the flumes, resulting in a nitrate concentration peak before the hydrograph peak. Nitrate concentration then decreases afterwards, as the amount of available nitrate has already been transported from the point source. Figure 5.7 illustrates a typical summer event and response characteristics of Nitrate Concentration in comparison to the event hydrograph. The rising limb of the hydrograph is observed to contribute most to the nitrate concentration within the upper Mkabela catchment. The nitrate concentration plot also displays a very similar shape to that of the event hydrograph, indicating that nitrate react more immediately than overland flows within a catchment.

When performing a general assessment of the trends measured from nitrate and suspended solid concentrations in relation to the event hydrographs, there is a clear increase in peak flow between Flume 1 and Flume 2, however a noticeable decrease in the maximum nitrate and suspended solid concentrations. Event 4 (Appendix C4) recorded a maximum flow rate of 2109m^3/h at Flume 1, and 6274m^3/h at Flume 2, almost three times the flow rate at Flume 2 than at Flume 1. This can be expected, as Event 4 was the highest intensity event of the 10 sampled events (165.9mm/h) and also recorded the highest volume of rainfall at 47mm. However, the recorded nitrate concentration dropped from 6.5mg/l at Flume 1 to 5.9mg/l at Flume 2, and the recorded suspended solid concentrations dropped likewise from 800mg/l to 533.3mg/l, largely due to the increase in channel flow and the effects of dilution. The decrease in nitrate concentration may be attributed to the majority source of the nitrate, being the plot itself. Flume 1 was located in the upper catchment, amongst newly planted sugarcane, and so the application of chemical, many containing nitrate, would have been more prevalent at the plot scale, resulting in the high concentration of nitrate. In between the two flumes, nitrate may be deposited en route either in the furrow channel or in field, resulting in a decrease in the concentration at Flume 2. Furthermore, the decrease in suspended solid concentration may be attributed to the location of the bare, young crop plots as well. As will be described later in this section, soil particles are most susceptible to be dislodged and transported from a bare field, or one that has a young crop. These types of fields are most evident in the upper catchment, above Flume 1, where the gradient of the landscape is greater than the gradient in between Flume 1 and Flume 2, hence resulting in more sediment being mobilised in solution. As the gradient lessens after Flume 1, some of the larger soil particles lose momentum and deposit in channel, as the velocity of the channel flow decreases. These result in a decrease of SS concentration measured at Flume 2. Furthermore, the deposition of soil particles in between the two flumes (as the velocity of channel flow decreases during the event aftermath) may also account for some of the decrease in nitrate (in solution) and phosphate (as attachment) concentrations.

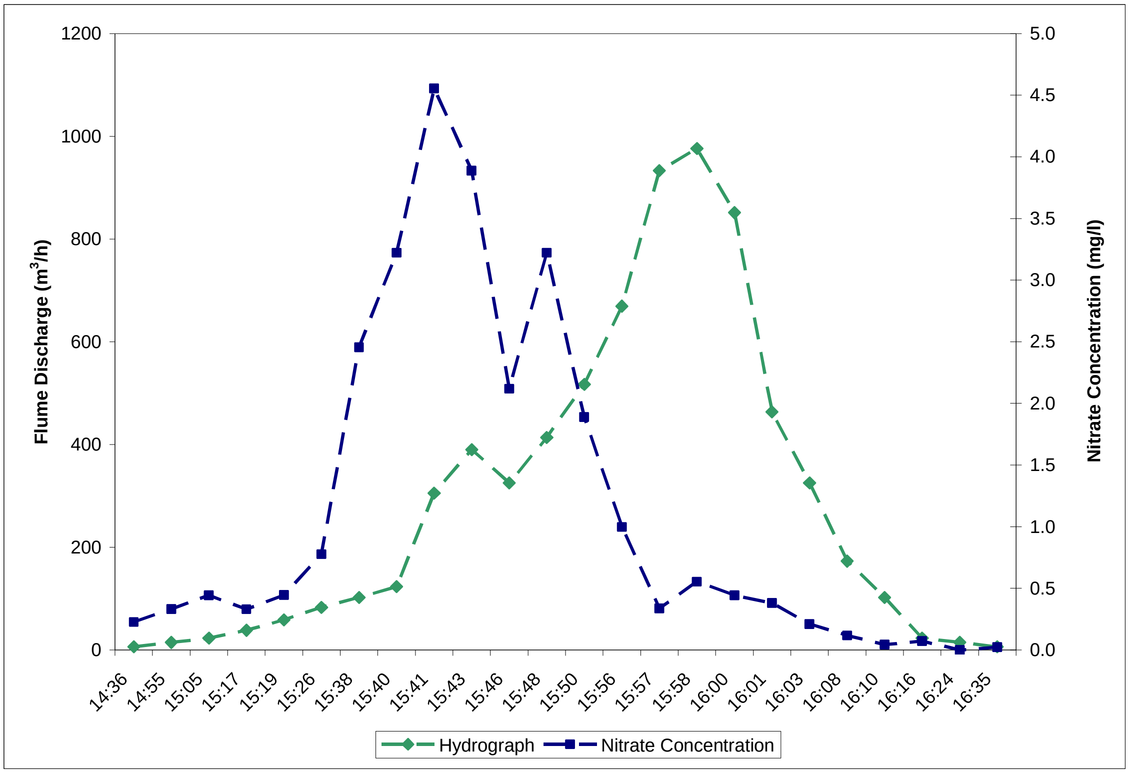

Figure 5.4 Nitrate Concentration and Event Hydrograph - Event 3, Flume 1

Event 3 and Event 7 will now de detailed to illustrated the observations and trends identified during the study.

While overland flow contributes most to the hydrograph during summer months, it has been observed that subsurface flows contribute most to event hydrographs during winter months (as results for winter graphs show minimal to zero overland flow results, both at runoff plots and the flumes). This is further substantiated when considering the winter event plots in Appendix C, where the nitrate concentration peak lags behind the hydrograph peak. Subsurface flow takes a considerably longer period to move through a catchment and reach the flume, and so the nitrate concentration lag can be expected, and confirms the thought that subsurface flows are the most dominant during the winter month events. Figure 5.4 illustrates the delayed lag in nitrate concentration for a winter event. The falling limb of the hydrograph is observed to contribute most to the nitrate concentration within the upper Mkabela catchment.

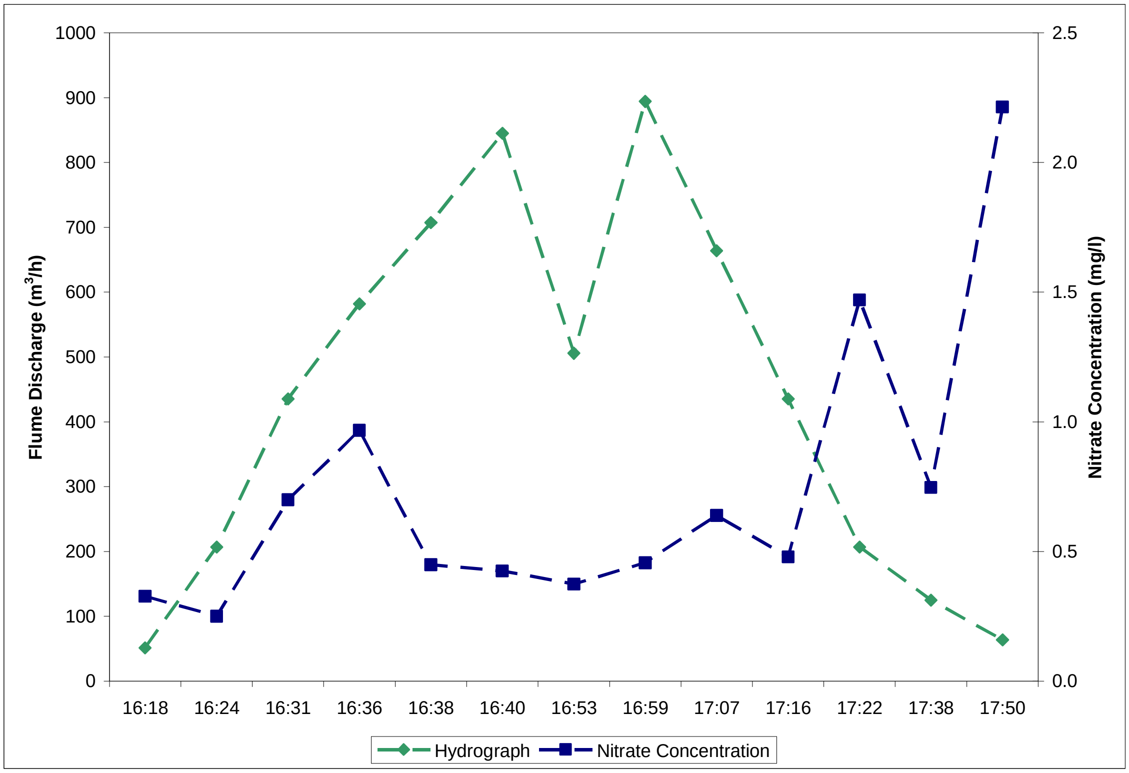

Figure 5.5 Nitrate Concentration and Event Hydrograph - Event 7, Flume 2

The greatest yield of suspended solids (SS) is observed at the very beginning of the event. Sediments are most likely to be yielded at the beginning of the event when the initial forces of runoff and raindrop impact dislodge the sediments and transport them in suspension as part of the runoff component. After the first 2 to 3 events, the topsoil exposed has been eroded due to exposure to these events, and hence suspended solid loads are high (such as those shown in Figure 5.4 at Flume 1 for Event 3).

For the summer events, the peak of SS concentration occurs before the peak of the event hydrograph, whereas during the winter events, the SS concentration peak is after the initial peak of the event hydrograph.

SS concentration is increased where there is bare, open ground, and where there is loose soil particles unbound to roots, vegetation or crops. With depth in the soil, so the bond between soil particles increases and becomes stronger, increasing the force needed to dislodge the particle and transport it in suspension as a SS. Therefore, the concentration of SS's in suspension depends on the crop present in a field, its growth stage and the field's agricultural condition (recently ploughed or not). A typical summer event is illustrated in Figure 5.6, and the peak of the suspended solids concentration is clearly evident.

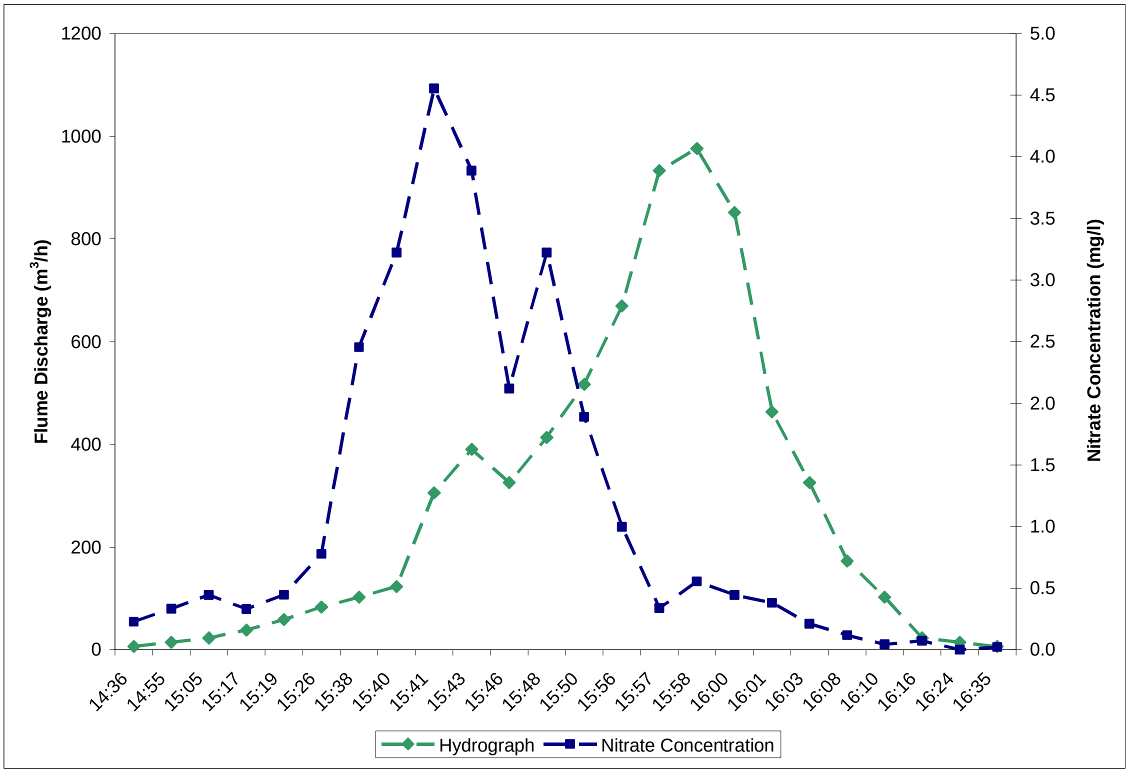

Figure 5.6 Suspended Solids Concentration and Event Hydrograph - Event 3, Flume 1

Furthermore, the maximums in the SS concentration coincide closely with the peaks of the nitrate concentration. This trend is consistent for all summer events, as illustrated in Appendix C. Nitrate and SS display similar characteristics in the Mkabela catchment, even though their mechanisms of transport are different (solution vs suspension). Further substantiation of this suggestion is based on the sampling data obtained from the 'Dam In' and 'Dam Out' points, where there is a marked decrease in both nitrate and suspended solid concentrations between the two points, clearly indicating that dams act as natural water quality filters. The Ungauged points within the catchment will be described at a later stage.

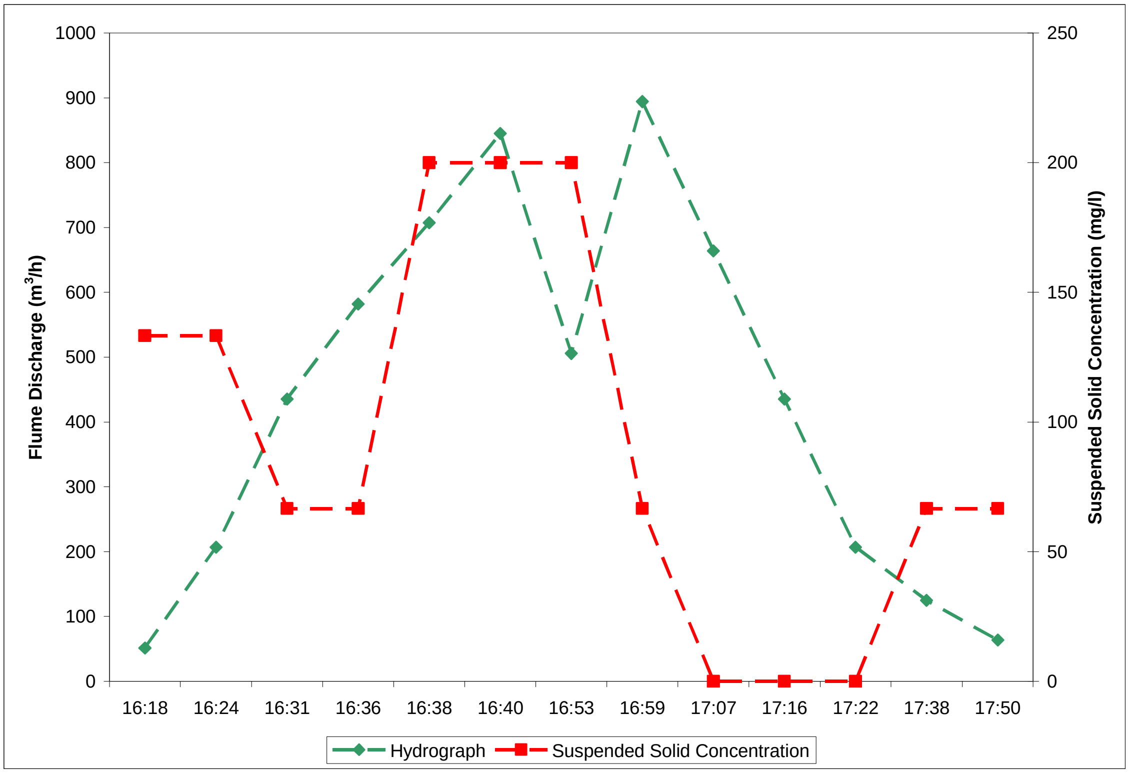

Figure 5.7 Suspended Solid Concentration and Event Hydrograph - Event 7, Flume 2

The suspended solid concentration trend during the winter events, such as Figure 5.8, may be seen as more erratic. There is an initial peak in concentration due to a small volume of overland flow that occurs, after which subsurface flows contribute most to the hydrograph. Subsurface flows are not conducive to the transport of suspended solids, as the velocity of flow is often not great enough to transport the particles. This is evident in Appendix C (Graph 10 b), where only a small concentration of suspended solids were recorded, most probably having been generated through subsurface flows that had increased in velocity as the event had progressed.

Winter events, where a low intensity and long duration rainfall is experienced, often records several peas in both the concentration values and the hydrograph flows due the erratic nature of the rainfall, whereas the summer events show a more clear trend and single concentration and flow peaks.

5.3 Ungauged Monitoring Sites

The remainder of the Mkabela Catchment was sampled manually using grab samples at intervals during each of the 10 events. A channel morphology study was conducted at each of the ungauged sampling points, and rating curves were developed using the channel morphology data. Rating curves allowed for an estimate of discharge at each of the ungauged points. The key question in this study is the translation of NPS pollution from the small scale through to the large catchment scale, with an emphasis on detailed observation within the upper catchment. Nitrate and suspended solid concentrations have been obtained for the ungauged points for each of the ten events, and so a comparison of concentrations may be conducted. Appendix C contains the graphs for each of the events. The graphs plot nitrate and suspended solid concentrations over a series of scales (using different locations), from the point scale through to the large catchment scale.

General trends can be identified when assessing the movement of pollutants through the system for each of the events. Measured nitrate concentrations are highest in the upper catchment (Figure 5.9 below), and decrease steadily through to the large catchment scale. This may be expected for several reasons. Firstly, nitrate are applied to the fields in the upper catchment, and so the concentrations in the upper catchment can be expected to be higher because the scale of observation coincides with the point of nitrate application. The larger scales of observation are further away from the scale of application, and so the concentrations measured at these scales are less due to the effect of dilution. This may be attributed to the volume of overland flow, channel flow and subsurface flow which is that much smaller in the upper catchment, and so concentrations can be expected to be higher. At the larger scales, there is a greater volume of channel flow, and so concentrations become more dilute. When assessing loads, however, there is an inverse relationship that exists compared to concentrations.. Throughout the observed data, the nitrate concentrations and loads, as well as those of suspended solids, have decreased in between the ‘Dam In’ and ‘Dam Out’ sampling point. This may be attributed largely to the decrease in flow velocity as channel flow enters the dam, causing SS to deposit within the dam. Only an extremely large event that has the capability to cause several currents in the dam will mobilize the deposited soil particles and result in an increase or transfer of nitrate and suspended solids through the 'Dam Out' sampling point (Figure 5.8 and Appendix C). Samples taken from within the cane and maize are understandably the highest, as surface runoff has directly interacted with the point of contact where chemicals have been applied.

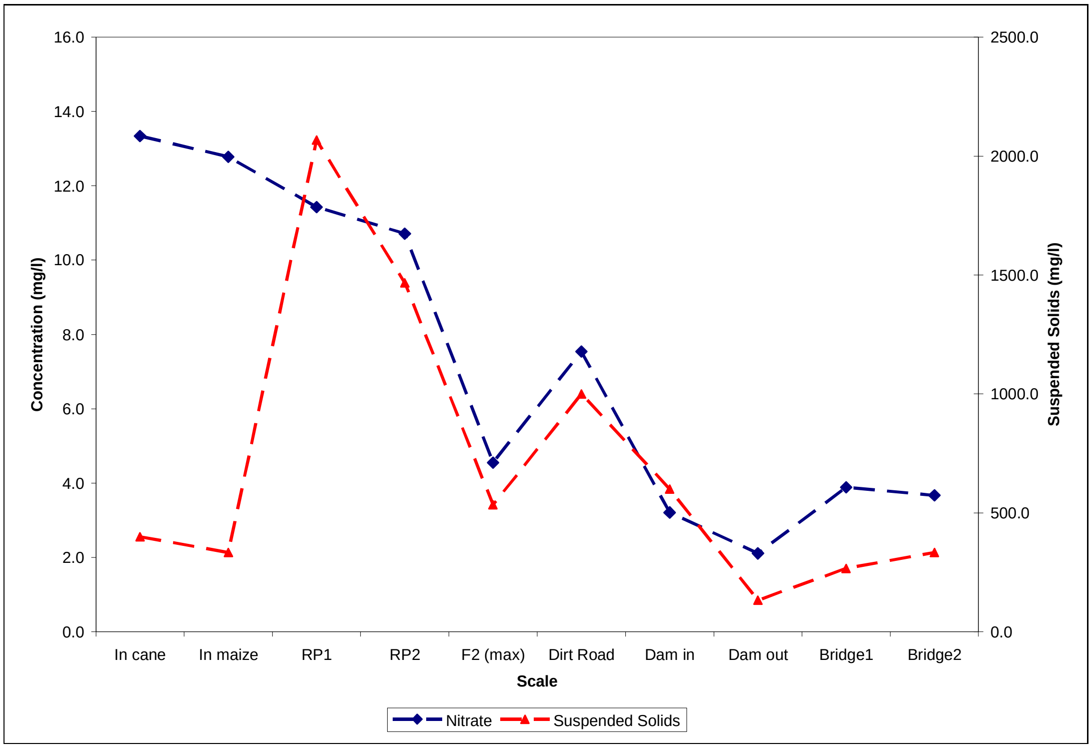

Figure 5.8 Nitrate and Suspended Solid Concentrations: Small to Large Catchment Scale, Event 3

The observed trend shown for suspended solids is similar, with the greatest erodibility being observed at the upper catchment scale. Land preparation and condition are the influences on this.

Scaled concentrations of nitrate and suspended solids are more consistent and display clearly identifiable trends during summer months. The nature of the rainfall event, short duration high intensity, is the major contributing factor to this as overland flow is the dominant process. Winter events, however, are more erratic in nature, and subsurface flow is the major contributing process to Nutrients.

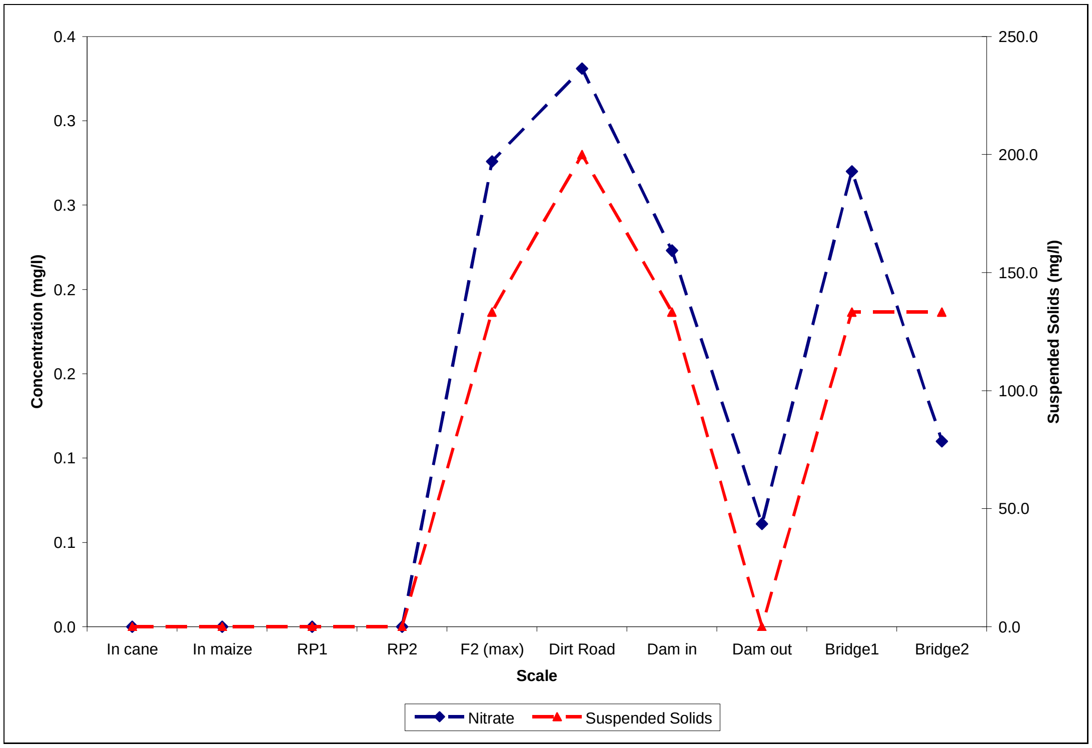

Figure 5.9 Nitrate and Suspended Solid Concentrations: Plot to Large Catchment Scale, Event 9

Winter rainfall events are that much more challenging to observe due to the low intensity nature of the event, resulting in low flow conditions. During such low flow events, nitrate concentrations are much lower than during summer events, and sediment load is less due to the lack of overland flow. Event 9, for example, measured zero overland flow.

The movement and concentration of both nitrate and SS through a system is directly influenced by the volume of surface water within the system, and so the intensity and volume of rainfall is a vital component when considering the movement of nutrients and sediments through a system. For this reason, emphasis during analysis has been placed on the nature of the events, namely summer or winter events.

This is evident when comparing specific events, such as the nitrate concentration values from Bridge 2 during Event 1 (summer event) to that of corresponding scale of observation but for Event 10 (winter event). Event 1 measured a nitrate concentration of 1.92 mg/l compared to Event 10, which measured only 0.117mg/l, some 16 times less concentrated than an equivalent sample taken during Event 1. Sediment data is somewhat erratic during these winter frontal events. It would be expected for sediment readings to decrease in general, as sediment yield is largely dependent upon high intensity events that generate large volumes of overland flow, hence mobilizing soil particles, as well as ground and vegetation cover.

When comparing the sediment load values measured at Bridge 2 during Event 1 and Event 10, both values were the same (66.7mg/l). This is surprising for two events with such different intensity characteristics. Measured suspended solid data (Appendix C) shows that the sediment load at larger scales increases through the season from Event 1 (66.7mg/l) through to Event 6 (886.7mg/l), after which it decreases to a possible base level of 66.7mg/l. The increase coincides with the summer events, and the decrease with the winter events, suggesting that the nature of the event, combined with the vegetation cover is the controlling factor when assessing the movement of NPS-P through different scales. The increase cross the summer events may be attributed to two factors. The intensity of the events increased, resulting in greater energy for transport and dislodgement of particles. In addition, the antecedent soil moisture conditions became more saturated as events occurred. The soil profiles therefore became saturated quicker, resulting in quicker generation of overland flows, as well as greater volumes. This increase in overland flow results in larger quantities of SS. The majority of mobilization of sediment occurs at the plot and field scale. Sediment then takes time to be transported through the catchment, reaching sampling points such as Bridge 2 several events after it was originally mobilised.

Further substantiation of this is gained by considering the sediment loads for RP1 from Event 1 through to Event 6. Consistent sediment concentrations are measured of approximately 2000mg/l. This large sediment concentration in the water system is then added to the overall system and passed through subsequent monitoring scales within the catchment. These subsequent monitoring scales clearly show an increase in sediment yield leading up to Event 6, indicating that the sediment originating from the upper reaches of the Mkabela catchment moves slowly through the system and is later measured at a much larger scale. In order to effectively monitor such movement and be able to place a timescale on sediment transport within the Mkabela Catchment, it is suggested that a tracer study be completed for more accurate results.

Although concentration is a useful indicator when considering NPS pollution, one needs to consider it in conjunction with nitrate loads at each of the sampling points. Although concentration may decrease as the scale of observation increases, the total nitrate load increases as the scale of observation increases.

5.3.1 Nitrate Loads

While concentration gives an indication of the presence of a nitrate in comparison to the amount of water within a system, the total nitrate load at a given scale is a vital consideration in this study. The scaled trend observed when assessing nitrate loads is directly opposite to that of concentration. Nitrate loads increase as the observation scale increases, and so can be seen as inversely proportional to concentration.

Seven observation points for Nitrate loads have been used throughout the study within the Mkabela Catchment. Loads have been calculated for:

- Each segment as a separate entity that is area weighted (i.e. without any upstream influences, expressed in kg/ha).
- The cumulative load observed at each observation scale that is area weighted (i.e. a value at each observation scale that takes into account the loads generated from previous observation scales, expressed in kg/ha)

Each of these assessments provides vital information when assessing the loads of nitrate moving through different scales of observation.

When assessing each segment individually, it is evident that the largest contributing scales of nitrate loads (kg/ha) are at the field scale and the large catchment scale, in particular during Events 4 and 5 (in the upper catchment), where Flume 1 measured 0.18kg/ha and 0.06kg/ha nitrate respectively for the two events. Table 5.4 shows the load generation trends observed, excluding upstream contributions.

Table 5.4 Nitrate Loads Excluding Upstream Contributions (kg/ha)

Segment Loads (kg/ha)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flume 1	0.02	0.01	0.04	0.18	0.06	0.01	0.00	0.01	0.00	0.00
Flume 2	0.00	0.00	0.00	0.15	0.03	0.00	0.01	0.00	0.00	0.00
Dirt Road	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00
Dam In	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dam Out	0.01	0.00	0.04	-0.02	-0.01	0.00	-0.01	0.00	0.00	0.00
Bridge 1	0.03	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Bridge 2	0.02	0.01	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00

It is evident from Table 5.4 that nitrate load generation is prevalent at the upper catchment scale, with the Dirt Road and Dam Out often producing negative load values. The Dirt Road sampling point has a very low slope and a wide flow channel exists, promoting slow flows and deposition within the channel. Negative values for Dam Out are experienced during events of medium to low rainfall volumes and intensity. As mentioned previously, dams within the Mkabela catchment have been observed to act as water quality filters, decreasing the nitrate load and concentration moving through the catchment. Except for Event 1, 3 and 5, where high intensity events produced enough overland flow entering the dam and turbulence within the dam to result in an increase in nitrate loads at the spillway of the dam. The major contributing factor would be the velocity of the flows entering the dam. Mixing also eliminates several temperature zones within the dam. Temperature zones often prevent sediment and nitrate from moving within an impoundment. The increase in velocity of the flows entering the dam has a huge effect on the mixing of water at different temperatures. Assessment of each scale individually provides an indication as to where the largest loads of NPS pollution are generated. The Mkabela Catchment has the largest loads produced at the field and large catchment scale, with scales in between contributing on a very small scale.

Table 5.5 Cumulative Nitrate Loads (kg/ha)

	Event:									
Location (loads in kg/ha)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flume 1	0.391	0.19	0.73	3.01	1.1	0.23	0	0.13	0	0
Flume 2	0	0	0	8.52	2.72	0	0.41	0	0	0
Dirt Road	0.267	0.09	0.376	0.41	0.09	0.39	0.03	0.01	0	0.03
Dam In	0.081	0.54	1.875	2.83	1.16	0.42	2	1.41	0.07	0.05
Dam Out	1.051	0.21	6.726	0.43	0.34	0.085	0.71	1.24	0.02	0.02
Bridge 1	42.34	20.9	25.97	21.4	6.42	0.923	3.37	1.86	0.62	0.01
Bridge 2	74.17	35	58.23	61.6	6.5	2.09	5.87	4.77	0.61	0.73
Total kg/ha from Catchment	**74.17**	**35**	**58.23**	**61.6**	**6.5**	**2.09**	**5.87**	**4.77**	**0.61**	**0.73**
Rainfall (mm)	**22.0**	**18.0**	**30.0**	**47.0**	**29.0**	**13.0**	**17.4**	**18.0**	**16.0**	**11.0**
Intensity (mm/hr)	**19.1**	**7.2**	**24.0**	**165.9**	**145.0**	**12.8**	**11.0**	**6.1**	**4.1**	**3.8**

An alternative and informative means of representing and assessing the nitrate loads was through the cumulative loads for each scaled observation point. These values represent the cumulative load monitored at that sampling point, including contributions from upstream. Table 5.5 shows the cumulative nature of the nitrate loads across the Mkabela catchment. It is evident that the mass of nitrate measured increases with scale, with the major contributing scales being the large catchment scale (74kg for Event 1). Interestingly, the largest cumulative loads were observed during events 1 through to 4. These were not the highest intensity events, however, the loads recorded may be due to the application of nitrate on the crops in the catchment. These were done before Event 1 through to Event 3, offering a reliable explanation as to why events 1 to 4 measured the most cumulative nitrate.

5.3.2 Sediment Loads

Sediment and nutrients in water bodies may also originate from sources other than those associated with local farming practices, for example from the atmosphere (Paerl, 1997), remobilisation of bottom sediments (such is the case in the Mkabela Catchment within the dams) and bank erosion within stream channels (Walling, 2005). While these variables have not been measured directly in the catchment, it is important to take them into consideration when assessing the results.

Assessment of SS measured at each of the respective sampling points produces a set of results that coincide with the results tabulated for nitrate loads over corresponding scales. Nitrate loads were observed to experience a negative load per segment value during several events at the Dirt Road and Dam Out locations. A similar trend exists for SS loads per segment. A decrease in suspended solid loads was measured between Flume 2 and the Dirt Road sampling points. This may be attributed to the morphology and slope of the Dirt Road sampling point, being flat with a wide channel, thereby decreasing the flow velocity and resulting in deposition of both suspended solids and nitrate. As was measured with nitrate loads, the location that showed the highest SS load was Flume 1, and again Events 4 and 5 measured 0.538kg/ha and 0.349kg/ha, respectively, as the two largest in comparison to the other sampling points and events.

Table 5.6 Suspended Solid Loads (kg/ha) Excluding Upstream Contributions

	Event:									
(Monitoring Points)	**1 (kg/ha)**	**2 (kg/ha)**	**3 (kg/ha)**	**4 (kg/ha)**	**5 (kg/ha)**	**6 (kg/ha)**	**7 (kg/ha)**	**8 (kg/ha)**	**9 (kg/ha)**	**10 (kg/ha)**
Flume 1	2.2	0.8	5.0	21.7	20.0	1.5	0.0	0.6	0.0	0.0
Flume 2	0.0	0.0	0.0	0.1	8.0	0.0	0.5	0.0	0.0	0.0
Dirt Road	0.0	0.0	-0.1	-0.8	-2.4	0.3	-0.1	0.0	0.0	0.0
Dam In	0.0	0.0	0.3	0.5	0.2	1.0	0.1	0.1	0.0	0.0
Dam Out	0.2	-0.3	0.6	-3.9	-1.4	-6.6	0.0	0.0	0.0	0.0
Bridge 1	0.5	0.5	0.9	1.6	0.5	0.9	0.0	0.0	0.0	0.0
Bridge 2	0.0	0.2	2.7	8.3	-0.1	5.4	-0.1	0.0	0.3	0.3

The Dam Out sampling point displays similar characteristics to that of the Dirt Road sampling point, with several negative suspended solid readings recorded for a number of events. The readings are consistent with the nature of the sampling point, as was the case with the nitrate measurements. Sediments entering the dam at settle within the dam, largely due to the lack of velocity within the dam that would initiate or continue transportation, and deposit on the dam banks or floor. In summary, the greatest contributing scales are the plot and field scale, and the large catchment scale. The scales occurring in between these contribute very small amounts to the overall cumulative suspended solid values.

Table 5.7 Cumulative Nitrate Loads (kg)

	Event:									
(Monitoring Points)	**1 (kg)**	**2 (kg)**	**3 (kg)**	**4 (kg)**	**5 (kg)**	**6 (kg)**	**7 (kg)**	**8 (kg)**	**9 (kg)**	**10 (kg)**
Flume 1	36.6	13.4	85.4	368.7	340.2	24.7	0.0	9.4	0.0	0.1
Flume 2	0.0	0.0	0.0	773.6	802.9	0.0	36.9	0.0	0.5	0.0
Dirt Road	52.4	3.8	49.9	60.7	17.6	129.4	0.5	0.5	0.6	5.2
Dam In	8.1	48.0	350.4	537.7	207.6	1022.4	103.7	92.6	40.0	29.8
Dam Out	31.7	9.6	424.9	28.7	22.7	157.0	0.0	87.0	0.0	0.0
Bridge 1	729.9	807.2	1780.8	2502.7	799.9	1538.2	287.8	0.0	303.6	5.5
Bridge 2	793.7	1106.8	5287.3	13414.0	608.4	8625.4	219.9	0.0	736.8	417.3
Total kg from Catchment	**794**	**1107**	**5287**	**13414**	**608**	**8625**	**220**	**0**	**737**	**417**
Rainfall (mm)	**22.0**	**18.0**	**30.0**	**47.0**	**29.0**	**13.0**	**17.4**	**18.0**	**12.0**	**9.0**
Intensity (mm/hr)	**19.1**	**7.2**	**24.0**	**165.9**	**145.0**	**12.8**	**11.0**	**6.1**	**2.8**	**2.3**

Event 4 produced the largest mass of sediment from any of the ten events recorded, with a total of 13 414kg measured at the outlet of Bridge 2 (3.16kg/ha). The loads recorded clearly show a response to the type of event that occurred. Events 1-6 clearly indicate that summer events produce greater masses of sediment load than winter events. This can be attributed, as with nitrate trends during similar type events, to the high intensity and short duration of the summer events. Summer events generation large volumes of water at high velocities, and therefore induce particle dislodgement and transportation, resulting in higher readings of suspended solids. In addition, summer events are characterised by rain drops that are larger and travelling at greater velocities than winter events. Their impact with the soil results in further particle and sediment dislodgement, resulting in greater suspended solid measurements.

When assessing Events 1 and 2, it is evident that the latter yielded more SS (1107kg) than Event 1 (794kg), yet it had much lower rainfall intensity than Event 1. Event 1 was the first of the season, and so the ground conditions were dry and compact. Event 1 most likely performed as a ‘softening’ process, increasing the soil moisture content and breaking up soil clods. Event 2 then occurred, and the sediment that was yielded during Event 2 may well have been as a result of the actions and intensity of Event 1. However, this didn’t apply to Nitrate.

When quantifying the total loads of sediments yielded by each of the events, it is evident that when assessed as a value per hectare, that the Mkabela Catchment yields very little sediment at its outlet point Bridge 2. The largest yielding event, Event 4, yielded an average of 3.17kg per ha across the entire Mkabela Catchment. Reasons for such low yields of sediment may be attributed to good farming practices such as tillage and contour ploughing. . Siltation is an obvious side effect that would influence the volume capacity of the impoundments as sediments are deposited within the dams as a result of rainfall events. Event 8 is an interesting case study, as it yielded no sediment at the outlet point. The event was a very low intensity event (6.1mm/hr), and so sediment mobilization would have been extremely low, if any occurred at all. Table 5.6 shows that sediment was produced at the sampling point from the field scale through to the Dam Out sampling point, after which the sediment readings are zero. This may be attributed to a large dam that exists between Dam Out and Bridge 1. This impoundment may be acting as a total sediment filter during small winter events, resulting in minimal stream flow that contains on miniscule sediments that cannot be picked up by the equipment used in this study.

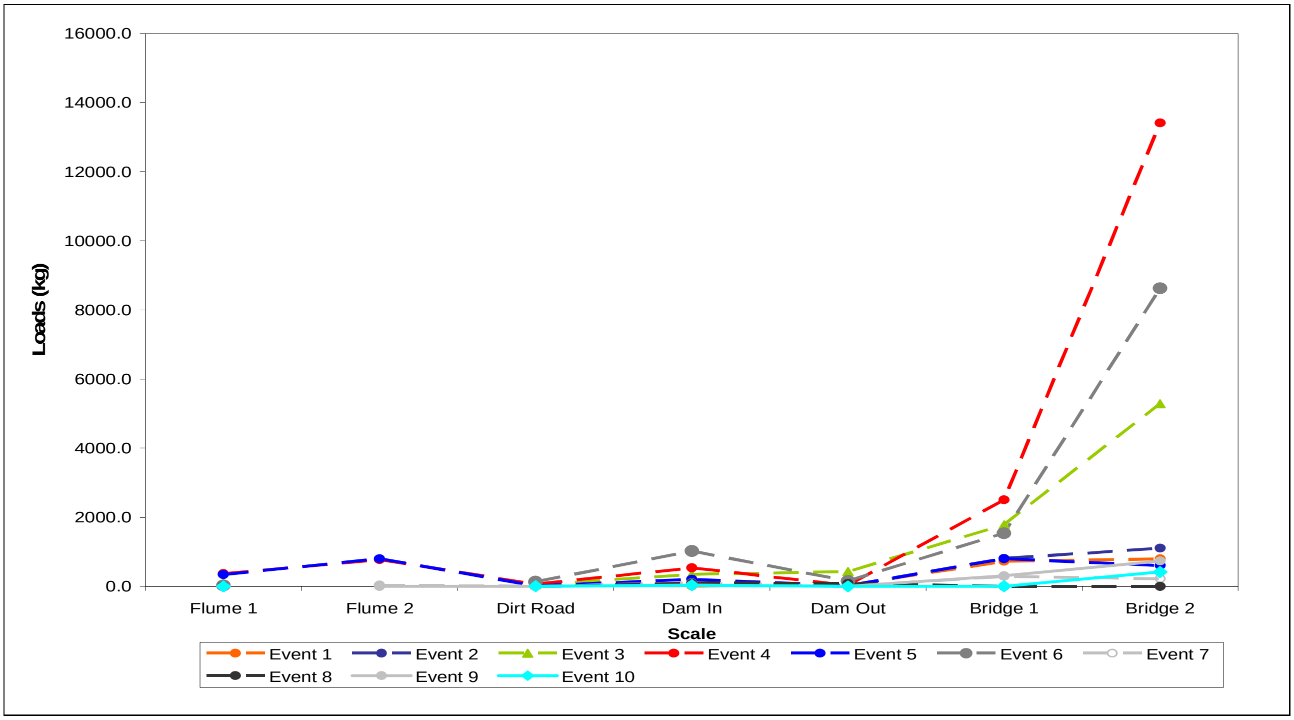

Figure 5.10 Cumulative Suspended Solid Loads (kg)

Figure 5.10 illustrates that the catchment area between the Bride 1 and Bride 2 sampling points contributes most to the overall yield of sediments. This is again consistent with the trends displayed by nitrate offering further evidence that suspended solids and nitrate behave very similarly to each other during rainfall events with reference to mobilization, transport, loads and concentrations.

6. CONCLUSIONS AND RECOMMENDATIONS

NPS pollution is subject to a variety of complex process and influencing factors that affect the movement of pollutants such as sediment and nitrate through a catchment. The movement of pollutants through a system, across varying scales of observation, posses a clear challenge in the understanding of processes involved in the regulation and driving of such movements.

The importance of scale in such observations has highlighted the lack of suitable models to effectively observe and measure the movement of NPS pollutants through a catchment, and so the need for a comprehensive model that addresses varying scales of measurement is not only lacking, but noticeably evident. Existing models such as SWAT, CREAMS, SWRRB and BASINS are effective in addressing a specific scale of measurement; however they fail to model processes that influence NPS pollution across different scales of observation and were never designed to do so. The WRC-NPS pollution study has identified the gap between scale specific models and catchment representative models, and aims to close the gap between these two through the eventual establishment of a catchment NPS pollution model that effectively addresses the translation of processes (how they vary and change over differing scales) and NPS pollution from the field through to the catchment scale of observation.

The inherent vulnerability of land as affected by rainfall patterns, soil type, slope and stream density have been identified as major contributors to the transport of nitrate and suspended solids within the Mkabela Catchment, all of which are outside the farmer’s control. However, this pattern of vulnerability is heavily modified by land use management factors which are under the farmer’s control, including land use, N and P inputs, cultivation practices, crop management and manure management (Evans, 2006; Sharpley *et al.*, 2001). The Mkabela Catchment shows signs of effective farming practices in this regard, substantiated by the measured results for suspended solids in particular, where a maximum of 3.17kg/ha was recorded during Event 4, a relatively low yield per unit area.

The main purpose of this study was to assess the movement of NPS pollution through the Mkabela Catchment, with the aim of identifying major contributing sites and processes within the catchment. It is clear that the nature of the rainfall event, combined with land use, slope and soil type, is the most defining aspect when assessing the transport of nitrate and suspended solids. Overland flow is the most dominant process during summer rainfall events, where large volumes of flow occur in a short period of time, resulting in leaching, mobilizing and transportation of both nitrate and suspended solids to larger scales. During the summer, the initial few events yield the largest mass of suspended solids and nitrate due to them coinciding with the preparation of the agricultural land and application of fertilizers. Winter events however, are dominated by subsurface processes, and so nitrate and suspended solids are less likely to be leached, mobilised and transported due to the lack of energy in the channel and subsurface flows.

It is believed that a clear gap exists in the modelling of NPS pollutants. The key conclusions to be taken from the research period include the following:

- the influence of dams on the movement of NPS pollution through a system affects the water quality and movement of Nitrate and SS.
- the preparation of agricultural land (followed by rain) results in an increase in suspended solid concentrations.
- the application periods for pesticides and fertilizers result in increases in sampled concentrations when sampled close to application periods
- the subsequent stage of growth of crops results in a marked influence on overland flow, and hence nitrate and suspended solid concentration. Developed crops decrease the amount of overland flow, SS yields and nitrate concentrations.
- topography influences the gradient of the land, and hence the transport of sediment and nitrate in solution. Low gradient areas in the Mkabela Catchment, such as the Dirt Road monitoring point, show clear signs of settling and deposition, thereby decreasing the SS moving through the system, until a larger event moves through and mobilizes the particles again.
- the nature and seasonal timing of the event has a major influence on the movement of NPS pollution through a system, as well as the dominant processes acting on NPS pollution. Major rainfall events (summer events) generate greater overland flow, and hence bigger SS yields. Minor rainfall events (winter events) produce less overland flow and more subsurface flow, decreasing the SS yields.

The following recommendations are made for future research conducted within the Mkabela Catchment, as well as general NPS pollution research:

- The development of an NPS model is crucial for effectively understanding and monitoring NPS pollution. All current models fail to address the translation of process from a field to a catchment scale, and it is this lack of adaptive characteristic that has caused such a gap in existing models. To develop a fully fledged operational model for NPS pollution will take some time and will need several more studies in varying catchments from that of the Mkabela. Certain processes need to be included at specific scales of observation. Groundwater and subsurface movement are particularly vital when considering the small scale observation. Dams and other impoundments have shown a clear ability to filter NPS pollution out of the mobile water system, and so any catchment including such features needs to include an impoundment option (for a model) or section (for a research project).
- Gradient and topography need to be identified within the river course system. Areas of low gradient need to be measured regularly and compared to upstream and downstream measuring points to determine whether deposition is occurring at that point in the catchment. This obviously has a vast impact on the movement of SS and nitrate through a system.
- Although good results were obtained for a large number of events during the sampling period, the quality of the data will be improved should all sampling points become automatic gauging points that are operationally sound. This would ensure that samples are all taken at exactly the same time during events, as opposed to manual grab samples which cause a minor lag in the results.

For NPS-P remediation, measures must be targeted at those areas of the catchment where combinations of landscape and land management generate the highest risk of nutrient pollution, in particular the field and plot scales. Targeting all subcatchments areas equally has been shown to be neither cost-effective (EPA 2003), nor likely to reduce pollutant discharge (Jokela *et al.,* 2004; Granlund *et al.,* 2005). Farming practices in the Mkabela Catchment are very effective, as shown by the sediment yield results, and so effort is being made to address NPS pollution. In addition, several wetlands and dams exist within the relatively small catchment, thereby acting as water quality filters and sediment traps throughout the Mkabela Catchment. In terms of the overall Mgeni Catchment, the Mkabela Catchment can be seen as a minor contributor to the overall NPS pollution within this larger catchment (provided data on the larger scale is available).

Future research within the WRC-NPS project should continue to sample from the designated research points and add several more seasons of data to the first year of sampling. This will ensure a greater accuracy in observed trends and help add to the justification of the hypothesis that scale contributes greatly to the movement and concentration of SS and nitrate through a catchment. Tracing experiments or observations would also be valuable in defining the sources and pathways of the pollutants.

In addition, once a reasonable number of seasons have been sampled and analysed within the Mkabela Catchment, the initiation and development of an effective, representative scaled NPS model that addresses the movement of pollutants throughout a whole catchment is necessary to be able to successfully model and predict the movement of NPS through catchment systems. In particular the effects of the controls afforded by the road crossing, wetland and farm dams should be taken into account in the modelling of sediment and nutrient movement from field to catchment scale.

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APPENDIX A

SCS-SA Output Estimates for Design of Flume 1 and Flume 2

H-Flume 1 Proposed Site (SCS-SA Output Estimates):

```
CATCHMENT NAME                    :  Wartburg
PROJECT NO                        :  Wartburg#1
RUN NO                            :  #1
TOTAL CATCHMENT AREA (km^2)       :  0.29
STORM INTENSITY DISTRIBUTION TYPE :  2
CATCHMENT LAG TIME (h)            :  0.44
COEFFICIENT OF INITIAL ABSTRACTION:  0.10

CURVE NUMBERS:           Initial    Final
  Sub-catchment 1         60        60.0

RETURN PERIOD (YEARS)                 2      5     10     20

DESIGN DAILY RAINFALL DEPTH (mm)     55     76     87    102

DESIGN STORMFLOW DEPTH (mm)
  Sub-catchment 1                   7.0   15.3   20.5   28.4

TOTAL RUNOFF DEPTH (mm)             7.0   15.3   20.5   28.4

DESIGN STORMFLOW VOLUME
(thousands m^3)
  Sub-catchment 1                   2.0    4.5    6.0    8.3

TOTAL STORMFLOW VOLUME              2.0    4.5    6.0    8.3
(thousands m^3)

COMPUTED CURVE NUMBER              60.0   60.0   60.0   60.0

PEAK DISCHARGE (m^3/s)              0.3    0.6    0.9    1.3
```

H-Flume 2 Proposed Site (SCS-SA Output Estimates):

```
CATCHMENT NAME                    :  Wartburg
PROJECT NO                        :  Wartburg#1
RUN NO                            :  #2
TOTAL CATCHMENT AREA (km^2)       :  2.00
STORM INTENSITY DISTRIBUTION TYPE :  2
CATCHMENT LAG TIME (h)            :  2.17
COEFFICIENT OF INITIAL ABSTRACTION:  0.10

CURVE NUMBERS:           Initial    Final
  Sub-catchment 1         60        60.0

RETURN PERIOD (YEARS)                 2      5     10     20

DESIGN DAILY RAINFALL DEPTH (mm)     55     76     87    102

DESIGN STORMFLOW DEPTH (mm)
  Sub-catchment 1                   7.0   15.3   20.5   28.4

TOTAL RUNOFF DEPTH (mm)             7.0   15.3   20.5   28.4

DESIGN STORMFLOW VOLUME
(thousands m^3)
  Sub-catchment 1                  14.0   30.6   41.0   56.9

TOTAL STORMFLOW VOLUME             14.0   30.6   41.0   56.9
(thousands m^3)

COMPUTED CURVE NUMBER              60.0   60.0   60.0   60.0

PEAK DISCHARGE (m^3/s)              0.6    1.4    2.0    2.8
```

APPENDIX B

ISCO generated hydrographs, Runoff Plot 1 and Runoff Plot 2 Tip Data for Events 1 to 8 for the upper Mkabela Catchment.

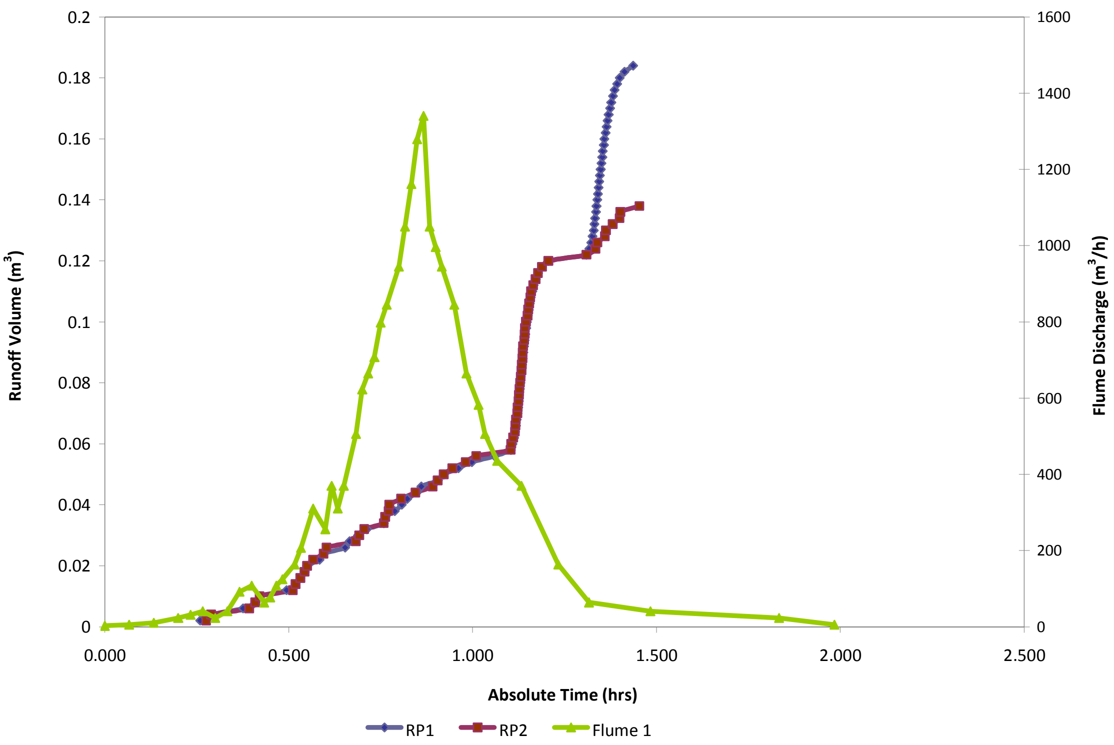

Figure B1: Event 1

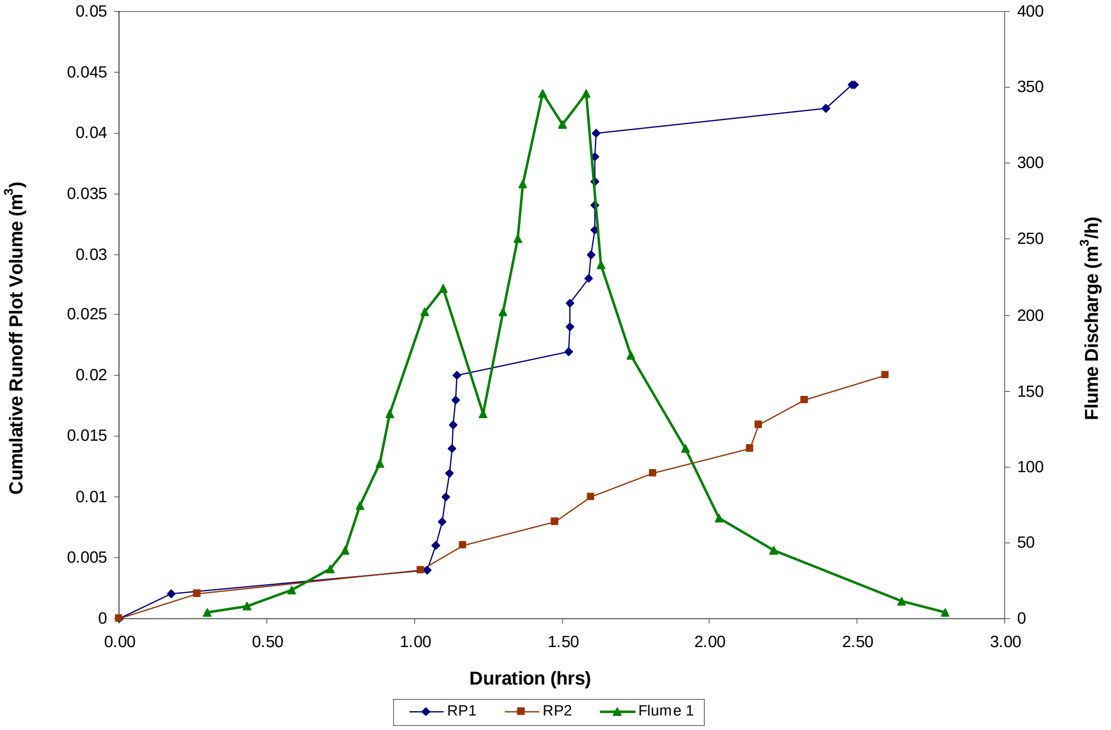

Figure B2: Event 2

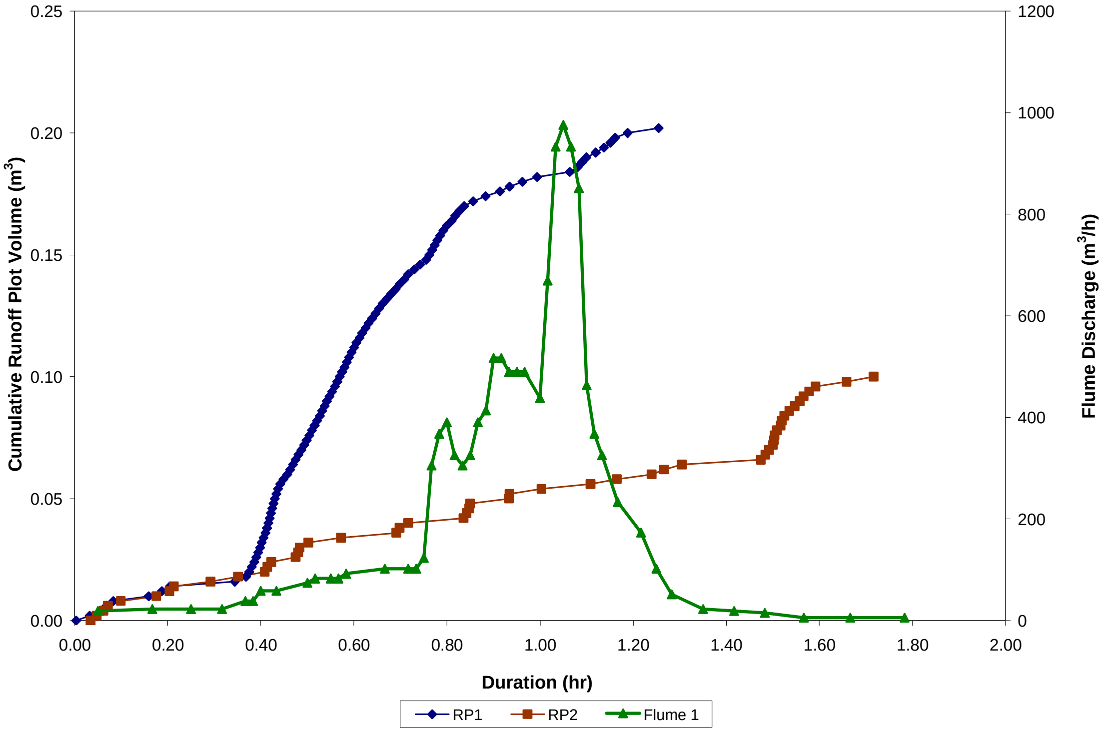

Figure B3: Event 3

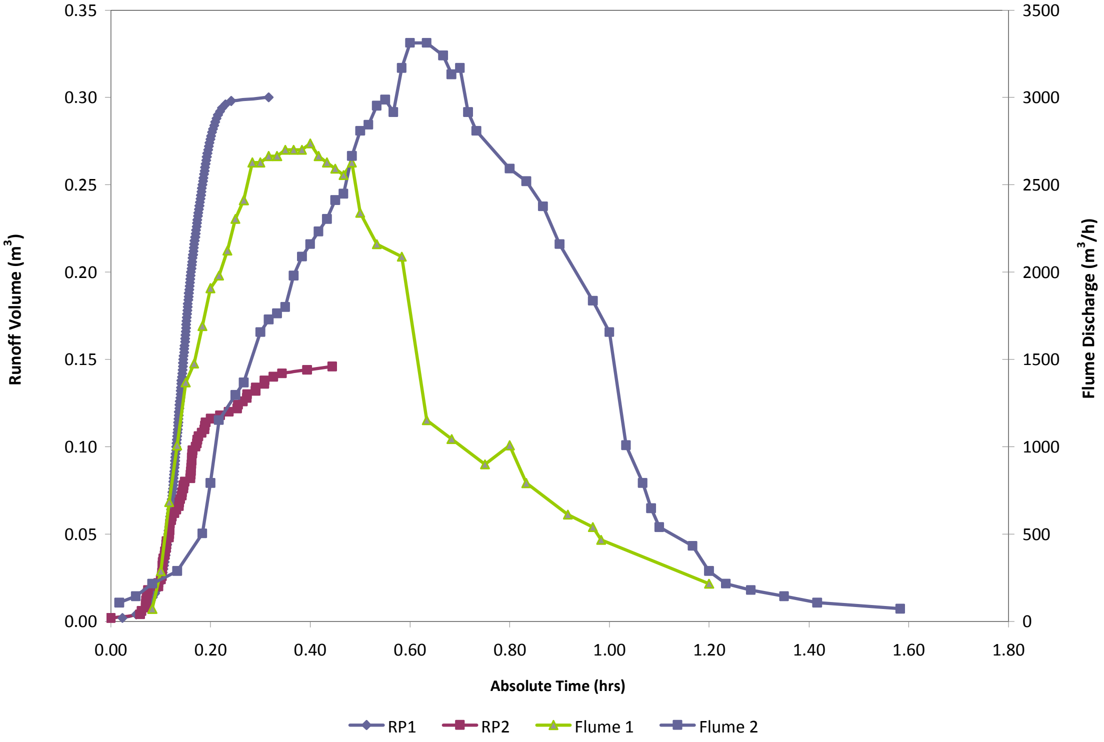

Figure B4: Event 4

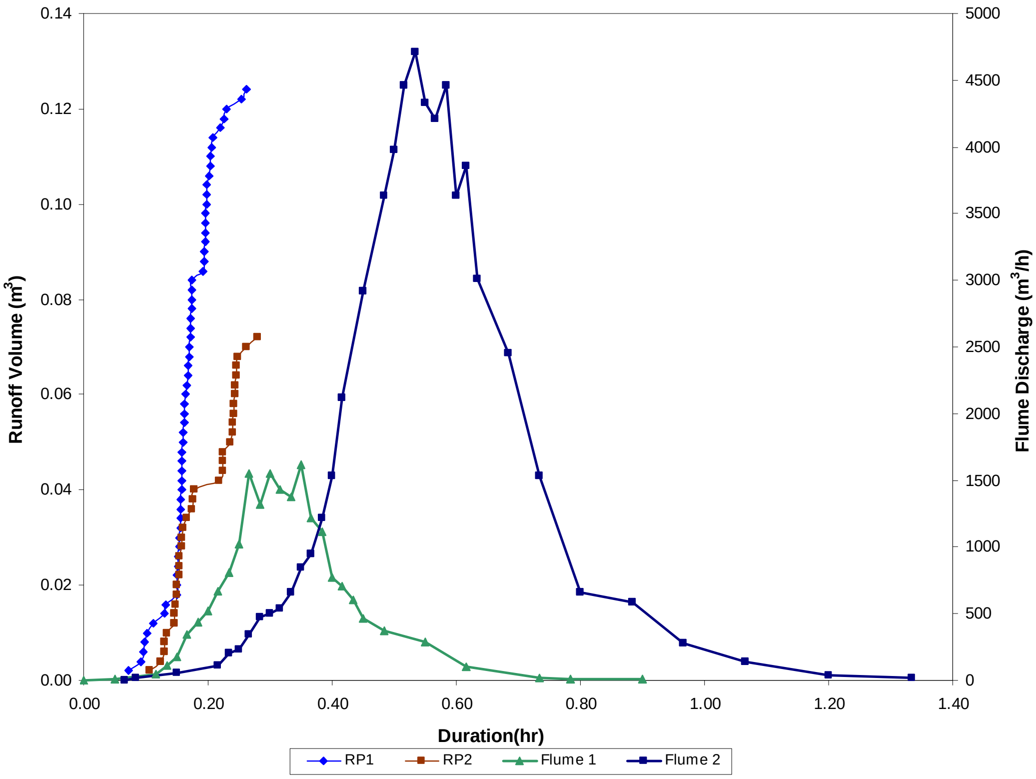

Figure B5: Event 5

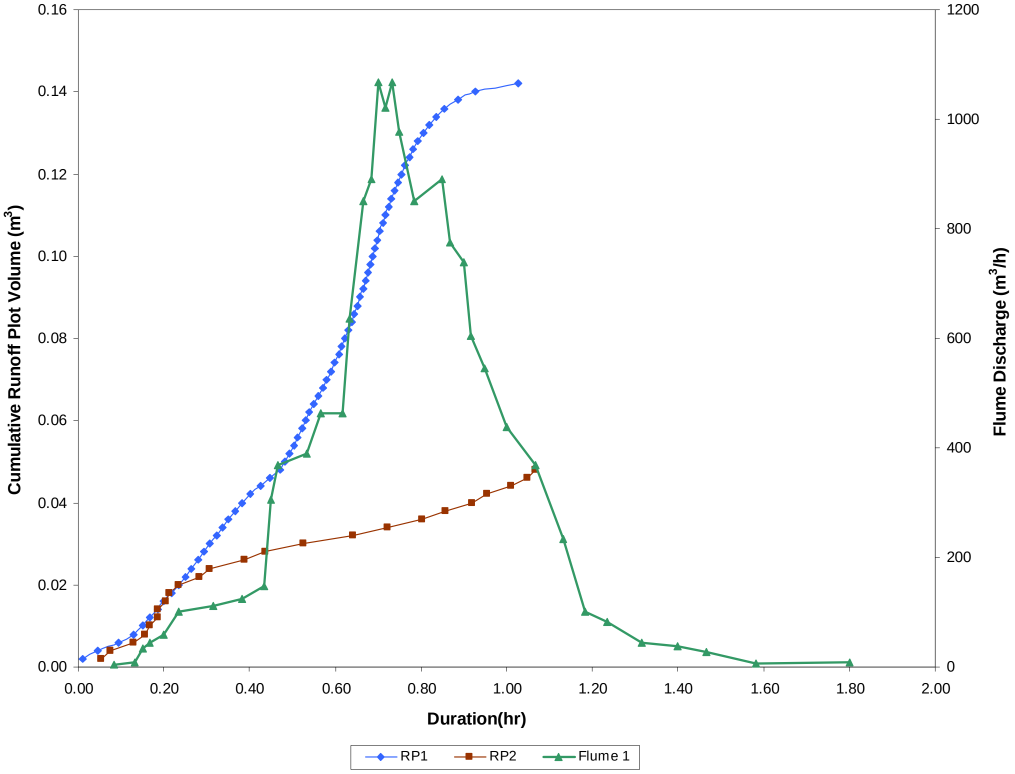

Figure B6: Event 6

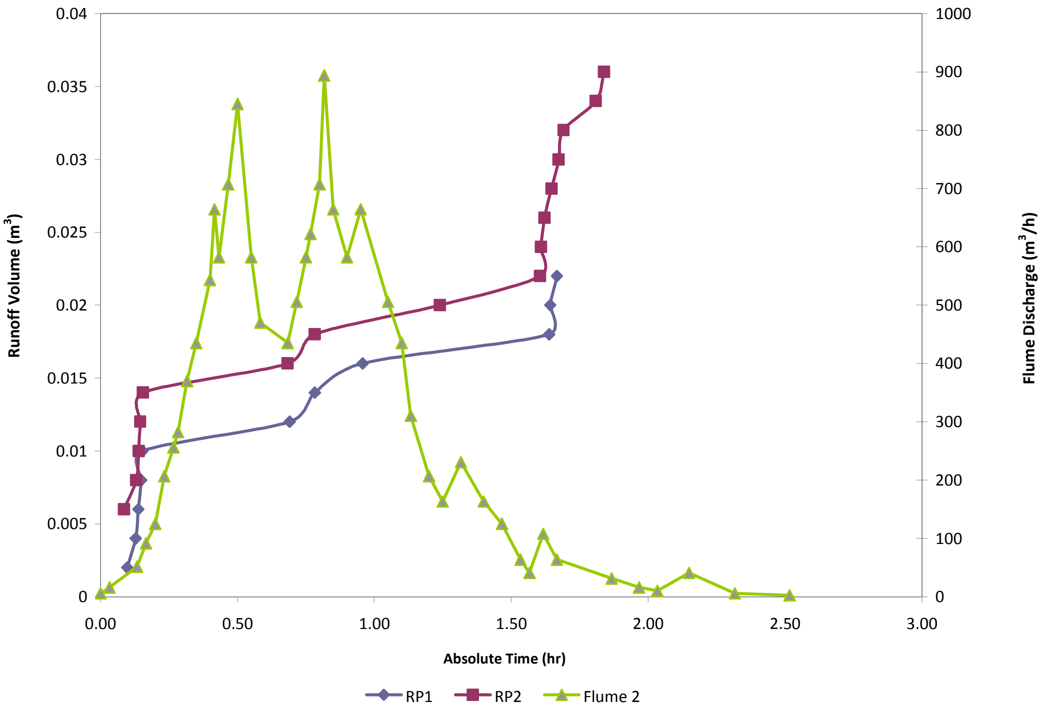

Figure B7: Event 7

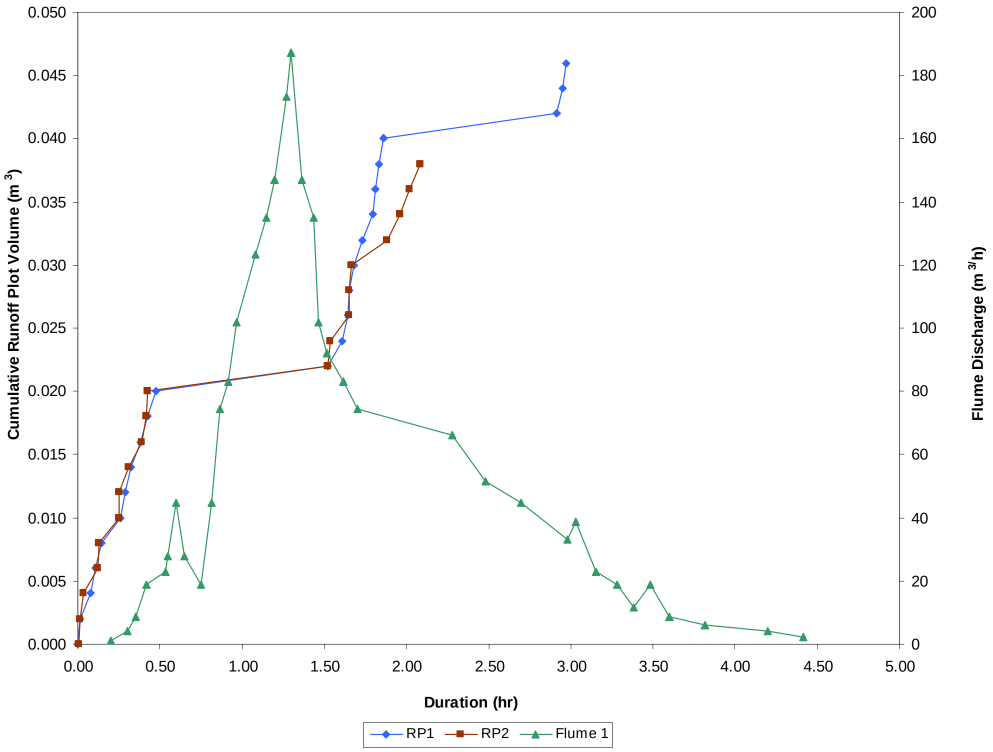

Figure B8: Event 8

APPENDIX C

Graphical Representation of Nitrate Concentration and Suspended Solids versus Event Hydrograph for Events 1 to 10.

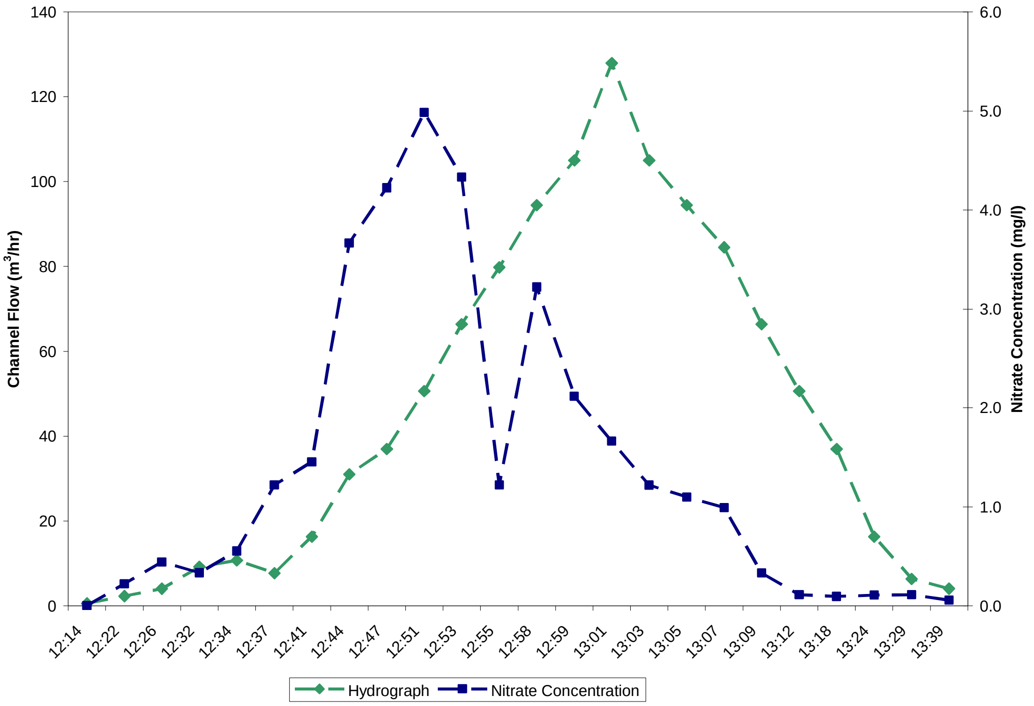

Figure C1 (a) Nitrate Concentration: Event 1 Flume 1

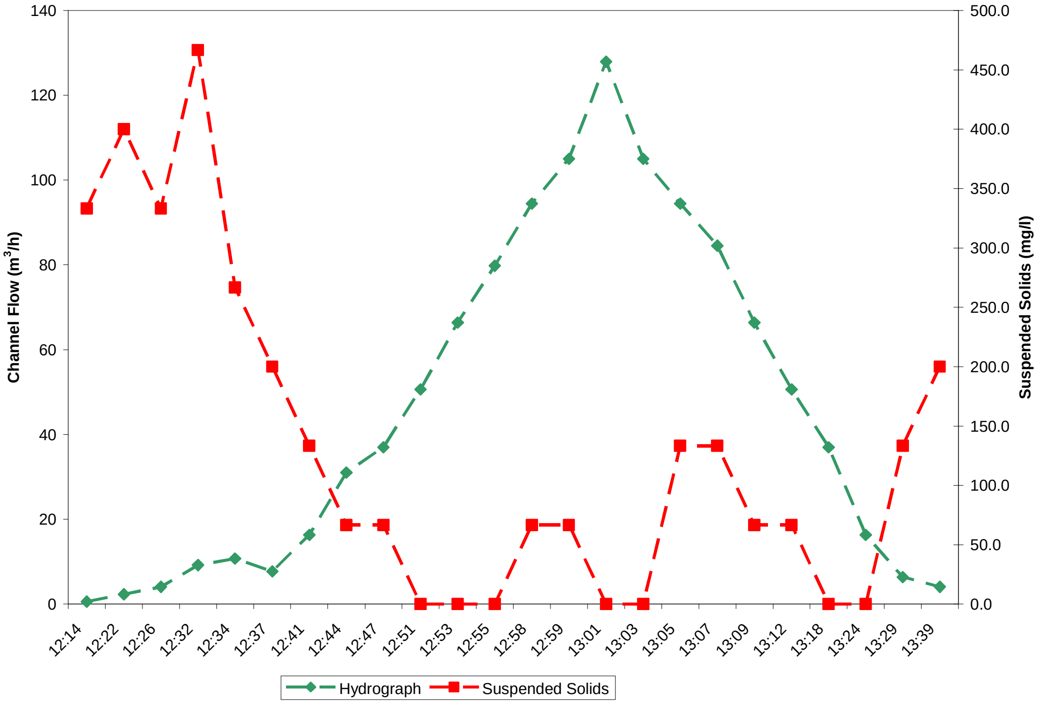

Figure C1 (b) Suspended Solids: Event 1 Flume 1

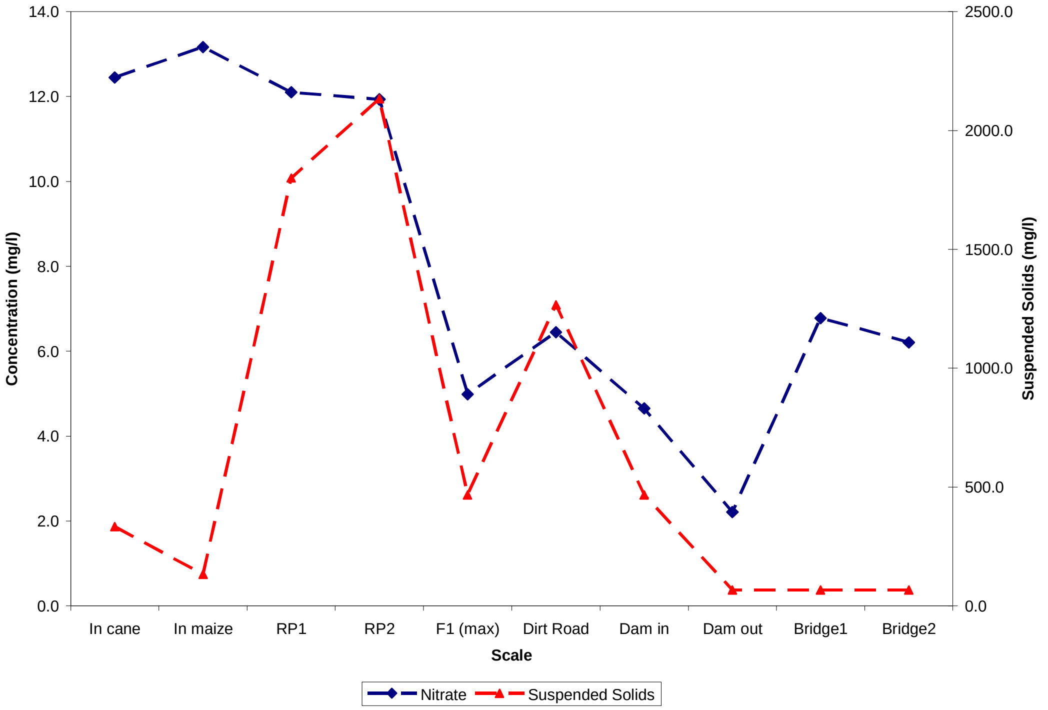

Figure C1 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 1

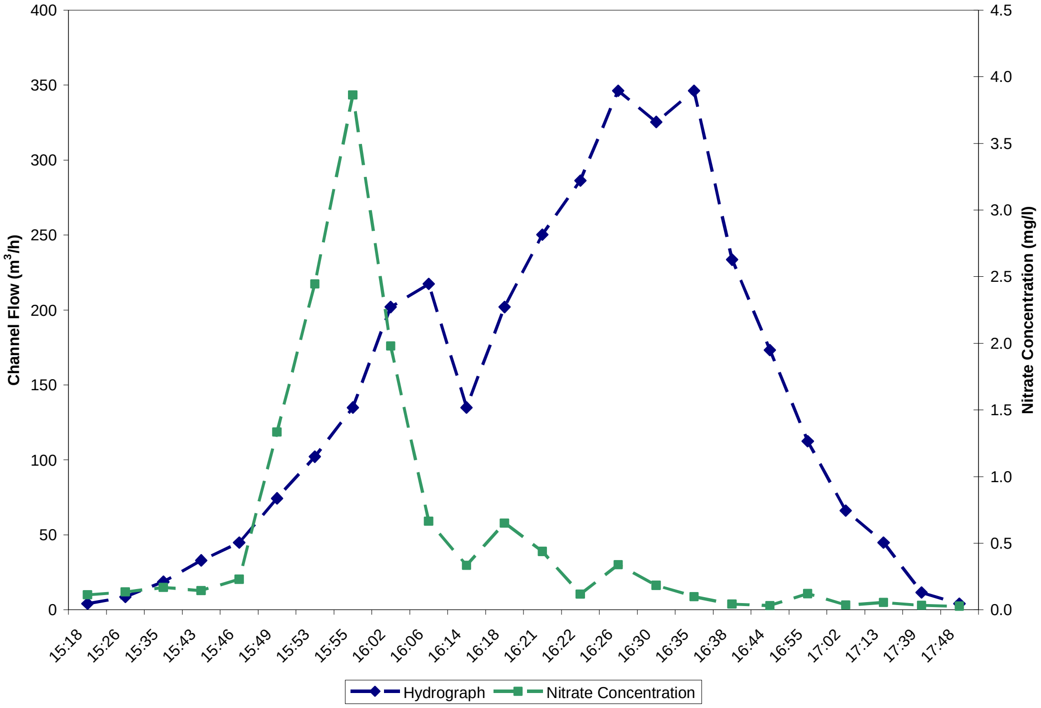

Figure C2 (a) Nitrate Concentration: Event 2 Flume 1

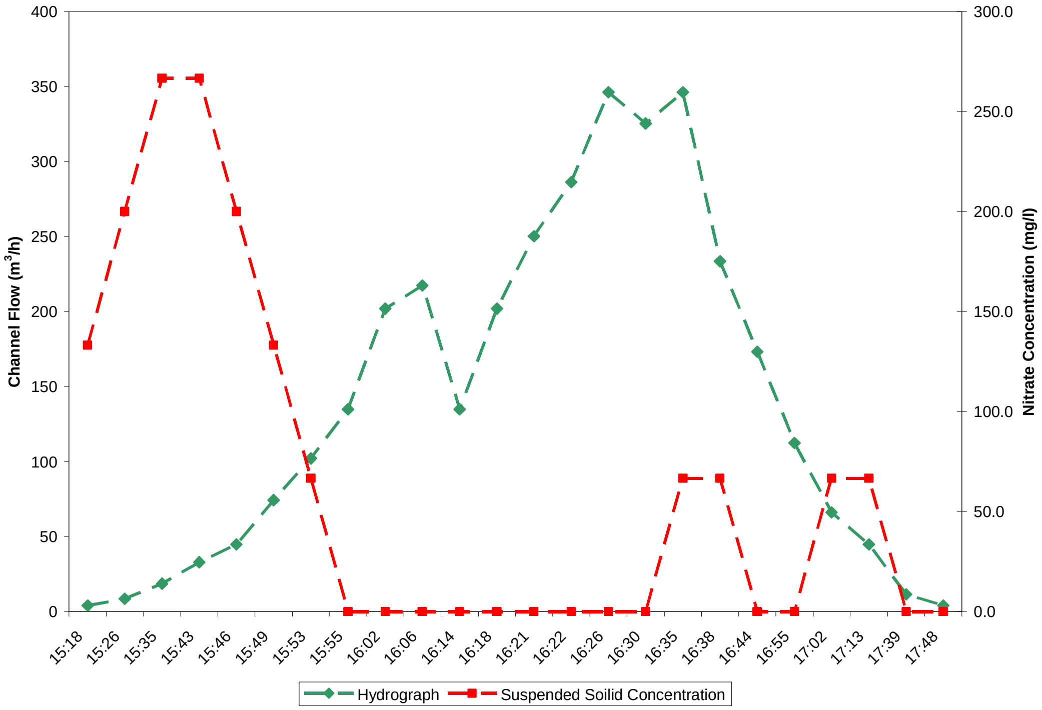

Figure C2 (b) Suspended Solids: Event 2 Flume 1

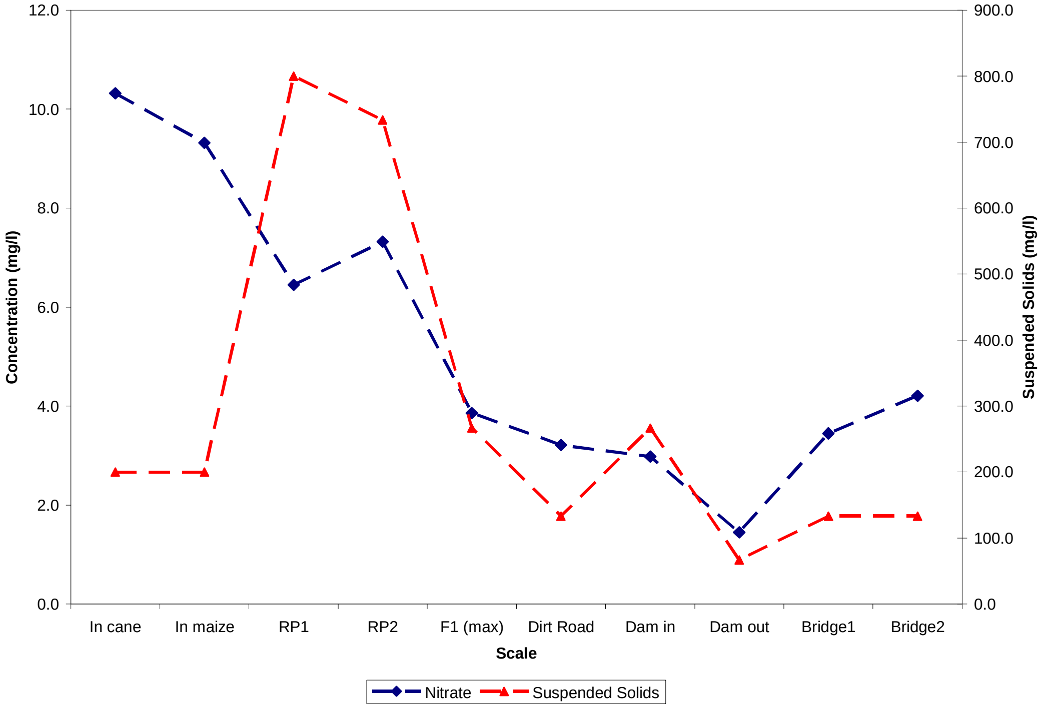

Figure C2 (c) Scaled Observation of Nitrate Concentration and Sediment Load Event 2

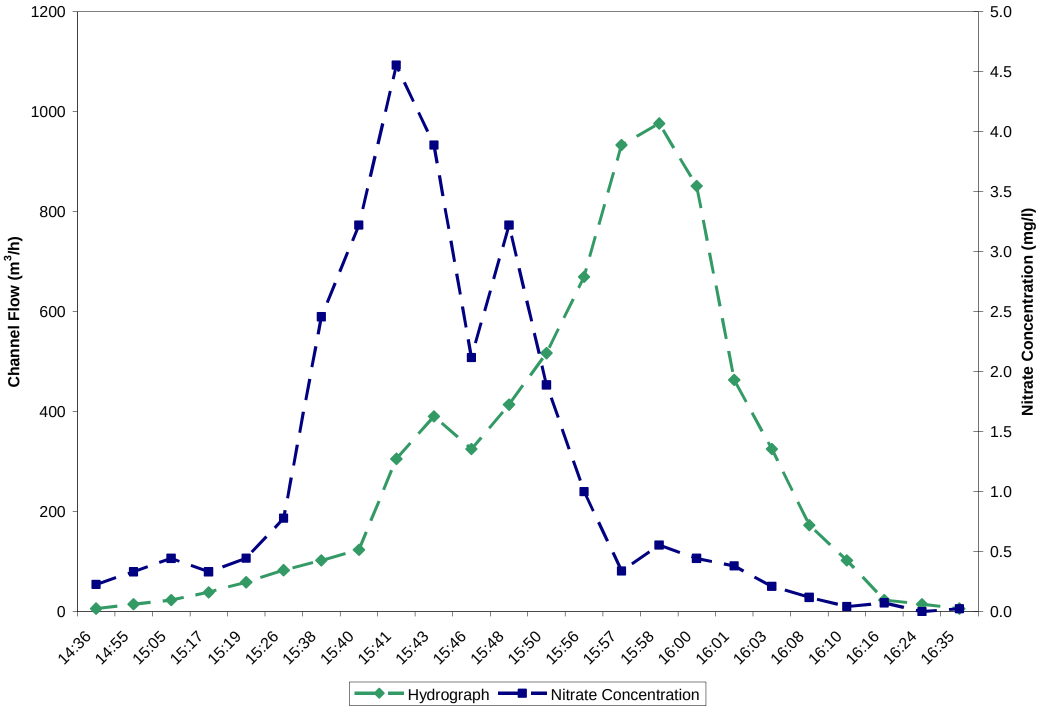

Figure C3 (a) Nitrate Concentration: Event 3 Flume 1

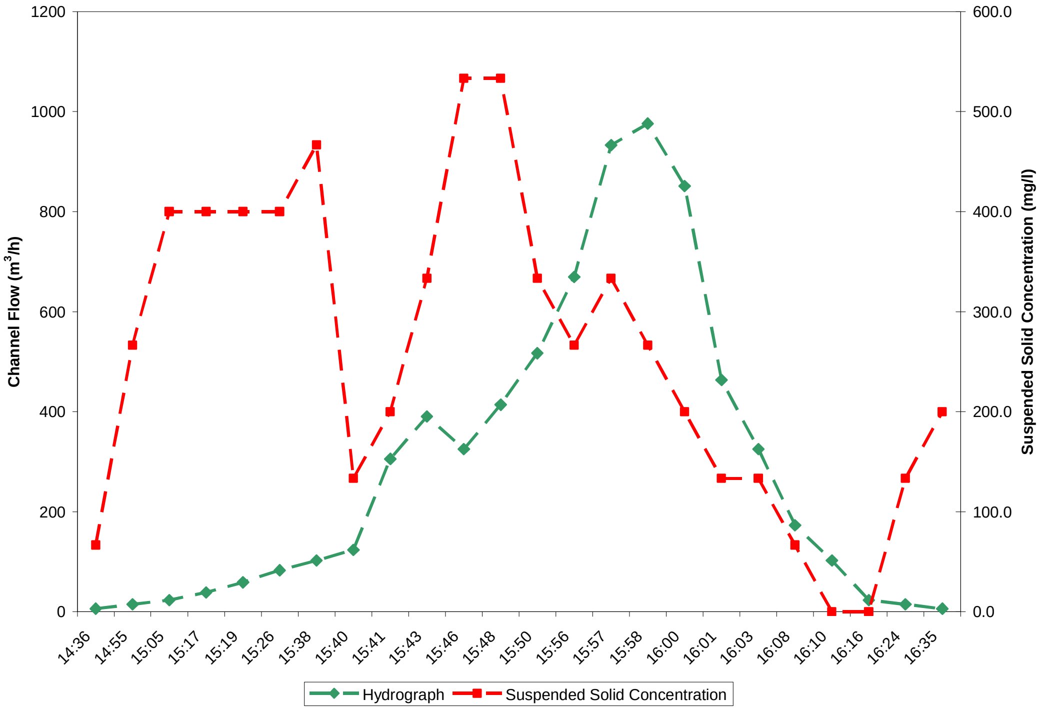

Figure C3 (b) Suspended Solids: Event 3 Flume 1

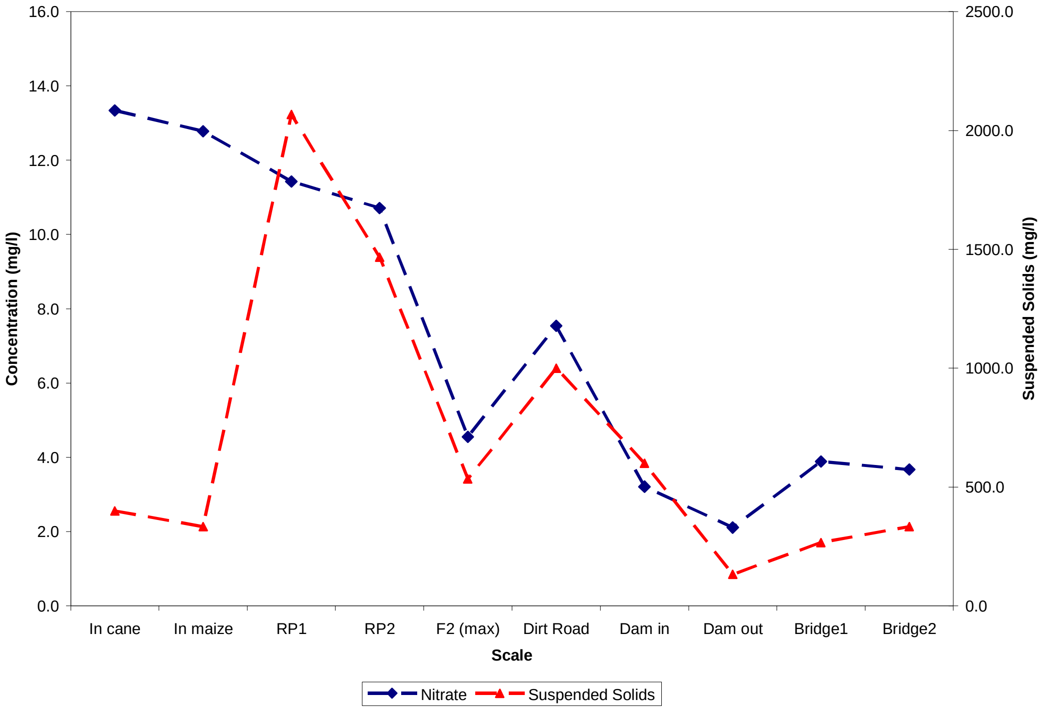

Figure C3 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 3

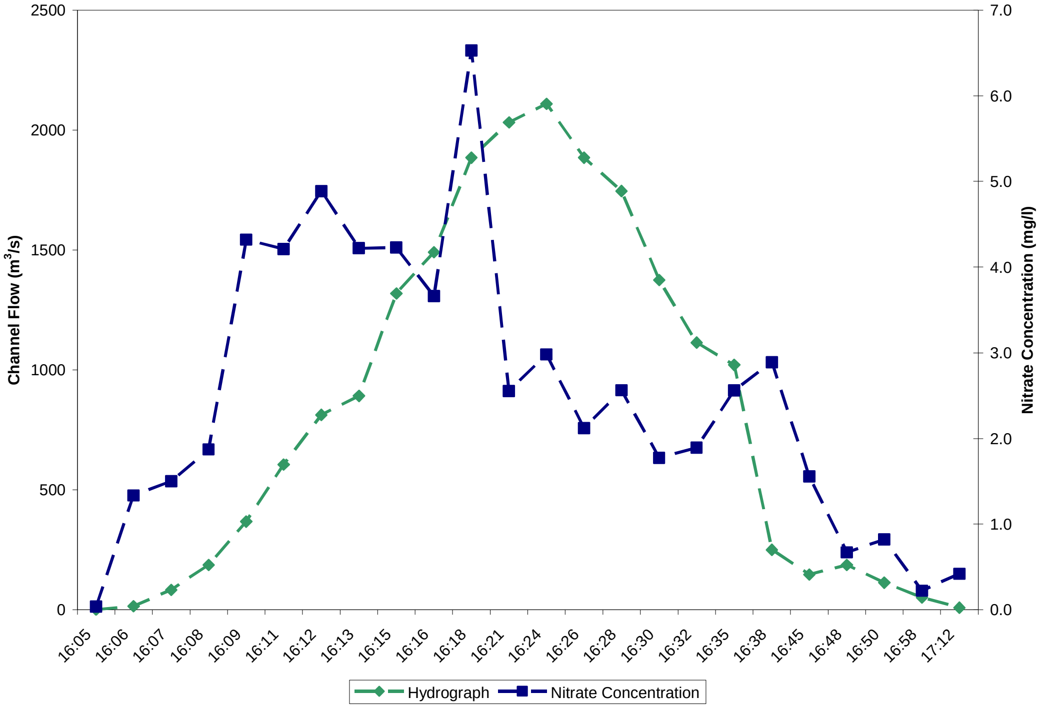

Figure C4 (a) Nitrate Concentration: Event 4 Flume 1

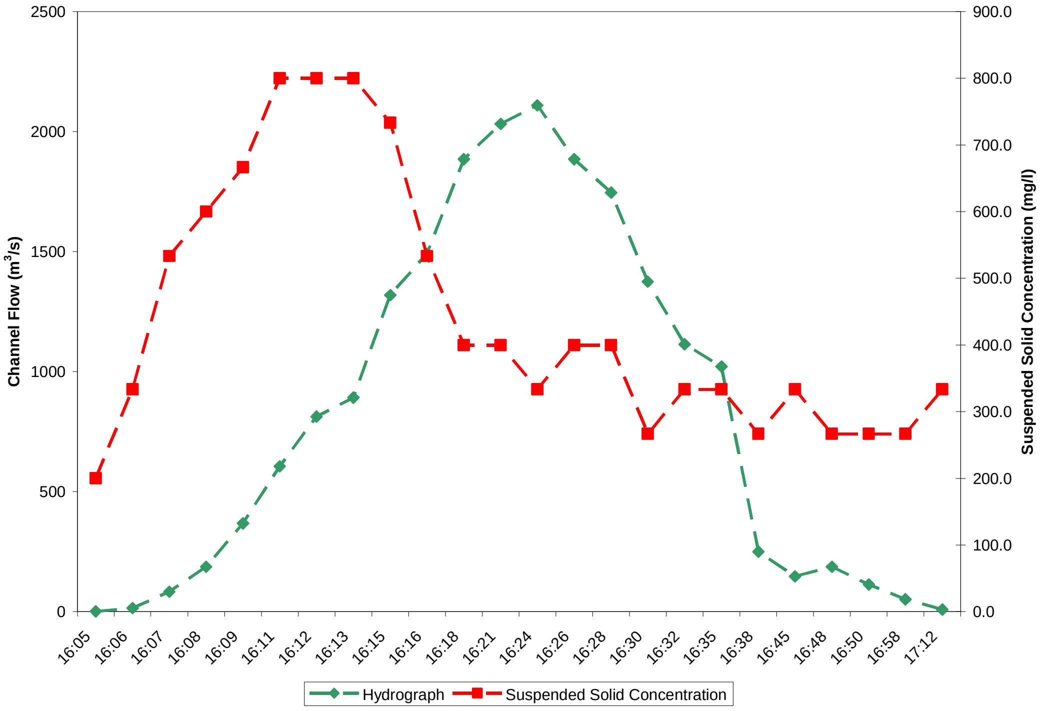

Figure C4 (b) Suspended Solids: Event 4 Flume 1

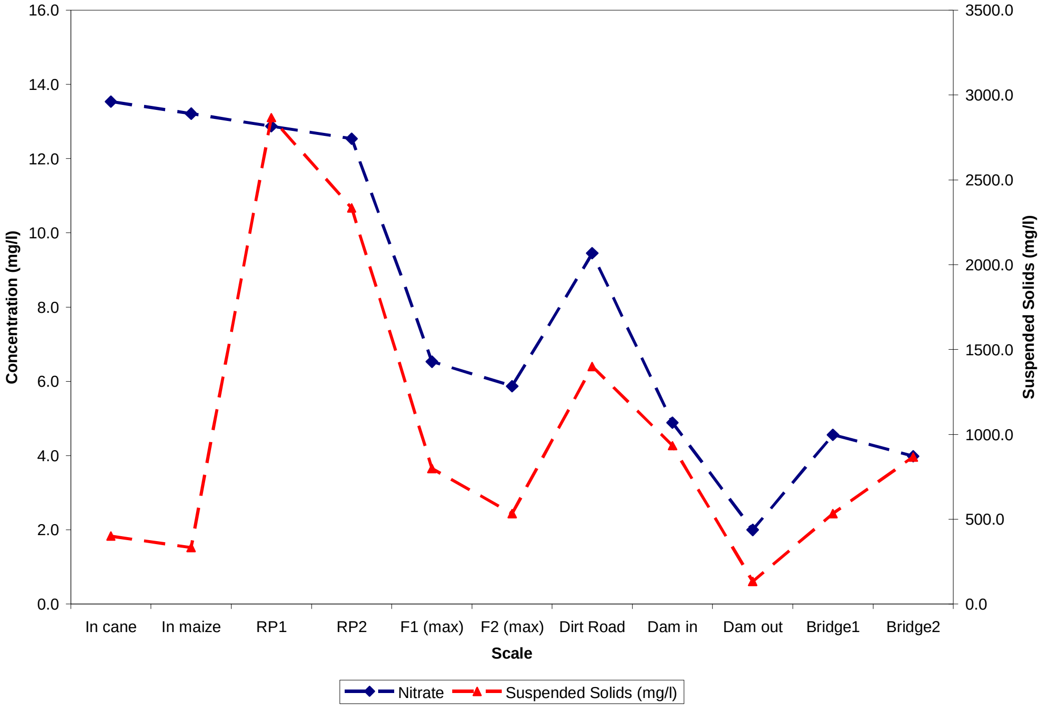

Figure C4 (c) Scaled Observation of Nitrate Concentration and Sediment Load

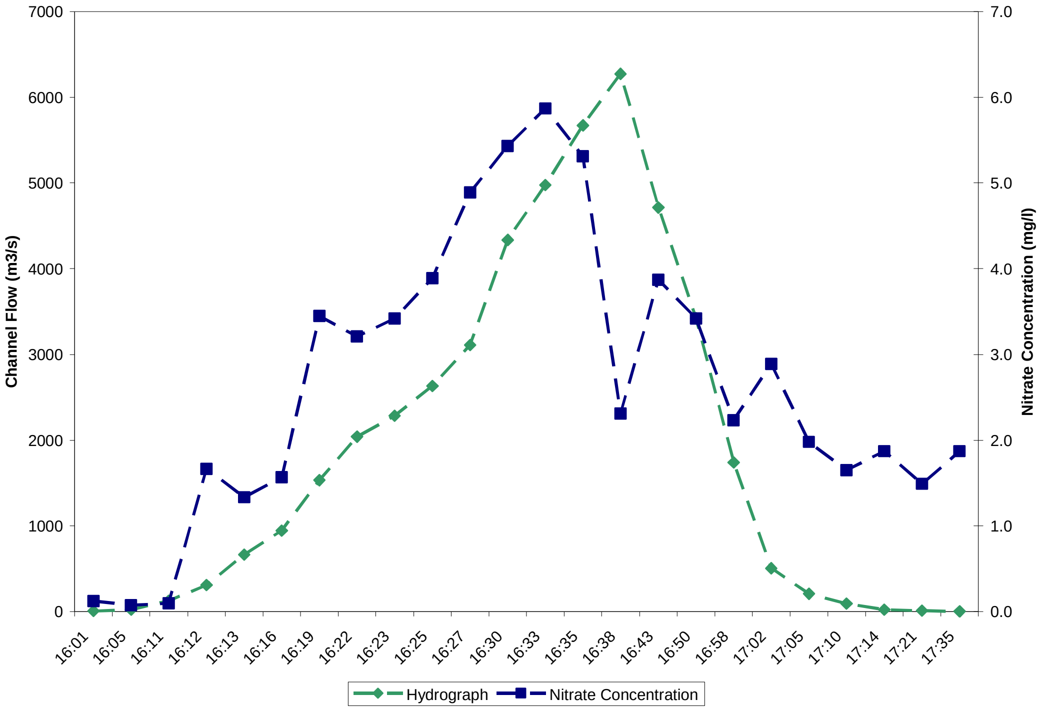

Figure C4 (d) Nitrate Concentration: Event 4 Flume 2

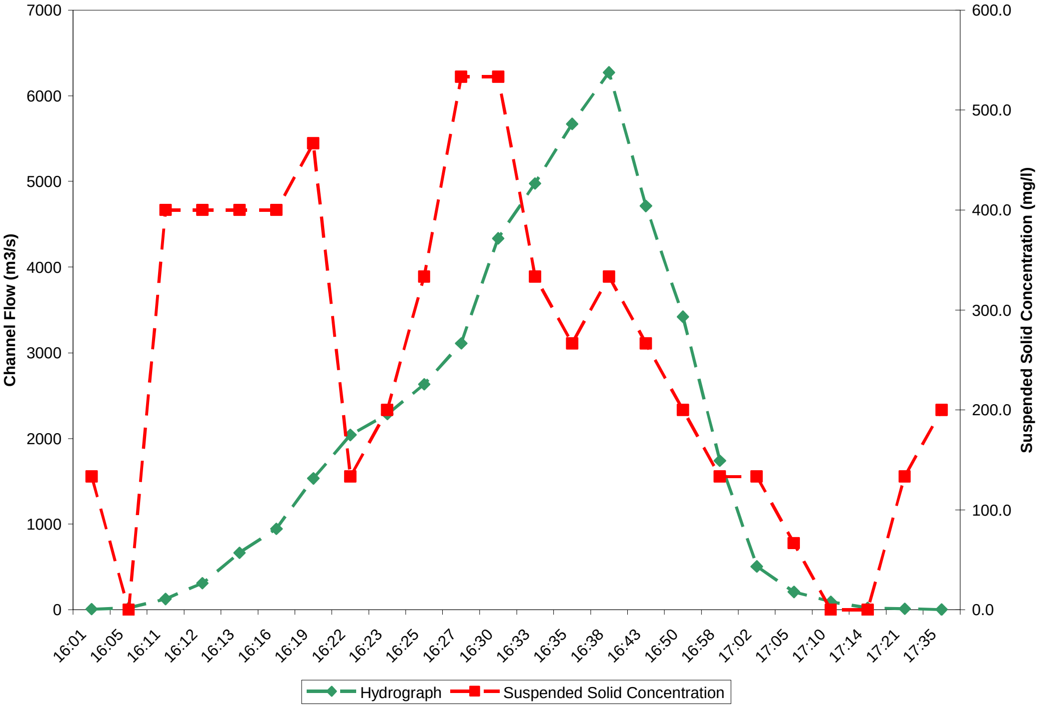

Figure C4 (e) Suspended Solids: Event 4 Flume 2

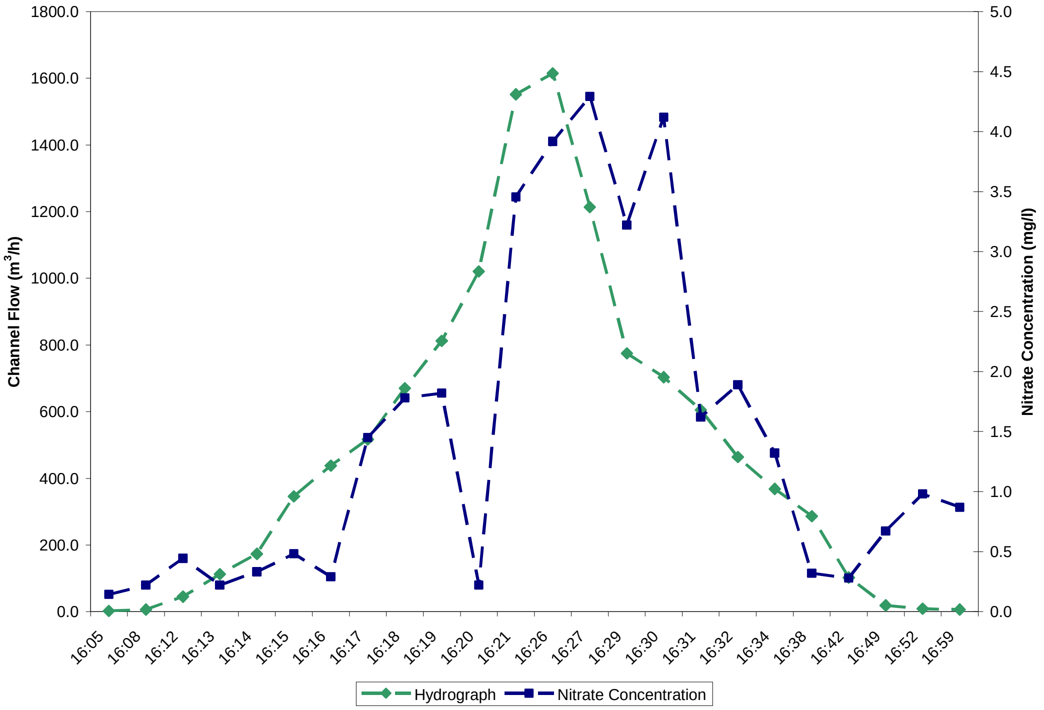

Figure C5 (a) Nitrate Concentration: Event 5 Flume 1

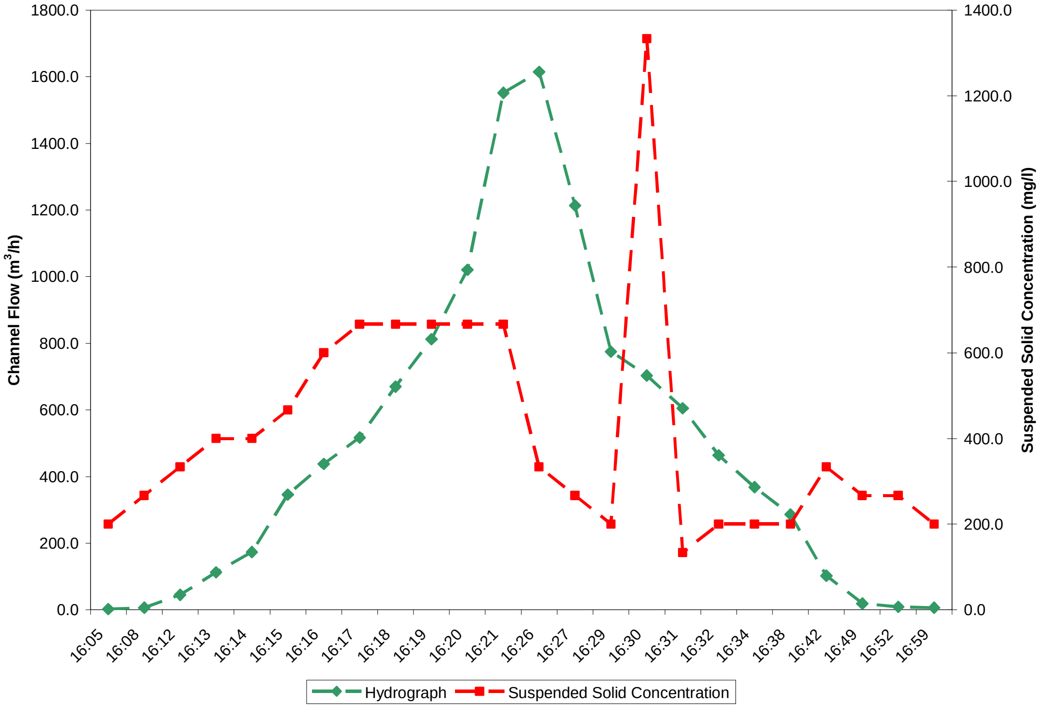

Figure C5 (b) Suspended Solids: Event 5 Flume 1

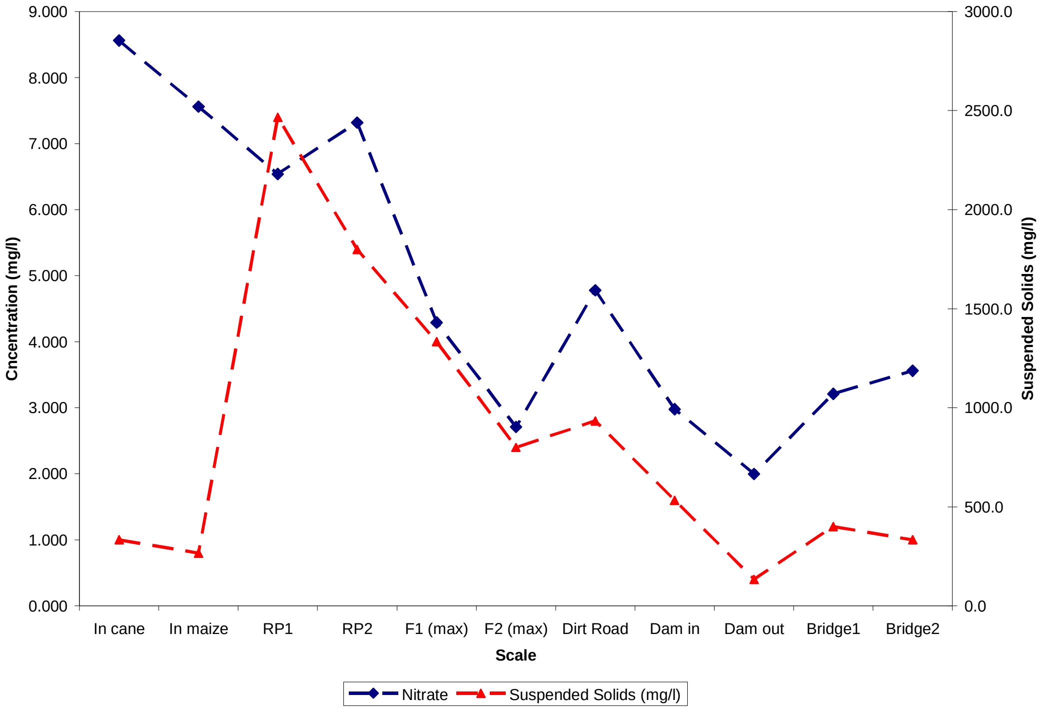

Figure C5 (c) Scaled Observation of Nitrate Concentration and Sediment Load

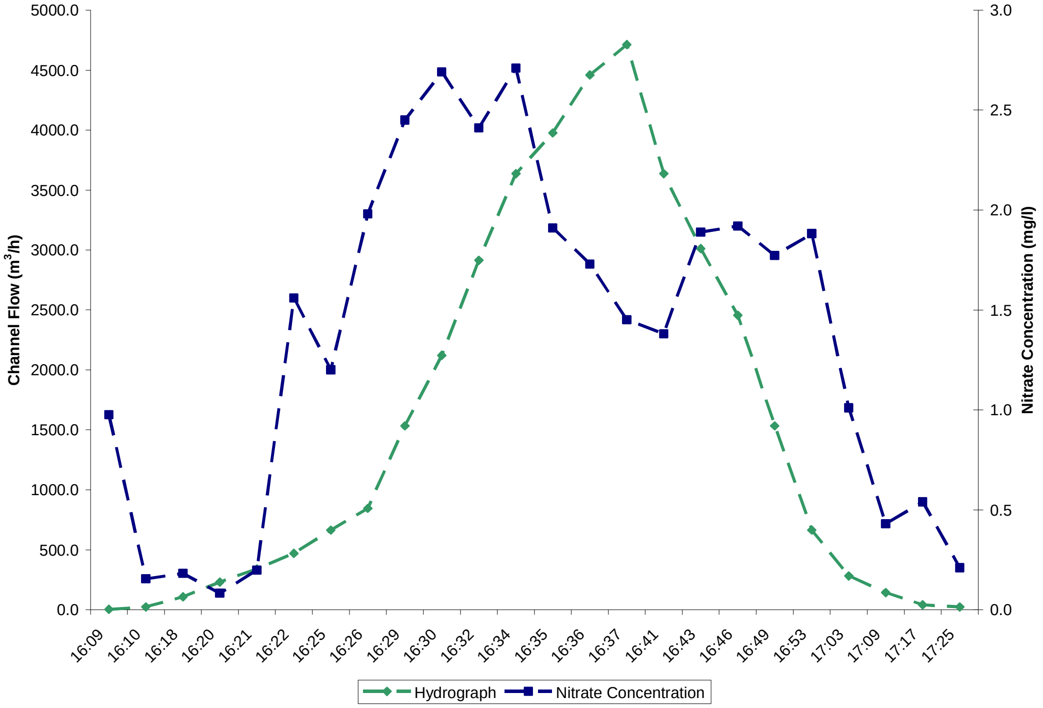

Figure C5 (d) Nitrate Concentration: Event 5 Flume 2

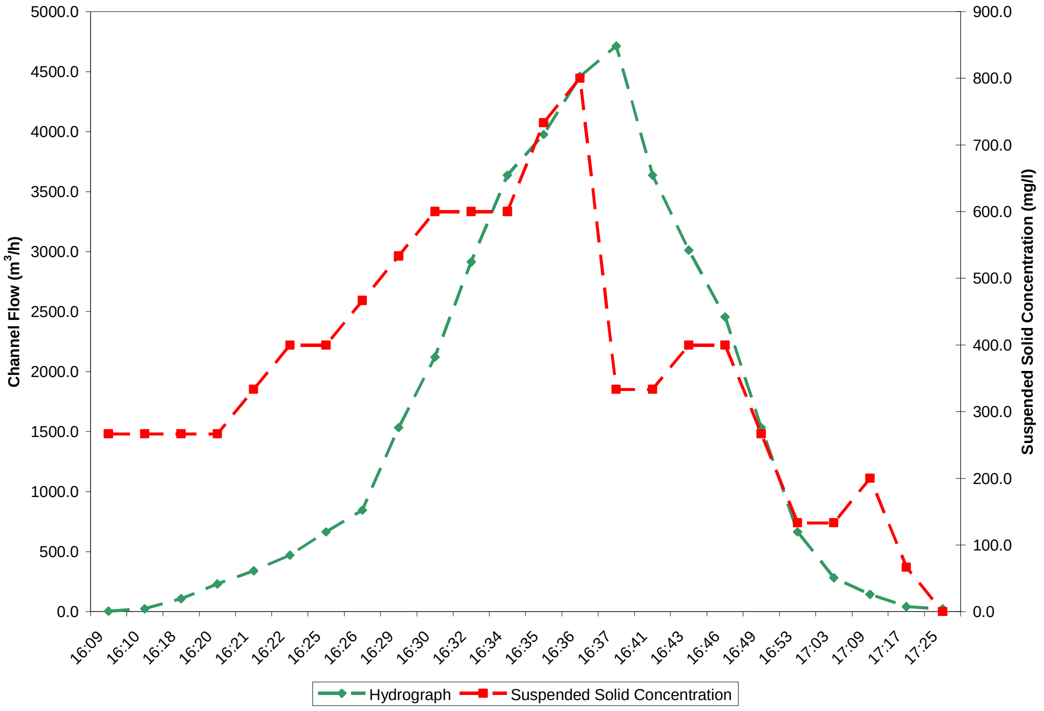

Figure C5 (e) Suspended Solids: Event 5 Flume 2

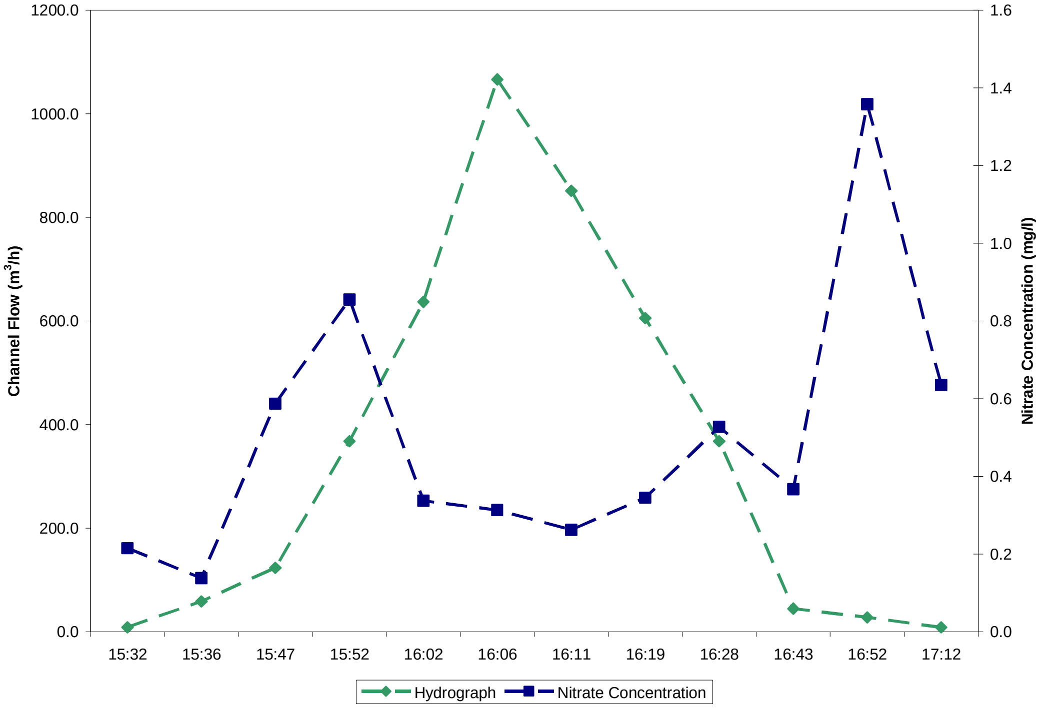

Figure C6 (a) Nitrate Concentration: Event 6 Flume 1

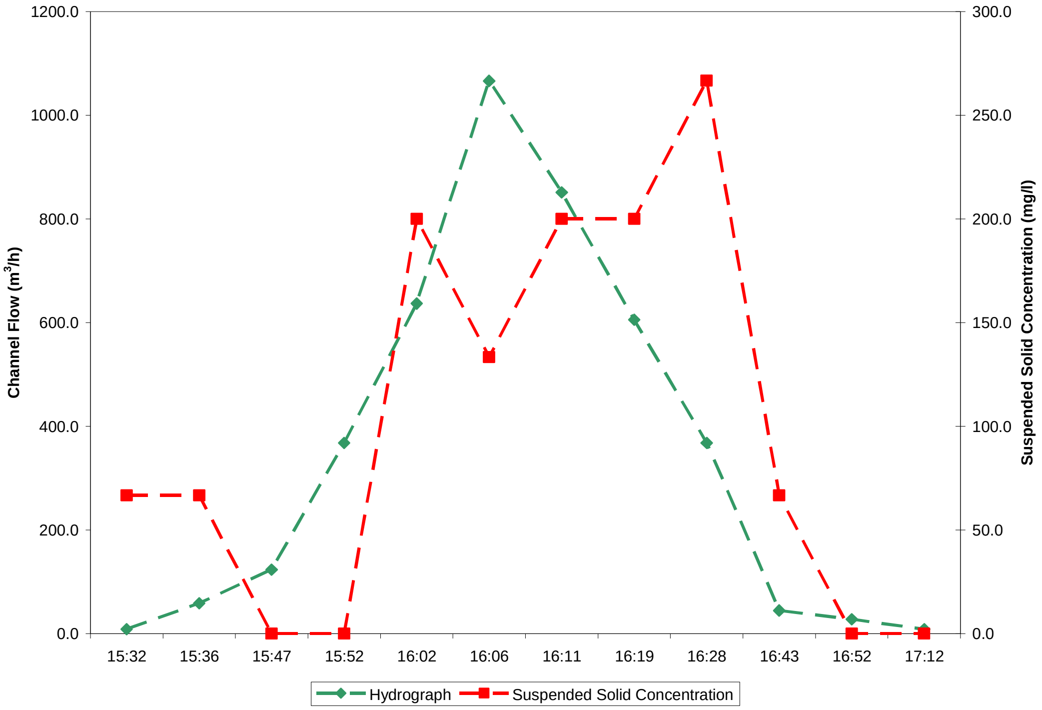

Figure C6 (b) Suspended Solids: Event 6 Flume 1

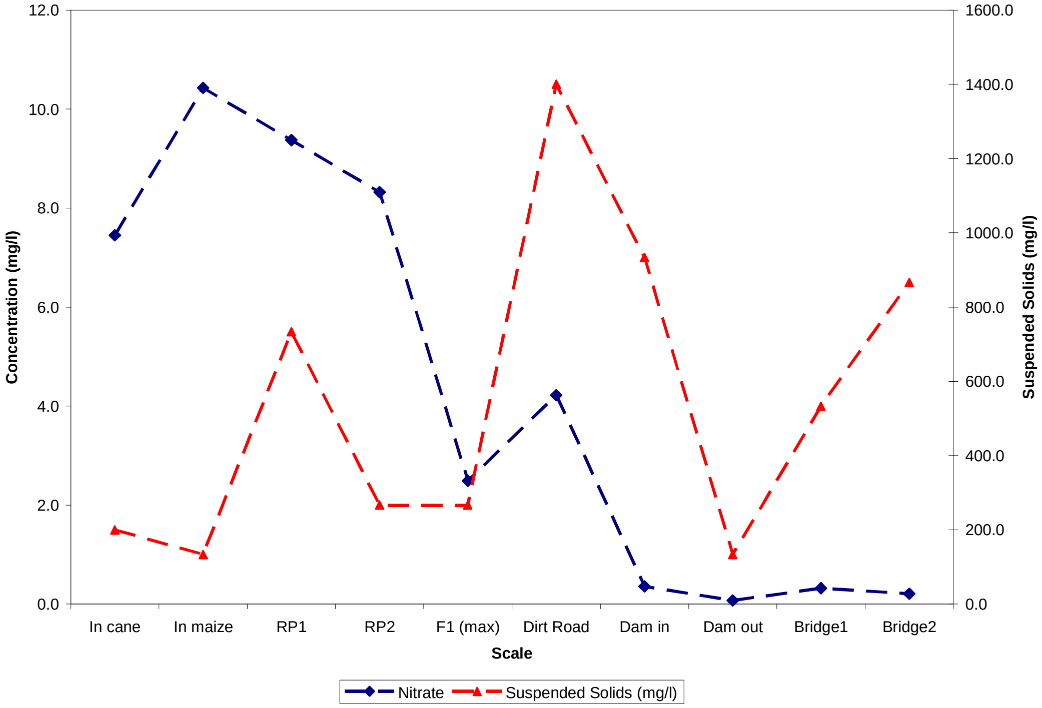

Figure C6 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 6

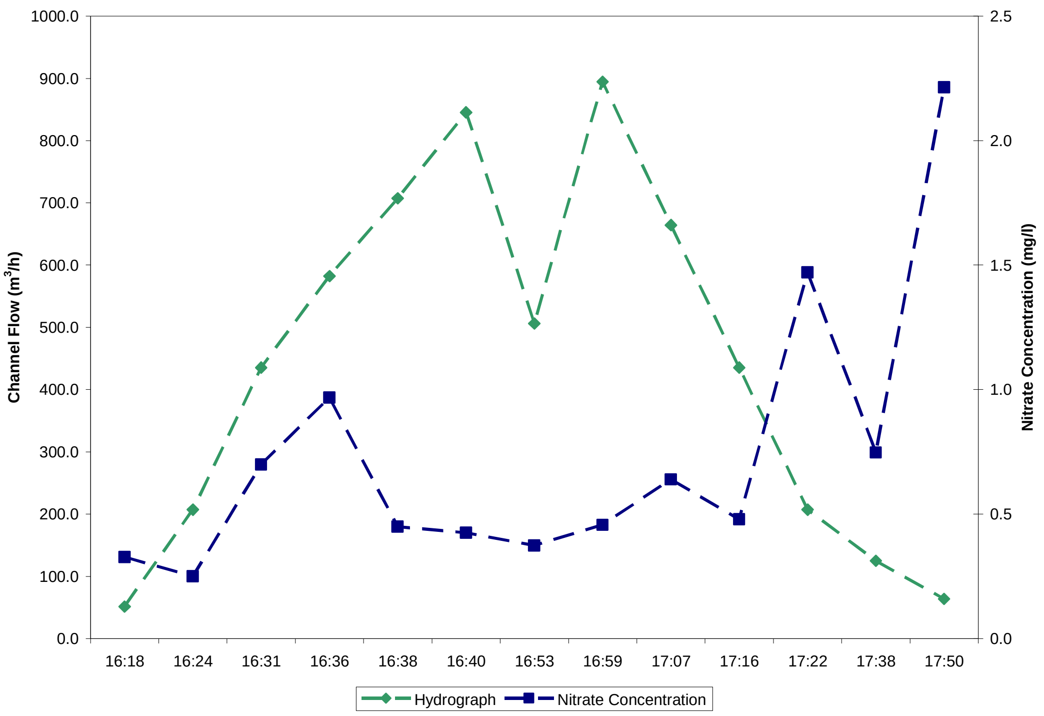

Figure C7 (a) Nitrate Concentration: Event 7 Flume 2

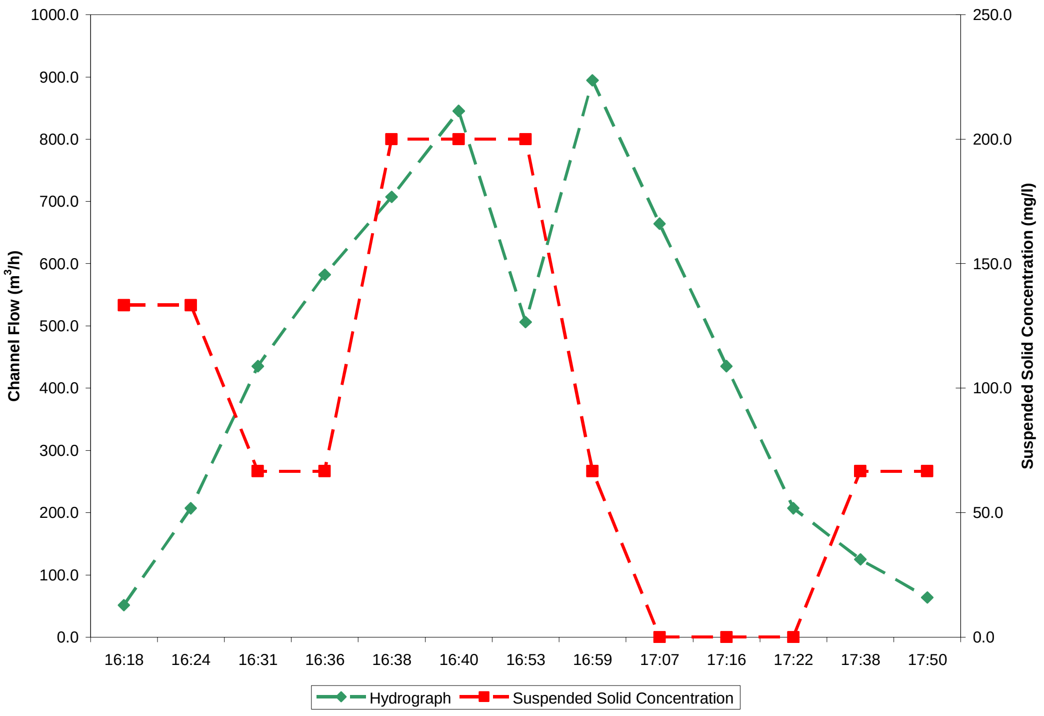

Figure C7 (b) Suspended Solids: Event 7 Flume 2

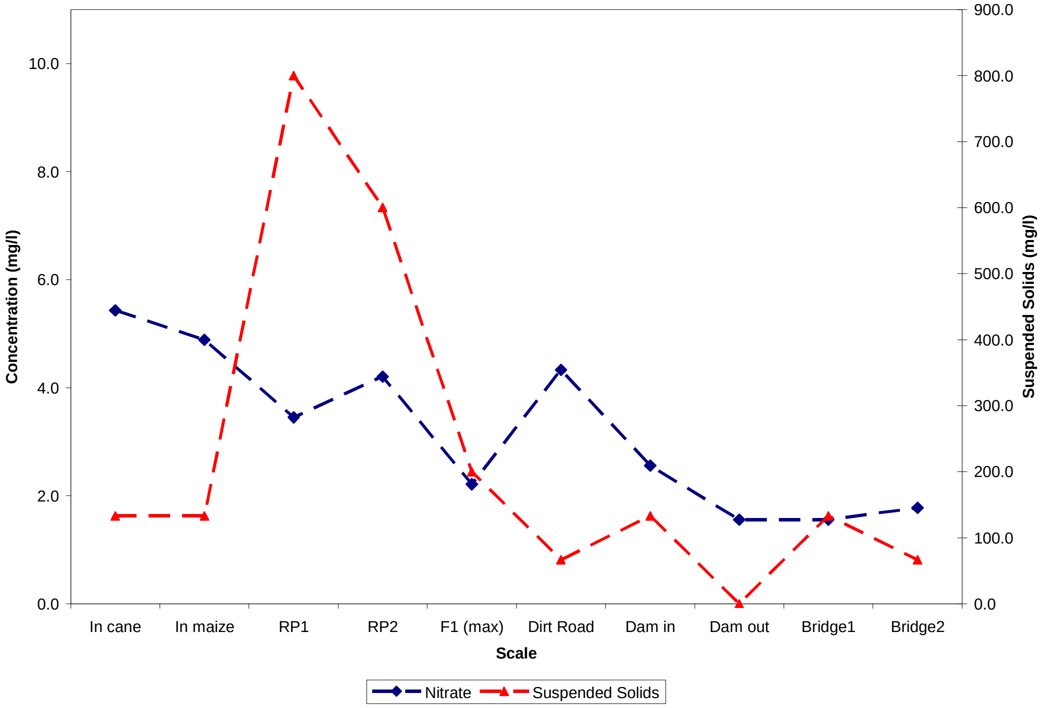

Figure C7 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 7

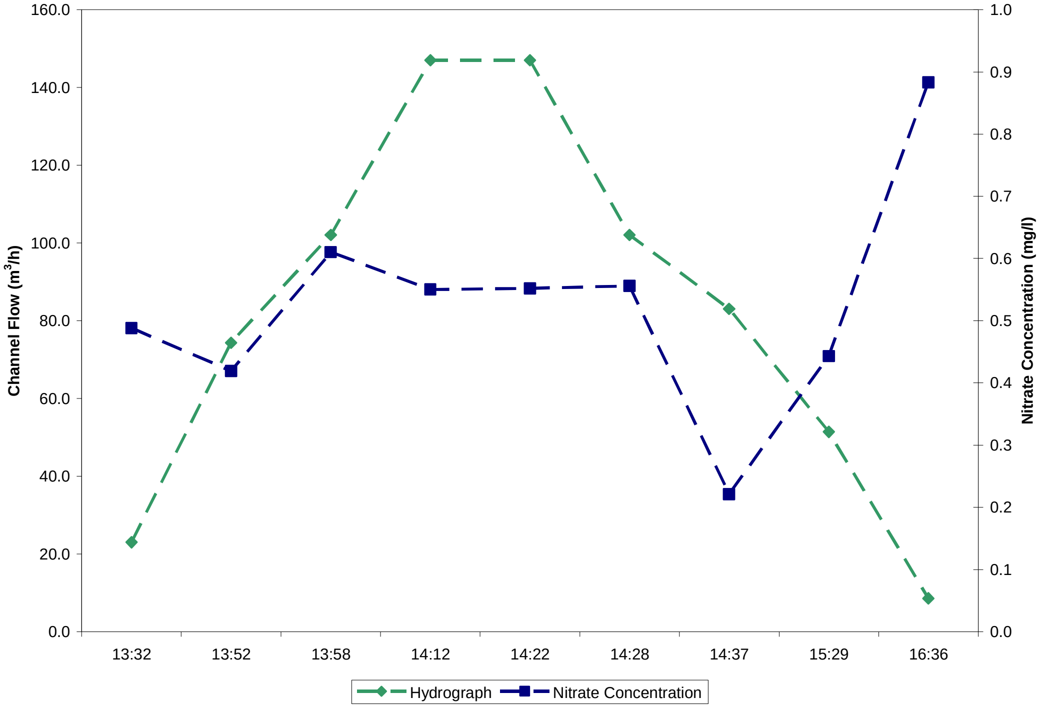

Figure C8 (a) Nitrate Concentration: Event 8 Flume 1

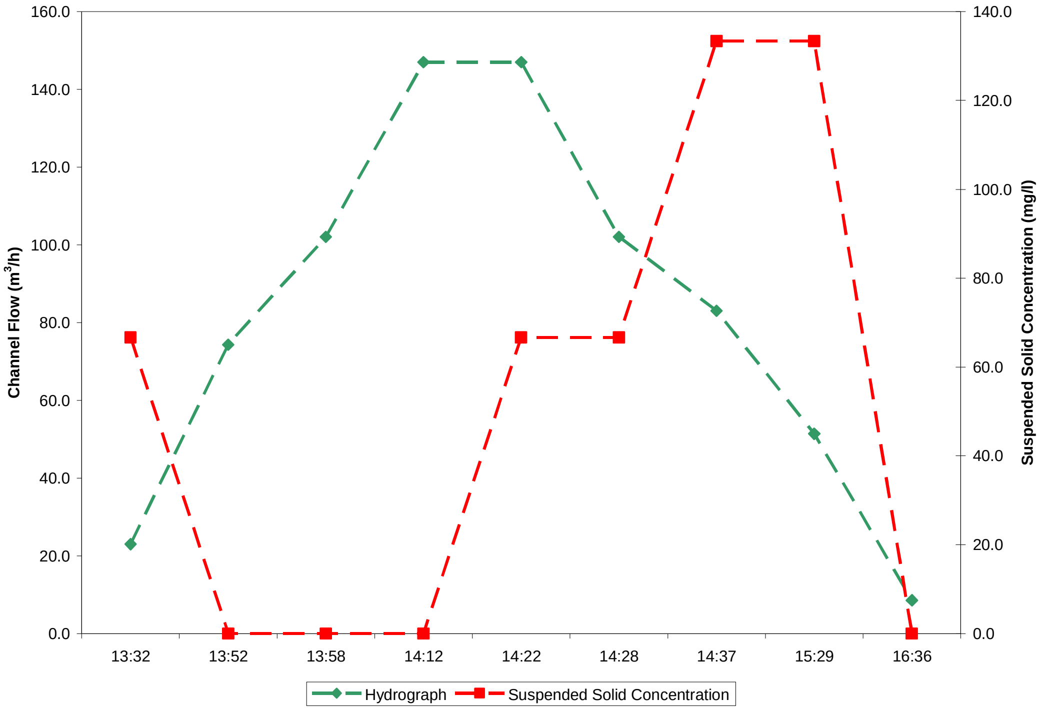

Figure C8 (b) Suspended Solids: Event 8 Flume 1

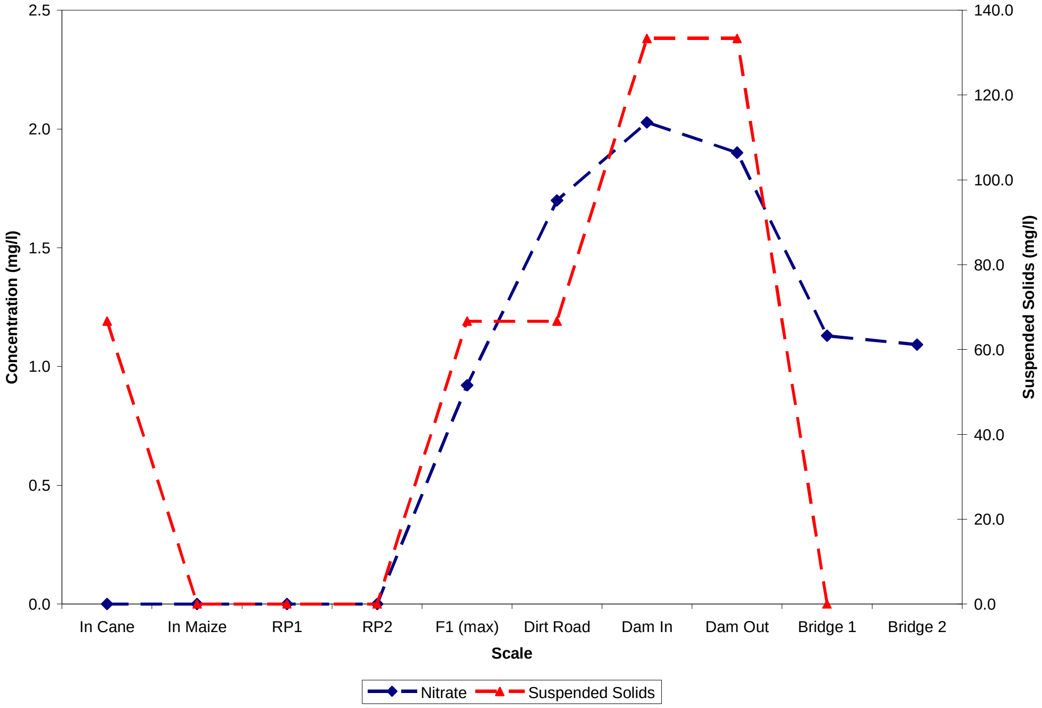

Figure C8 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 8

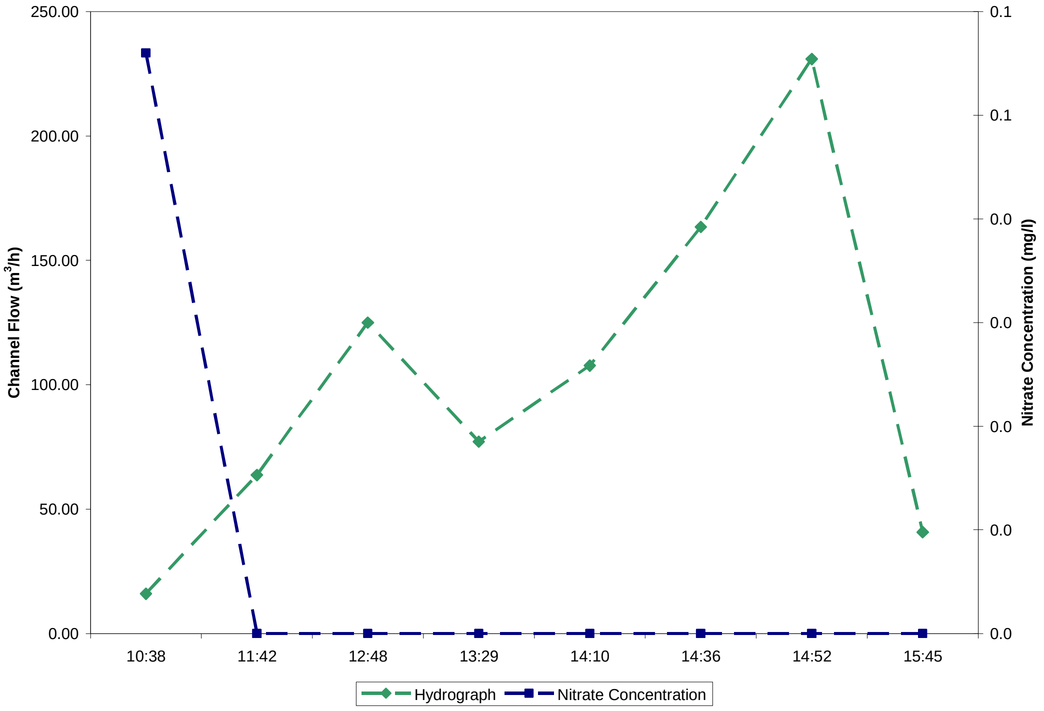

Figure C9 (a) Nitrate Concentration: Event 9 Flume 2

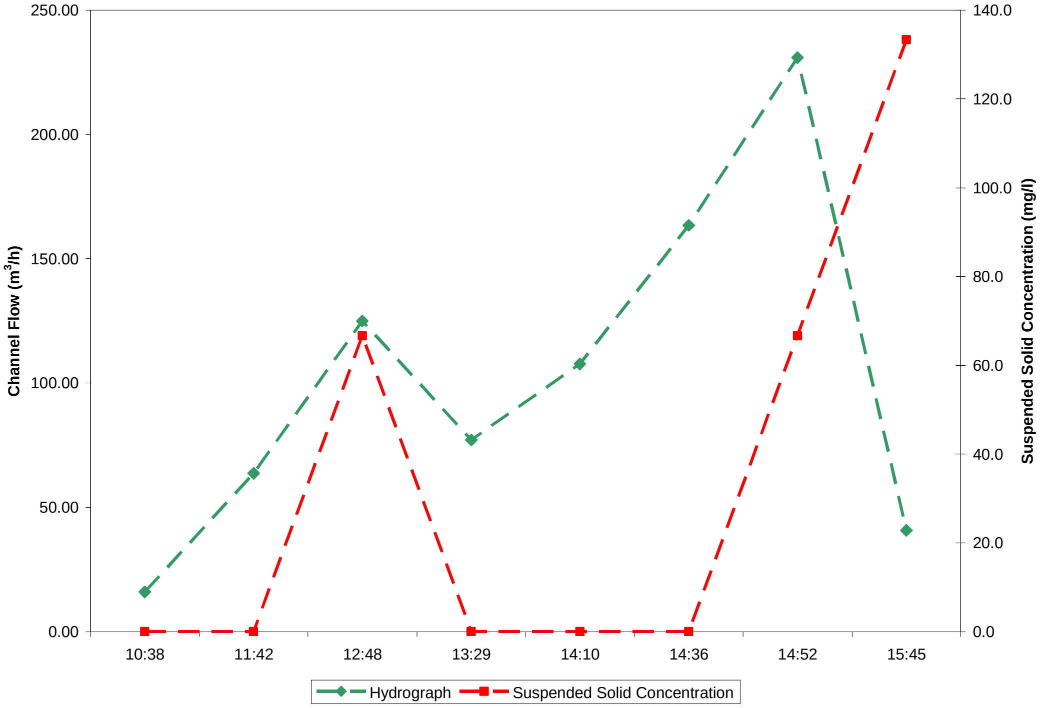

Figure C9 (b) Suspended Solids: Event 9 Flume 2

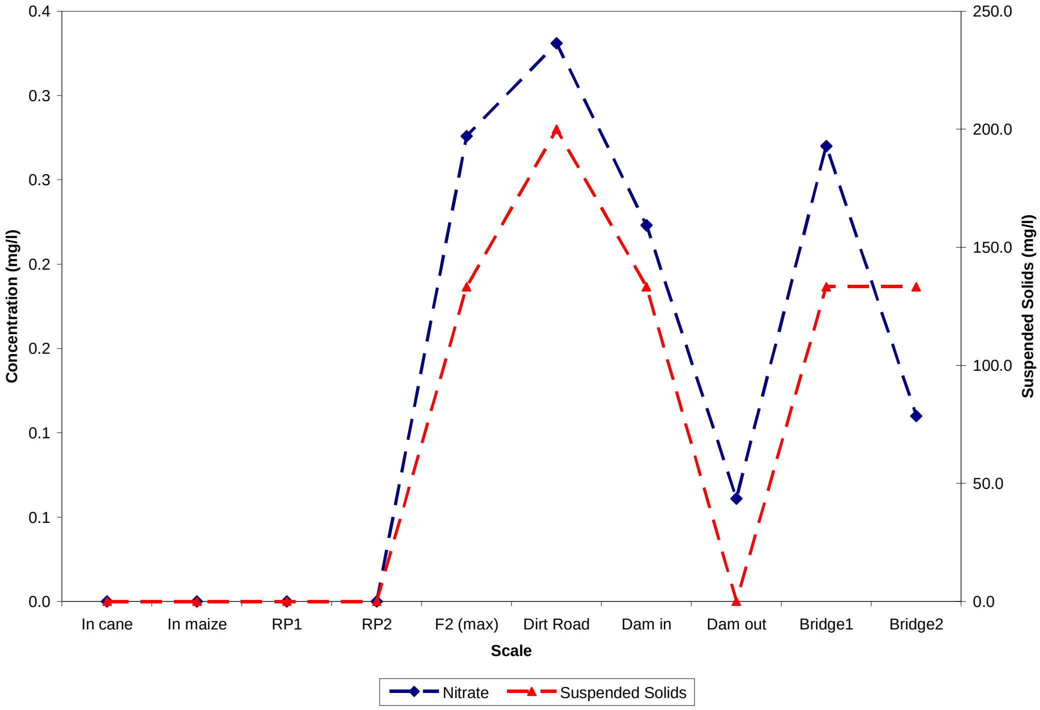

Figure C9 (c) Scaled Observation of Nitrate Concentration and Sediment Load, Event 9

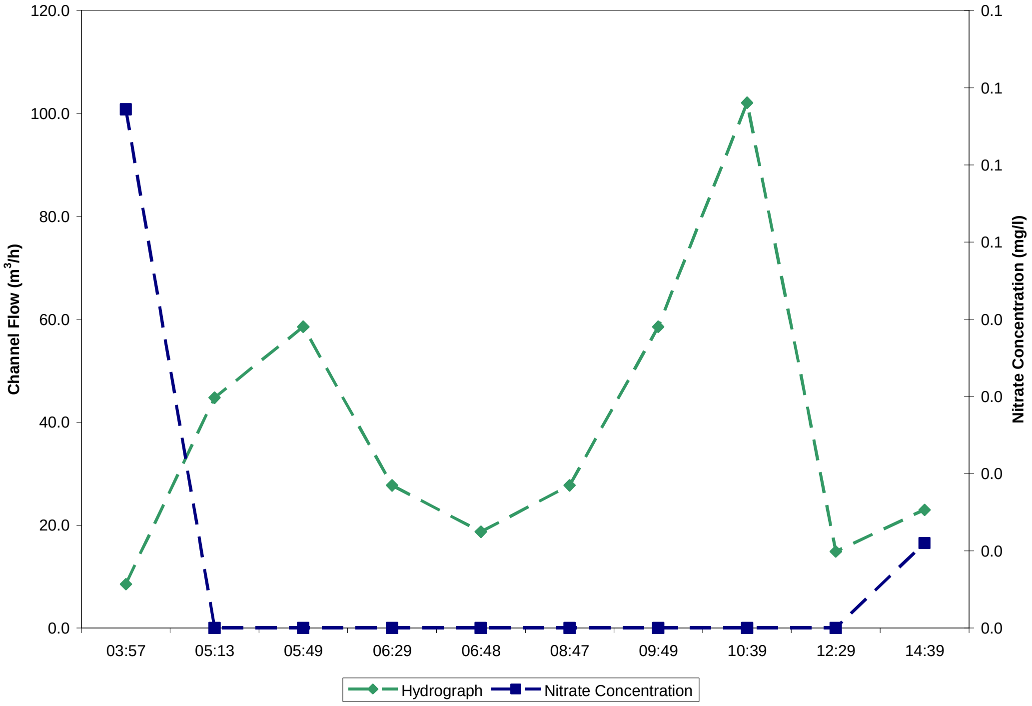

Figure C10 (a) Nitrate Concentration: Event 10 Flume 1

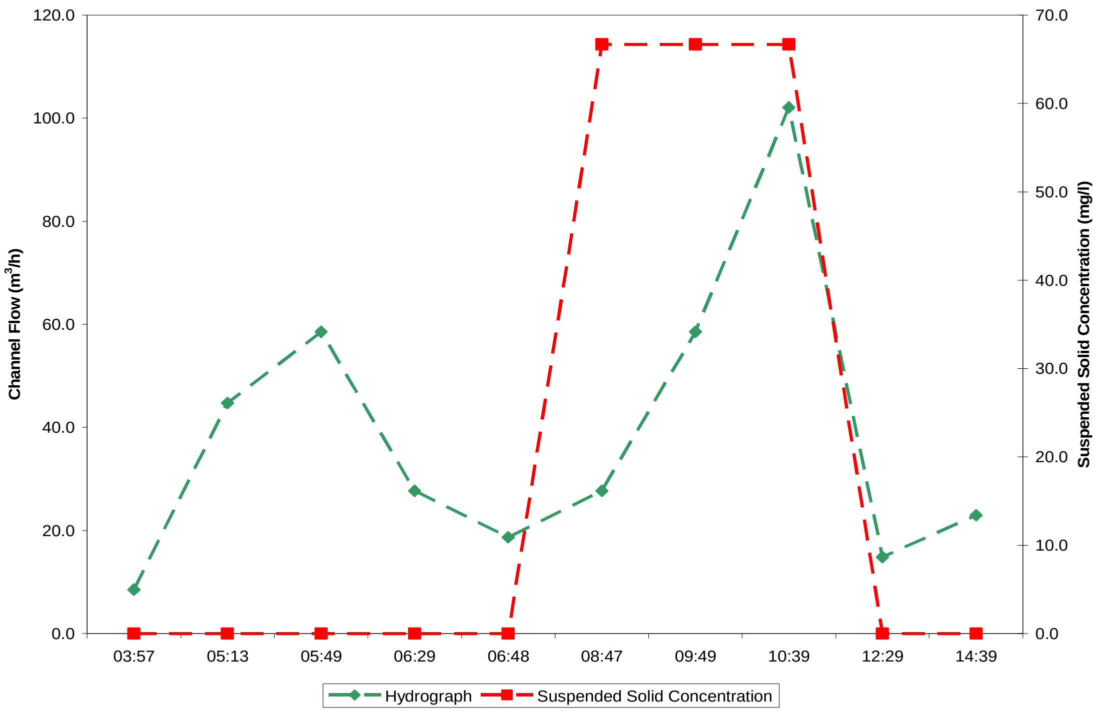

Figure C10 (b) Suspended Solids: Event 10 Flume 1

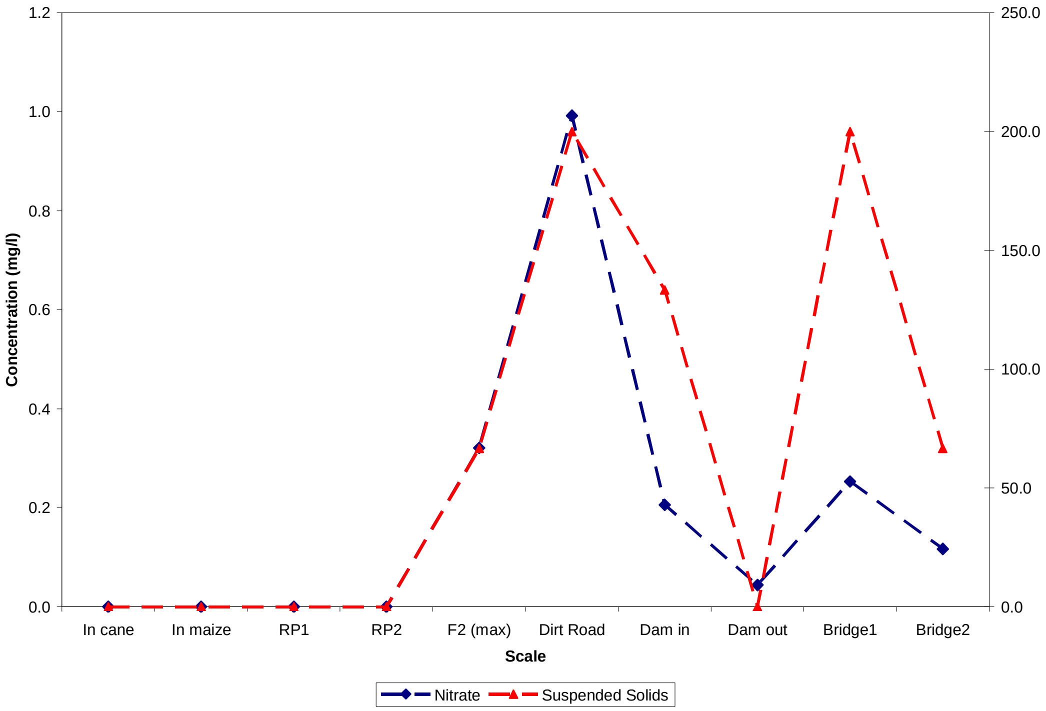

Figure C10 (c) Scaled Observation of Nitrate Concentration and Sediment Load