A STUDY OF THE RELATIONSHIP BETWEEN HYDROLOGICAL PROCESSES AND WATER QUALITY CHARACTERISTICS IN THE ZULULAND COASTAL REGION

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EXECUTIVE SUMMARY

INTRODUCTION

In many countries the rainfall and surface water resources have declined in quality to the extent that there is serious concern at all levels of management for the viability and sustainability of environmental systems. In South Africa and particularly Kwa Zulu/Natal, the scarce freshwater resources are under extreme pressure to sustain a growing industrial and agricultural society that contributes to the problem of declining quality in an ever increasing cycle.

The effects of many different management actions on sections of the environment have been examined at selective scales over the years. The hydrological processes involved in the supply and distribution of the fresh waters have been researched and actions are being applied through catchment management practices to try and control the hydrological response to specific anthropogenic conditions. However, the integrated effect of many non-linear reactions between the sources, the sinks and the processes involved in physical and chemical interactions and pathways are not well known for heterogeneous catchment systems. Consequently, the transfer of knowledge between scales of hydrological system is not well understood at the catchment scale.

OBJECTIVES

The main objective of this study was to determine the relationship between ***selected water quality characteristics*** and ***specific hydrological processes***. The water quality characteristics were chosen for their suitability for monitoring on a continuous basis, their response to land use changes in the Zululand region, and their tracer characteristics. The hydrological processes selected for examination in the project were those associated with the surface (overland) and sub-surface flow paths. Only runoff events derived from short duration high intensity storms that produced a short sharp discharge response were considered for the main scope of this report.

Technological advances now provide instrumentation, storage and retrieval systems with sufficient resolution for detailed monitoring of some of the physical and chemical characteristics in catchment hydrology. This study developed a continuous monitoring system for field applications, using appropriate technology in order to evaluate the relationship between the hydrological processes operating in the Zululand coastal region and some of the measurable water quality characteristics.

LOCALITY

The study sites chosen were part of the paired and nested research catchments of the University of Zululand situated in the Ngoye hills near the Empangeni and Richards Bay metropolitan areas (Figure 1). This area has a projected population growth rate of 2.8% per annum and an estimated growth in water demand of over 830% between 1988 and the turn of the century. There is a massive influx of migrant workers to the area that is placing an ever increasing burden on the catchment resources and is leading to severe environmental degradation. Two main research catchments were chosen to represent an undisturbed natural system (part of the Ngoye Nature Reserve) and an almost identical paired catchment containing rural subsistence settlements (Figure 1). These two catchments are representative of developments in the Zululand region and have many geomorphological features that are also representative of large areas of the Zululand region. The physical features of the research catchments covering the land use, geomorphology, geology, climate and hydrology have been described in detail in Chapter 3 and in other reports.

INSTRUMENTATION AND MONITORING

Previous studies of the hydrological response to land use changes in these catchments identified the need for high temporal resolution monitoring to achieve an understanding of the relationship between water quality characteristics and specific hydrological processes. A monitoring system was developed to measure specific water quality characteristics on a continuous basis. The physical and chemical characteristics of the

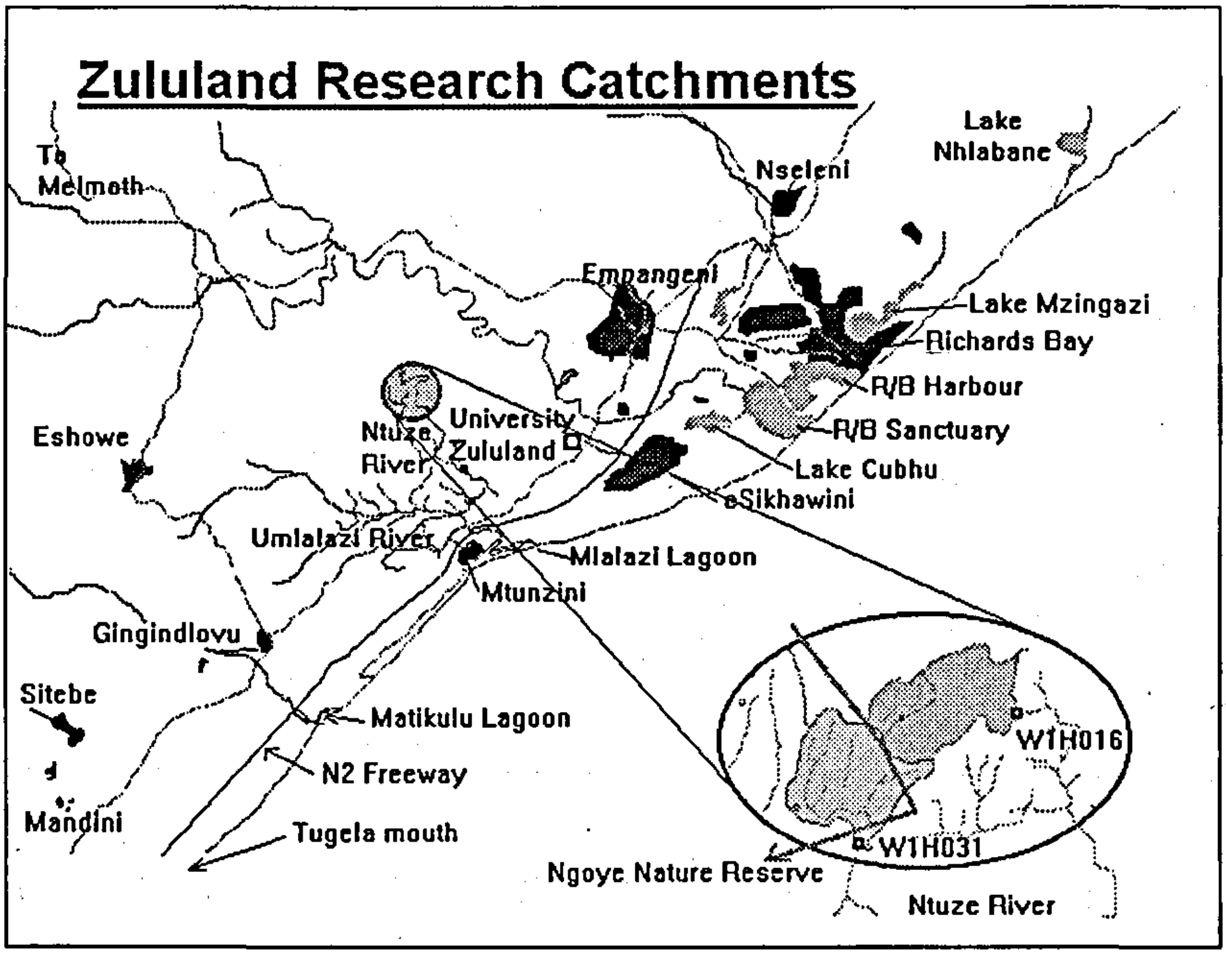

Figure 1 Location of the Ntuze Research Catchments

catchment that were measured using the continuous field monitoring systems developed for this study were the rainfall rate, the stream discharge rate, electrical conductivity, pH, turbidity and temperature. The monitoring system was also developed to activate an automatic water sampler and to record the physical and chemical conditions of the system at the time of sampling. The water samples were collected on a weekly basis, or more often if necessary, for laboratory analyses of nitrate [as N], phosphate [as P] and suspended solids concentrations.

The electrical conductivity is assumed to be representative of the total dissolved solids concentrations in the laboratory and field measurements. The turbidity was derived using a sensor that determines the attenuation of transmitted infrared radiation. Unfortunately these continuous observations did not provide an acceptable correlation with the grab samples analysed in the laboratory using an instrument that measured the scattered radiation in the visible spectrum while also accounting for transmission losses (colour). Chapter 4 discusses this issue in detail. The probable reasons for this discrepancy between the continuous and grab sample systems includes; differences in the sampling technique, the standing time of the samples, the measuring technique and possible contamination sources. While there are problems with the sampling and monitoring system developed for this study which still need to be overcome, they are not unique to this project. However, the project results discussed in this report are dependant on the relative temporal changes in concentrations, rather than the absolute values.

GENERAL RUNOFF FEATURES

The general hydrological processes, which determine the water quality behaviour of the catchments, covered a large range of climatic conditions during the study period. During the previous 15 years of flow monitoring, the rivers within the research catchment had not stopped flowing for any extended period. However, a severe drought during the first three years of this study resulted in very few storms of the required characteristics. In two of the hydrological years the flow through the monitoring weir on the disturbed (subsistence farming) catchment stopped intermittently for several months. These two years started with virtually no flow in any of the rivers being monitored and the two years experienced very different storm rainfall patterns that have been described in Chapter 5.

The two research catchments received very similar rainfall quantities and distribution during the study period but had significant differences in their discharge characteristics which resulted in different export loads of various substances. The export loads of suspended solids for the two years presented in chapter 5 displayed large differences between the years and between the catchments. The export loads that were examined indicated that the difference between the estimated loads were very dependent on the estimation techniques used in calculating the export loads. These estimation techniques involved various estimates based on the flow-related grab samples and the continuous turbidity measurement. For the natural catchment (W1H031) in the one year, the export loads were almost identical for the three estimation techniques, but deviated substantially in the next year. However, the estimation techniques gave very different export loads for the two years in the disturbed catchment (W1H016). The differences between the estimation techniques all showed clearly that the estimated export loads of suspended solids are critically dependent on the estimation and sampling technique used in the monitoring system. However, all three methods showed that the main differences in the export loads between the two catchments appears to be associated with the individual storm events that contribute the largest proportion of the sediment loads. Consequently, the storm processes and responses are examined in much more detail in subsequent sections of the report.

The export of total dissolved solids, based on electrical conductivity measurements, were almost identical for the two catchments during one of the years but showed big differences for the catchments in the other year (Figure 2). Again the main difference was associated with individual storm events which induced a large export from one of the catchments. The nitrate and phosphate export loads during the same two years examined in this project, exhibited very big differences between the two catchments that could also be associated with individual storm events.

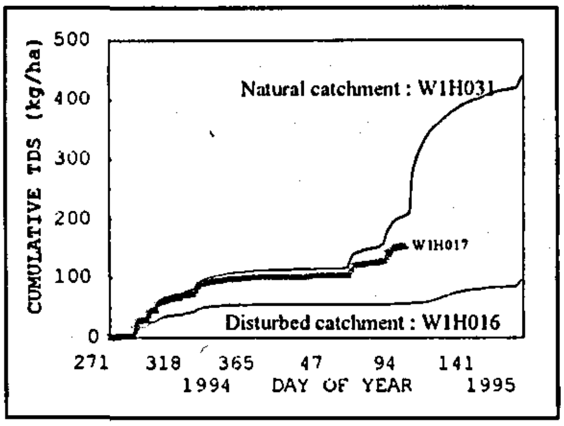

Figure 2 Differences in TDS export for the research catchments.

STORM ANALYSES

The individual storms have a major impact on the export loads of nutrients and sediment from the research catchments. Consequently, selected storm analyses are presented in greater detail in chapter 7 of this report. These cover the main hydrological flow-paths that are likely to affect the selected water quality characteristics.

The storms selected are those associated with short duration high intensity rainfall events that are assumed to produce runoff that can be associated with both surface and sub-surface flow-paths. The characteristic hydrograph for both research catchments have distinct features that are linked to the stream network and different contributing areas. Specific points (peaks) in the discharge hydrograph from the disturbed catchment are linked to different contributing areas that may help in identifying the sources, the sinks and the pathways of hydrological and chemical constituents.

The severe drought during the study period limited the number of identifiable storms to 29 that could be used for analyses. Not all of these were suitable for the objectives of this study. Instrument failure, monitoring conditions and other problems also reduced the number of factors for analysis in some of the storms used in the analyses. However, an attempt was made to identify certain reproducible traits in the water quality factors during suitable storms that were consistent for most of the storms. The storms identified for analyses varied considerably in their peak discharges and in their time to peak. Those chosen for analyses had a time to peak of less than five hours and a peak discharge which was generally between 1000 and 10000 m^3/hr (0.3 cumec - 3 cumec).

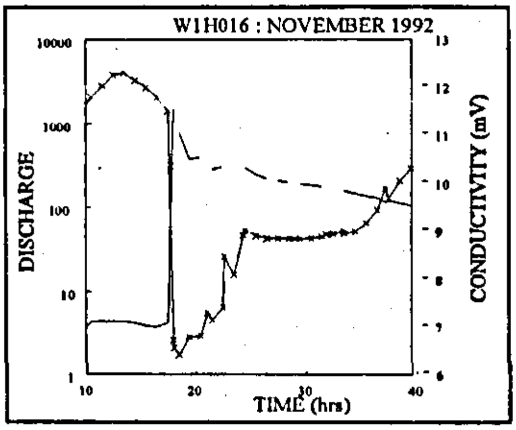

Figure 3 Characteristic changes in conductivity in relation to discharge

The water quality response to selected factors during a storm is considered to be "typical" when the response can be observed in several storms that were adjudged to have surface flow conditions. Some of the predicted responses are speculative and not very consistent but are based on one or two individual cases where there was sufficient data during the storm. The most consistent storm condition to be observed was the immediate drop in conductivity with the onset of storm flow which is assumed to indicate a dilution of the total dissolved solids in the system that have become concentrated in the conditions prior to the rainfall event (Figure 3). The time and rate at which the response occurs and the minimum values attained are linked to the rate at which the discharge hydrograph responds to rainfall. For very short duration storm runoff events, the conductivity response is almost instantaneous. This indicates a very rapid runoff response to the short duration high intensity rainfall event from the contributing catchment areas. Following the initial response, the recovery of the conductivity appears to be closely linked to the size of the storm event. The initial recovery rate is very rapid. There is often a point of inflection in the discharge hydrograph that coincides with the reversal in the conductivity trend. These are considered to be associated with the relative changes in subsurface flow processes that differentiate the "new" water (derived from rainfall with low conductivities) with the inter-flow and base-flow runoff of the "old" water from the soil. There is also a further discontinuities in the recovery rates of the conductivity which generally coincides with the change in dominance of the different hydrological flow processes and possibly with separate contributing areas routed through the system (see the discontinuities in Figure 3).

The pH measurements within and between storms is highly variable. This large variability has been observed in other field studies. However, an attempt is made to identify some systematic trends during the selected storm events but these are very speculative and need further research. The pH often drops with the onset of the storm hydrograph (Figure 4) and reaches a minimum at some time during the storm event before the dominance of base-flow conditions. The recovery to pre-storm conditions, where they can be identified, is very variable and not consistent between storm events.

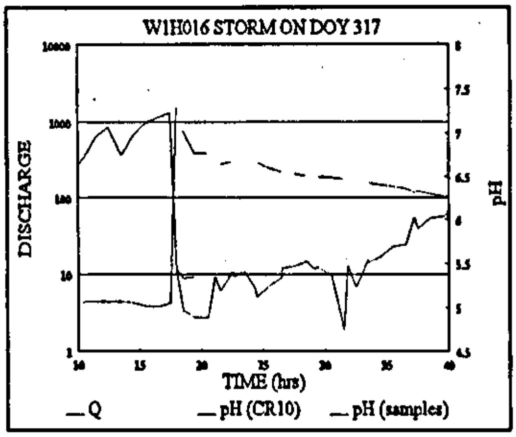

Figure 4 Characteristic changes in pH in relation to *discharge.*

The turbidity variations during a storm event show some very distinct traits in the disturbed catchment that are not as apparent in the clearer waters of the undisturbed (natural) system. There is nearly always a very short, sharp peak in turbidity that coincides almost exactly with the rising limb of the storm hydrograph (Figure 5). This peak in turbidity seldom lasts for as long as the discharge hydrograph for the short duration high intensity storms.

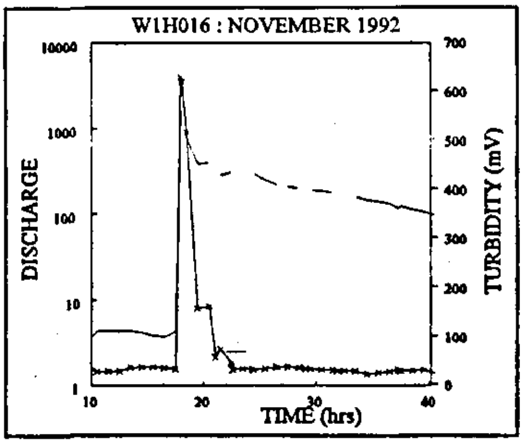

Figure 5 Characteristic changes in turbidity in relation to discharge.

The suspended solids, nitrate and phosphate trends could only be gauged from flow related grab samples that were nearly always inadequate for the analyses required. Either the sample frequency was too short in the case of large storms that filled up the sampler long before the bottles could be replaced for logistic reason (flooded roads) or the sample frequency was too long and there were not enough samples to cover the essential periods of the storm event in the case of the smaller storms. However, some cases were evaluated and specific events presented as possible models of typical storm events for the case of nitrate conditions.

There is a definite difference in the composition and colour of the suspended sediments during the passage of a storm hydrograph. The rising limb and recession component displays two different relationships between the turbidity and the suspended solids concentrations (Figure 6). The composition of the rising limb is statistically different to the recession limb for all water quality factors examined. This makes it very difficult to use turbidity to estimate suspended solids for these catchments.

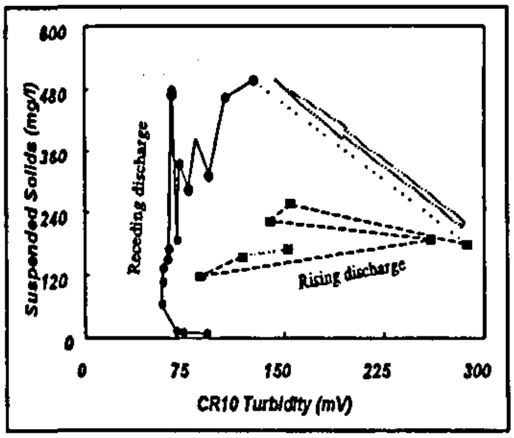

Figure 6 Hysteresis in turbidity field calibrations for storm on DOY 100, 1995

The turbidity measurements show several discontinuities for the disturbed catchment (W1H016) that coincide with identifiable discontinuities in the discharge hydrograph that have been associated with different contributing source areas, in particular the nested catchment monitored by W1H017. These traits in turbidity are not as clear in the undisturbed catchment because the water generally has much lower sediment loads and some discolouration. However, there is nearly always a sharp peaks in turbidity that correspond with the peak discharge (Figure 5) but do not always show the same recovery to pre-storm conditions.

The measurements for storm events with sufficient samples were partitioned using the hysteresis in turbidity shown in Figure 6. These sample sets indicated a significant (<99.9%) difference between the amount of suspended solids in the rising storm hydrograph and those in the receding hydrograph. Similar differences were observed for the nitrates and phosphates between the rising and falling limbs of the turbidity-graph. However, the analysis of each specific storm shows a very large variability within the storm event and between events.

Many of the storm events showed the nitrate concentrations rising in direct association with the increased discharge followed by a corresponding recession. There is usually a low concentration of nitrates (~100 µg/l) in the pre-storm base flow conditions. The rainfall generally introduces between 100 and 200 µg/l. Consequently, there is a general rise in nitrate concentration during a storm event that is produce by surface sources and the influx from the rainfall. The increased values in nitrate coincide with increased flow *for many of the storms and consequently they* are associated with increased flow of the "new" water linked to surface flow processes.

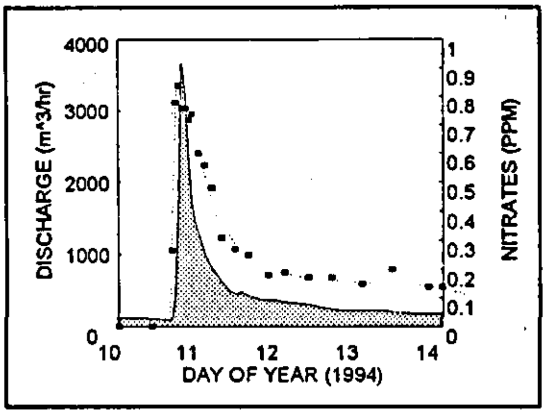

Figure 7 Example of the nitrate response for a typical storm event.

Total phosphates have been correlated to suspended solids in previous studies. The suspended solids show a conservative pattern that often conforms to the turbidity trends described above. Consequently, the <u>total</u> phosphate concentration would also conform to these trends. However, the <u>dissolved</u> phosphates concentrations are extremely low and show very little variation. Using sample separation method based on the hysteresis in turbidity during a storm event, the dissolved phosphates show a significantly (>99.99%) lower concentration with the receding hydrograph than with the initial flow conditions. This is observed in some individual cases for both W1H016 and W1H031. Insufficient samples and the very low concentrations of dissolved phosphate made it difficult to develop any significant relationship with flow patterns.

COMPOSITE MODEL RESPONSE

A composite model of selected storm characteristics was derived by synchronizing the peak discharges of all storm events and then superimposing (averaging) the hourly values of the storm variables. For sample data, the intermediate hourly values were interpolated from the sample values. The composite storm model, described in the report, shows the same basic features as those described above but obviously lacks some of the temporal resolution due to the composite technique applied to different sized storms. The composite storm is intended to portray typical conditions for specific rainfall conditions derived from short duration and high intensity storm events. There are several storms which do not conform to the composite model and these are discussed as individual case studies in the report.

ATYPICAL STORM RELATIONSHIPS

There are several variants on the proposed model response described above. There is an antecedent effect in turbidity for storms which occur fairly soon after a major storm event. Generally the initial storm removes the bulk of the sediment which is then not regenerated sufficiently fast to become available for the subsequent storm event. There are also cases where the conductivity response does not occur immediately with the increased discharge but is delayed several hours. This appears to occur after drought conditions when the catchment is too dry to support surface flow and there is time for the sub-surface "old" water to contribute initially to the discharge runoff.

There is also a definite variant of the nitrate model which is not linked to the drought or antecedent conditions. A medium sized storm with 24 samples covering the entire event shows the nitrate concentration reaching a peak value several hours after the peak discharge for the disturbed catchment (Figure 8). In these cases the nitrates must have been derived from sub-surface conditions (inter flow) and not the "new" water. However, there was generally insufficient resolution (number of samples) in the data to provide a clear indication of the direct links between the chemical changes and the hydrological processes. Similar conflicting results for storm events have been observed in other parts of the world that confirm the complexity of the ion exchange in these non-conservative chemical processes.

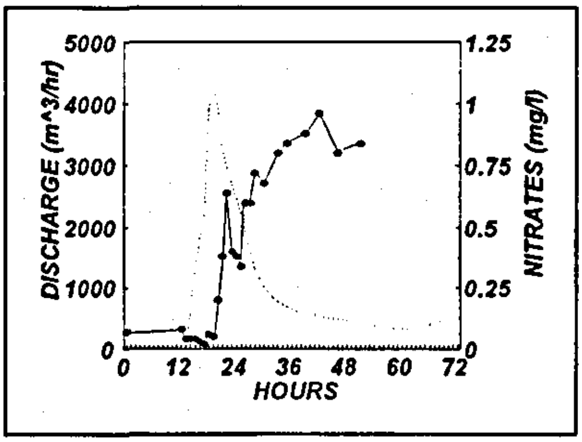

Figure 8 Variation of the expected nitrate response.

CONCLUSIONS

The project has identified and described some of the water quality responses which have been linked to hydraulic pathways that conform to hydrological processes. These observations have recently been observed in other research catchments. However, the relationships between many of the water quality constituents and the hydrological processes are complex and not easily identifiable, particularly through the analysis of grab sampling. Additional research with more intensive monitoring system using higher resolution sensors is needed to delineate the hydrological pathways if natural tracers are to be used. Numerical spatial analysis methods presented in an accompanying report are being developed to link the pathways in a catchment with source and sink areas. The method is designed to predict the theoretical hydrograph and chemograph response to various land uses (pollutant sources) which can be used for targeting specific sections of the hydrograph in order to establish a more intensive monitoring system.

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1 INTRODUCTION

Water forms the base of all living things. It is used extensively by all communities for a multitude of purposes. It forms the most important commodity in many countries in the world and is of such importance in South Africa that it warrants one of the largest Government Departments (Water Affairs and Forestry). Many wars have been fought over rights to water resources particularly in the arid and semi-arid parts of the world such as the Middle-East.

While water covers the greatest proportion of the earth's surface, there is still a very large disparity in its availability because the bulk of this water is not suitable for consumption and it generally cost too much to purify it to acceptable levels. The available fresh water reserves of the world are very limited in many areas and consequently, any deterioration in the quality of the water resource can reduce its availability or incur large recovery costs. With industrial development in most countries there has been a corresponding reduction in the quality of the water resources due to waste disposal. Similarly, developments in the agricultural sectors have also led to large scale pollution of water resources from leachate.

Agricultural and industrial developments have progressed from localised systems to more regional systems and there is now a growing body of evidence to suggest that many water quality issues have also increased in scale from what was once a local pollution problem to what is now one of regional dimensions (Heathwaite, Burt & Trudgill, 1993). However, the most severe water quality problems are still localised but in all cases they contribute substantially to the larger regional problems. Erosion at local scales will accumulate in rivers to the extent that substantial sediment export from a region can reach levels of up to 1000 tonne/km^2/year in parts of South Africa (Rooseboom, 1978). Salination of large rivers is linked to agricultural practices such as irrigation (Flügel and Kienzle, 1989). This degradation of the regional water quality often leads to huge water purification expenses which could be reduced if appropriate conservation measures were implemented.

Environmental degradation due to industrial development is normally localized and controllable. However, the degradation in water quality from non-point source effects involves many processes operating over large scales under different conditions that include vagaries of climate, land use and geomorphology. The great expense in the reclamation of polluted water as well as the loss of soil from valuable lands has led to extensive research on conservation measures. Many experiments have been done on small scale homogeneous plots under different management schemes. The results of these plot experiments are then extrapolated to larger scale system, usually through numerical studies, to evaluate the effect on regional water resources.

Experimental plots reduce the variability in natural processes to expedite rapid results under controlled conditions. However, the larger scale systems involve more processes and greater variability in controlling conditions which may drastically alter the response. For example it is difficult to isolate the links between the land use (such as diffuse sources of fertilizer applications, animal waste etc,) and the stream water quality (Dermine and Lamberts, 1987). The precise relationship between local rates of erosion and downstream sediment yields, which reflects the sediment delivery process operating in a catchment, remains a major uncertainty (Walling, 1984). A lot of this uncertainty can be attributed to changes in sediment availability within the catchment. Many of the difficulties associated with the identification and quantification of the processes involved in the sediment delivery lie in the measurement of the sediment transport (Weaver and Hughes, 1984).

The hydrological response to land use varies considerably between catchments due to a multitude of factors that include the geomorphology, climate, soils, and others. The variability between seasons and between catchments can be great. Simpson (1992) showed large differences between years and between coupled catchments in Natal which was reflected in significant changes in many water quality factors such as suspended solids and nutrient loads. Kelbe , Mulder, Bodenstein, Hattingh and Verwey (1992) tried to link these changes in the Ntuze catchments to hydrological processes but found the temporal resolution was not suitable.

The hydrological processes involving the flow of water through a catchment are fairly well defined and can generally be identified under specific conditions. However, the physical and chemical pathways in the catchment involve many different processes which are also linked to the flow dynamics. These processes, with complex feedback mechanisms, have not been extensively investigated at the catchment scale under heterogeneous land use conditions.

Atmospheric deposition, diffuse waste disposal and fertilizer application are major sources of pollutants which affect water quality in rural catchments. It is widely accepted (Heathwaite, Burt & Trudgill, 1993) that plant productivity responds to increases in the supply of available nutrients and consequently there has been a major increase in the application of fertilizers in many agricultural practices. The loss of fertilizers, particularly through such processes as sediment transport, leaching and volatilization of compounds are having a major impact on receiving waters. Up to 30% of nitrogen fertilizer application may be lost through leaching (Stewart and Rosswall, 1982). However, there is no simple relation between the nutrient losses and application on agricultural lands. Heathwaite, Burt & Trudgill (1993) cite many references to the numerous factors such as climate, soil type, soil drainage, fertilizer application rate and the presence of grazing animals which influence nutrient leaching losses. They also indicate that a 100-herd dairy produces the organic waste equivalent to a large village of 400 houses in Europe.

There are few studies which have examined nutrient losses in small catchments (<10 km^2) However, Burt and Haycock (1993) suggest that the small scale catchment studies are extremely important if the aggregation of plot studies covering variations in land use and topography are to be adequately linked to patterns in nutrient loss. Burt and Arkell (1986) studied the spatial pattern of nitrate runoff from different land uses in a 1 km^2 catchment which suggested that the water quality was sensitive to more than just the riparian land. Valley-side slopes and the plateau which drain through hill slope hollows, may also have a direct impact.

Catchment scale studies of water quality processes have been undertaken in many locations at various times. Fifty years of research on the Coweeta catchments have been presented by Swank and Crossley (1988), while extensive studies have been published on the Slapton catchments (Burt, Butcher, Coles and Thomas, 1993). However, it is only recently that the developments in monitoring techniques have provided the opportunity for more intensive investigation to be undertaken to examine the links between the different processes (Wolock and Hornberger, 1989; Burt and Arkell, 1986, 1987). This project was initiated in 1992 to develop a remote system with sufficient temporal resolution to examine the links between the hydrological processes and water quality conditions in the Zululand coastal region at the catchment scale.

The degradation of the water resources of Zululand have had serious consequences. The floods in 1984 caused the government to compensate farmers for the complete loss of their farms in the Umfolozi flood plain due to sediment deposition. The Richards Bay Harbour development was designed so that the reconstructed estuary (Sanctuary) would be self sustaining through hydraulic actions but excessive sediment loads in the Mhlatuze River have reduced the bay to less than half its original size and this has led to the complete collapse of the flow system. This degradation is generally attributed to the land use practise in the catchments of these major river systems. Consequently, improved understanding of the link between hydrologic response and causative factors in this area could help to reduce the degradation of the water resources in Zululand and to achieve sustainable development through appropriate management techniques.

While sediment is the most obvious pollutant in the rivers of Zululand, the change in land use to intensive subsistence and commercial agriculture could lead to other serious pollution problems, particularly from the application of fertilizers, insecticides and herbicides. The sugar industry has had to impose a moratorium on the use of certain substances because of the pressure from concerned pressure groups who believe their crops were being destroyed by the aerial application of herbicides. It is not clear if this apparent effect is through atmospheric or hydrologic contamination.

Following the concerns described above, this project was setup to examine the water quality problems and their association to specific hydrological process. The choice of a research site in the area depends on the suitability of the research catchments to be representative of the hydrological processes under investigation. Some specific water resources in the Zululand region near the Mhlatuze River have been monitored for changes in selective water quality characteristics over several years and these have been used to determine the extent of degradation and suitability for hydrological process research (Kelbe *et al*, 1992). The Mhlatuze River is the main water supply to Empangeni and satellite towns and consequently it is monitored at several sites by the Department of Water Affairs and Forestry. This river is also the main supplementary resource for Richards Bay and eSikhaweni. Consequently, any pollution in the catchment impinges on the reclamation costs of this water for domestic and industrial use. The general (average) water quality characteristics from several years of weekly grab sample monitoring are given in Table 1.1. Similar information is also given for the Matikulu River which is also monitored by the Department of Water Affairs and Forestry near the outlet to the sea. This information is compared (Table 1.1) to several other smaller river systems in the area which have been used for selective research (Archibald *et al*, 1985; Hope and Mulder, 1979; Simpson, 1992 and Kelbe *et al*, 1992).

There is no clear indication of increasing pollution loads with increasing catchment size for these Zululand rivers. While the highest Total Dissolved Solids (TDS) concentrations are observed in the largest catchments (W1H009) the smallest do not necessarily have the lowest concentrations. The highest concentrations in nutrients are shown for the small coastal streams (W1H018 & W1H019). Consequently, the *water quality emanating from a catchment is generally attributable to the land use* practice and not its dimensions.

The concentration of pollutants for the rivers shown in Table 1.1 is relatively high and could be a cause for concern to the Zululand region. The World Health Organization (WHO) reported 2000 cases of nitrate poisoning (methaemoglobinaemia) in the world of which 160 people died as a result of consuming water with a nitrate concentration greater than 25 mg/l of NO_3 (Heathwaite *et al*, 1993). The levels in the main rivers of Table 1.1 are several orders of magnitude below this level but the concentration in the Siyaya and Amanzamnyama were only one tenth of these lethal concentrations. These

Table 1.1 Characteristic values of physical properties and chemical concentrations of the Mhlatuze (W1H009), Matikulu (W1H010), Ntuze (W1H016 & W1H031 and the Siyaya (W1H018) and Amanzanyama (W1H019) Rivers.

Quality Factor (conc)	Weir	W1H09	W1H18	W1H19	W1H16	W1H31	W1H10
	River	Mhlatuze	*Siyaya*		*Ntuze*		*Matikulu*
Ave flow (m^3/day)		40000	100	100	3000	3000	49000
Runoff (mm)		calculate					
pH		7.65	6.88	6.56		6.85	7.14
TDS (mg/l)		332	157	182	108	102	162
SS(mg/l)		154	133	381	126	75	72.8
Turb (NTU)			17.6	18.1	24	8.5	
NO_3 (mg/l) [N]		0.261	1.721	2.483	0.256	0.107	
PO_4 (mg/l) [tot soluble]		0.03	0.036	0.057	0.017	0.045	0.019
Alkalinity		110	17.1	36.1			50.8
K (mg/l)		2.41	2.73	3.57			1.99
NH_4 (mg/l) [N]			0.137	0.147		0.014	0.061
SO_4 (mg/l)		13.3	20.5	14.6			7.65
Si (mg/l)		8.87	5.17	5.72			5.95
Cl (mg/l)		84.3	59.5	67.2		0.042	43.2
F (mg/l)		0.28					0.2
Ca (mg/l)		15.8	7.45	6.57			8.7
Mg (mg/l)		14.1	6.36	7.7			7.38
Na (mg/l)		67.5	30.5	35.5			31.1
DOC (mg/l)					8.7	8.7	

NB W1H009 & W1H010 from Dept Water Affairs and Forestry Data Bank
W1H018 & W1H019 from Archibald, *et al* (1985).
W1H016 & W1H031 from Kelbe *et al* (1992), and Simpson (1992).

high concentrations were due to heavy fertilizer application on very sandy soil under high rainfall conditions but have declined with changing land use. However, if similar agricultural development prevails in the larger catchments then the problem may become more serious.

The average water quality factors for the Ntuze River shown in Table 1.1 are generally within the range of values observed in the larger river systems of the region. Consequently, this river is considered be representative of the general conditions prevailing in the major part of the larger catchments in Zululand and would be an ideal research catchment for investigating the hydrological processes affecting the regional water resources.

The Ntuze research catchments comprise six nested weirs which have been used for research purposes since 1978 (Table 1.2). They share a common divide with the Mhlatuze River and have undergone considerable changes during the last ten years. The variation in the general water quality characteristics within the catchments are shown in Table 1.2. There is a rise in both conductivity (mS/m) and turbidity (NTU) with increasing catchment size. Consequently, this investigation of water quality conditions should be representative of the small headwater catchments and could be extrapolated to the conditions at the larger scales. The catchments monitored by weir W1HO16 and W1H031 have been chosen for this study (see Figure 3.1 for their location).

Table 1.2 Mean physical properties of grab samples from Ntuze catchments for 1992-94.

WEIR	SIZE	pH	COND	TURB
	(km^2)		mS/m	NTU
W1H012	82.0	8	31.8	18.4
W1H013	40.0	7	23.9	15.9
W1H015	13.6	7	24	10.9
W1H016	3.2	7	18	14.2
W1H031	3.2	6	15.5	6.2
W1H017	0.7	6	16	8.9

2 OBJECTIVES

The occurrence of natural and anthropogenic substances throughout the aquatic environment is dependent on the hydrological processes controlling the dispersion and transportation of these substances. This project was initiated to investigate the relationship between certain water quality features in a rural environment and specific hydrological processes affecting the general flow characteristics. The main objective was divided into two broad categories relating to ***firstly*** the measurement and evaluation of the water quality characteristics emanating from specific rainfall events which are described in this report and ***secondly*** to the numerical modelling studies of water quality conditions for various rainfall conditions described in an accompanying report. This report covers the first part of the study while the second part is presented by Kelbe, Snyman and Mulder (1996). Because the project experienced exceptional drought conditions (estimated to be 1:200 year drought) the expected number of events never materialized in spite of an extension of the project for a further two years. Consequently this report has broadened the objectives to include a general analysis of hydrological conditions not catered for in the original aims.

The specific objectives relating to this report are : -

Objective 1	To develop an automatic instrumentation system for the continuous monitoring and sample collection of catchment runoff for determination of selected water quality factors in the field.

No affordable commercial instrumentation for continuous field measurement of the selected water quality factors could be found when the project was initiated. Consequently, the first objective was to develop a continuous monitoring system which could measure and record the hourly (or shorter) observation of selected water quality parameters in the field where there was no commercial power supply. The system also needed to initiate and collect flow related water samples for further laboratory analyses and system calibrations.

Objective 2	To determine the relationships between water quality characteristics and specific hydrological processes which are typical of conditions in the Zululand Coastal Catchments.

The runoff hydrograph from short duration high intensity storms in a small research catchment can be partitioned into three identifiable components (Chow *et al*, 1988). These three components indicate the periods when base-flow, inter-flow (through-flow) and surface-flow (channel-flow/overland-flow) dominate the discharge hydrograph. With suitable monitoring, the identifiable changes in the different water quality factors during specific hydrographs could then be linked to the dominant hydrological flow regimes. This would provide a means of tracing the source of water pollutants if the flow path within the catchment (hydrological process) was known.

The objective of this report was to concentrate on the short duration high intensity storms when surface-flow (overland-flow) was assumed to occur. Surface runoff operates at considerably higher velocities than through-flow and would therefore be detectable from the start of the storm discharge to the first inflection points in the recession slope of the discharge hydrograph (Figure 2.1). Similarly, the through-flow would predominate between the cessation of overland-flow and the point where only base flow was observed (approximated by the second inflection point in the recession slope of the hydrograph). Changes in the water quality hydrograph can then be linked to specific hydrological processes.

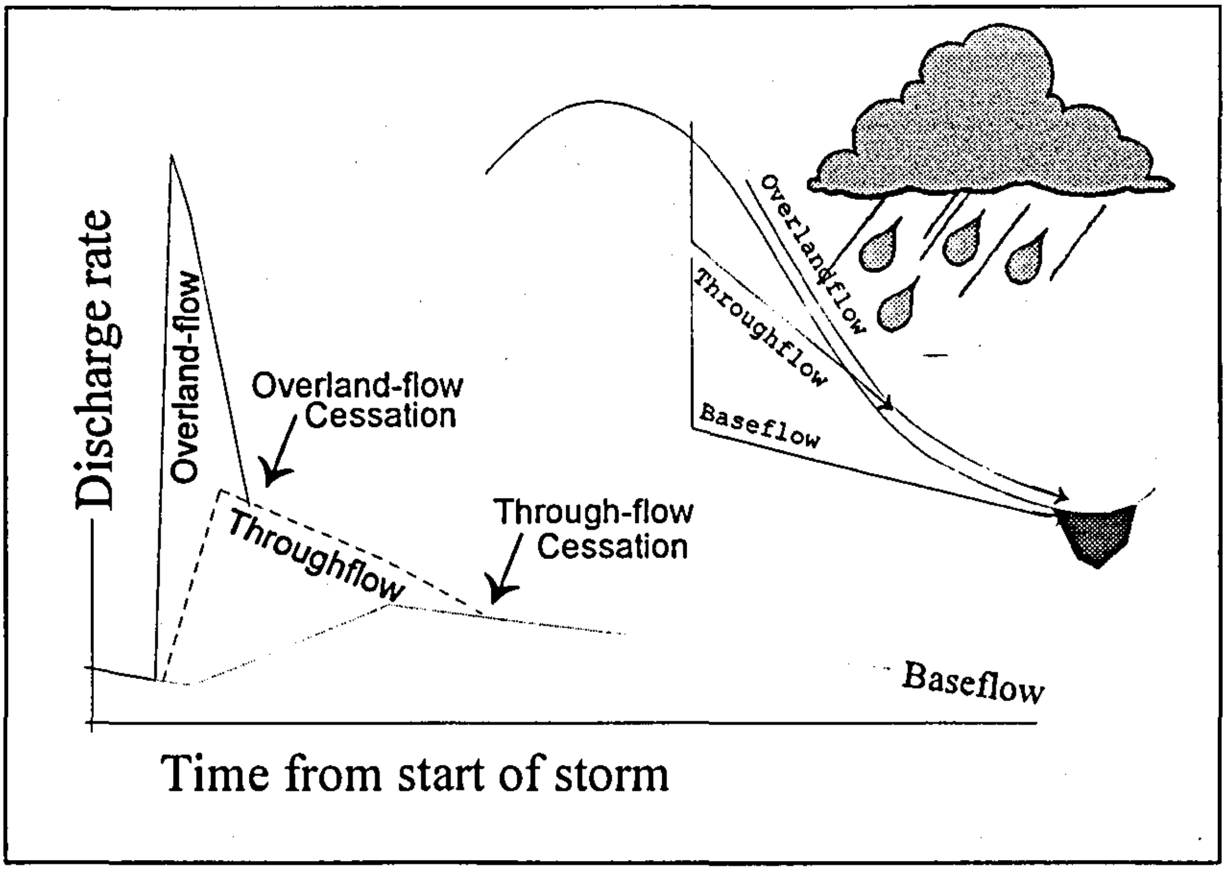


Figure 2.1 Schematic diagram of the hydrological processes under consideration in this project.

3 RESEARCH CATCHMENT

The principle objective of this project was to examine the relationship between water quality characteristics and hydrological processes. This required a monitoring system where specific hydrological processes and water quality characteristics could be identified. The principle hydrological processes considered in this study (as portrayed in Figure 2.1) are overland-flow, through-flow and base-flow (Chow *et al*, 1988). These processes have different response time because they travel along different pathways above and within the soil surface. To be able to detect these processes in the discharge hydrograph of a catchment, the catchment must be sufficiently small for each process to be completed (dominate) before the next process becomes significant in the discharge hydrograph (Figure 2.1).

Overland-flow occurs within a catchment when the rainfall rate exceeds the infiltration rate or saturated conditions must prevail so that the excess rainfall must flow directly over the land surface to the channel. This generally occurs with short duration, high intensity convective storms. These storms produce runoff from variable source areas which fluctuate with the antecedent conditions and the extent of the incident rainfall. Extended duration storms may produce overland-flow but they generally provide sufficient time for all the different hydrological pathways to produce a significant proportion of the discharge simultaneously in the hydrograph. Consequently the project required a catchment within an area where there were a significant number of high intensity, short duration storms. Garstang *et al*, (1987) and Kelbe (1985) have shown that the interaction of the subtropical circulation system with temperate latitude systems along the steep Drakensburg escarpment of KwaZulu/Natal is ideal for the development and propagation of severe storms. This region provides a high probability of cumulonimbus activity in most years.

Kelbe (1995) has analysed the distribution of rainfall within catchments of varying sizes for various types of storm events and has shown that there is a rapid increase in the variance of the fraction of a catchment receiving rainfall. There is also a very rapid decrease in both the cross-correlation and probability of simultaneous rainfall with increasing catchment size. Consequently, small catchments are required if the effects of rainfall variability are to be minimized and a separation of the hydrological processes in the discharge hydrograph are to be realised.

The nested Ntuze Research Catchments of the University of Zululand in the Ngoye hills of Zululand were considered suitable for this study because the ones chosen for this project are small (~3km^2), they share a common border, have almost identical geomorphological conditions (Kelbe *et al* 1992) and they normally receive a high incidence of the required type of rainfall events (Hope and Mulder, 1979).

3.1 LOCATION OF THE STUDY SITES

The location of the catchment in relation to the main water resources and the major metropolitan and industrial development in Zululand is shown in Figure 3.1. The Ntuze River is the main water source for all the rural subsistence settlements in the catchment and also the coastal resort of Mtunzini. The research catchments border the Mhlatuze catchment which is the main water resource of Empangeni, Ngwelezana, Richards Bay and many other rural and urban settlements in the region. Consequently, the research catchments are representative of an important region which has experienced very severe water shortages and water quality problems in the last few years and is presently undergoing rapid changes due to population dynamics. Significant changes in land use practice, particularly the development of sugar cane in traditional subsistence agricultural settlements and the introduction of irrigation, are having a profound influence on the river.

The Ntuze research catchment is also situated in the physiographic region, generally referred to as the Natal Coastal Belt (Schulze, 1982), which stretches along the entire coastal belt south of the Mhlatuze. The region generally comprises weakly developed soils (mainly sands) with high infiltration rates (Mulder, 1979). Consequently, these catchments are considered to be fairly representative of large sections of the Natal coastal region, including the areas surrounding the large metropolitan centre of Durban.

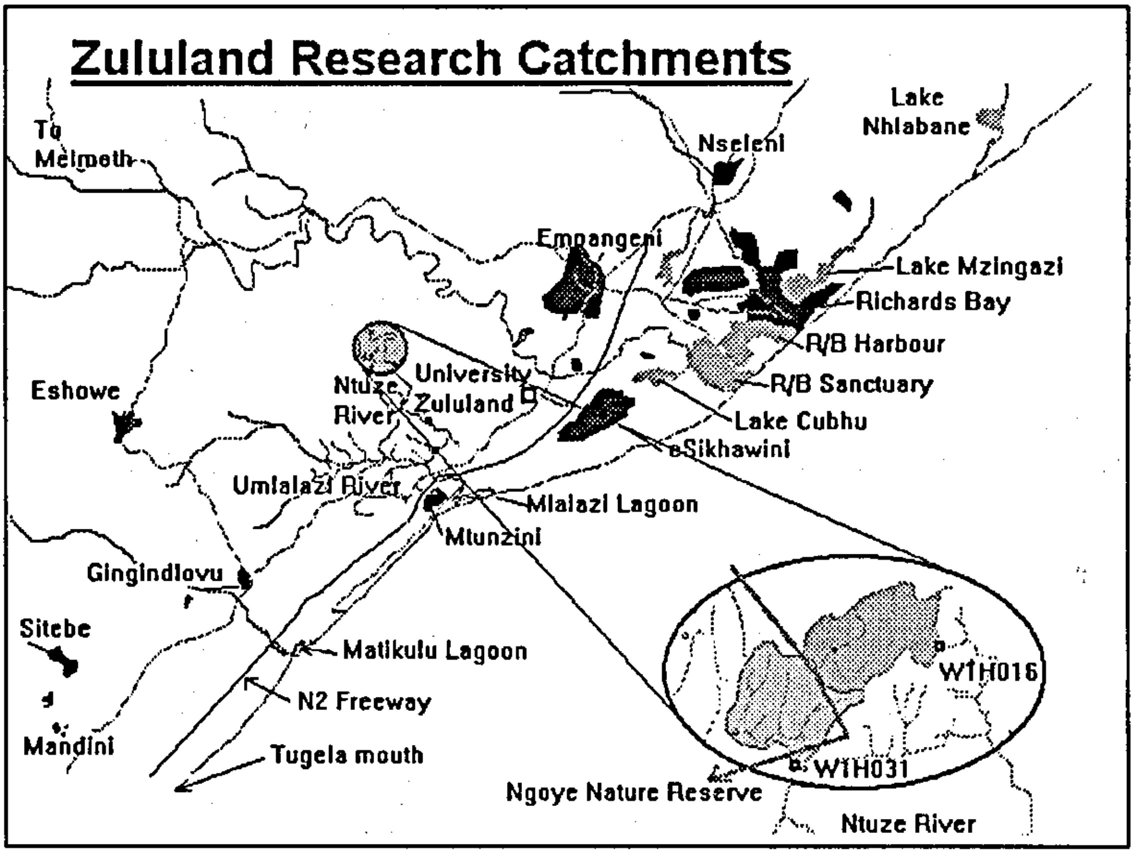


Figure 3.1 Location of the University of Zululand, Ntuze Research Catchments

The Ntuze research catchments have been described in detail by Hope and Mulder(1979), Kelbe *et al* (1992) and Mulder and Kelbe (1992). The area comprises six nested catchments ranging in size from 0,7 to 82 km^2 that have been monitored for rainfall and runoff since 1976. Detailed climatological and geological surveys of the research catchments have been conducted and hydrological response units identified (Hope and Mulder, 1979; Mulder, 1984, Kelbe *et al*, 1992 and Mulder and Kelbe, 1992). This study has been restricted to the two smaller catchments shown in Figure 3.2 and referred to by the national designated weir identification numbers as W1H016 and W1H031. There is a smaller catchment, W1H017, nested within W1H016. The weir at W1H031 lies just outside the eastern boundary of the proclaimed Ngoye Nature Reserve (*Figure 3.2*) so that the bulk of the catchment area falls within the Reserve Boundaries. The catchment area for W1H016 and W1H017 falls within a developing informal rural subsistence community which is showing a rapidly increasing population density (Kelbe *et al*, 1992) and a changing land use.

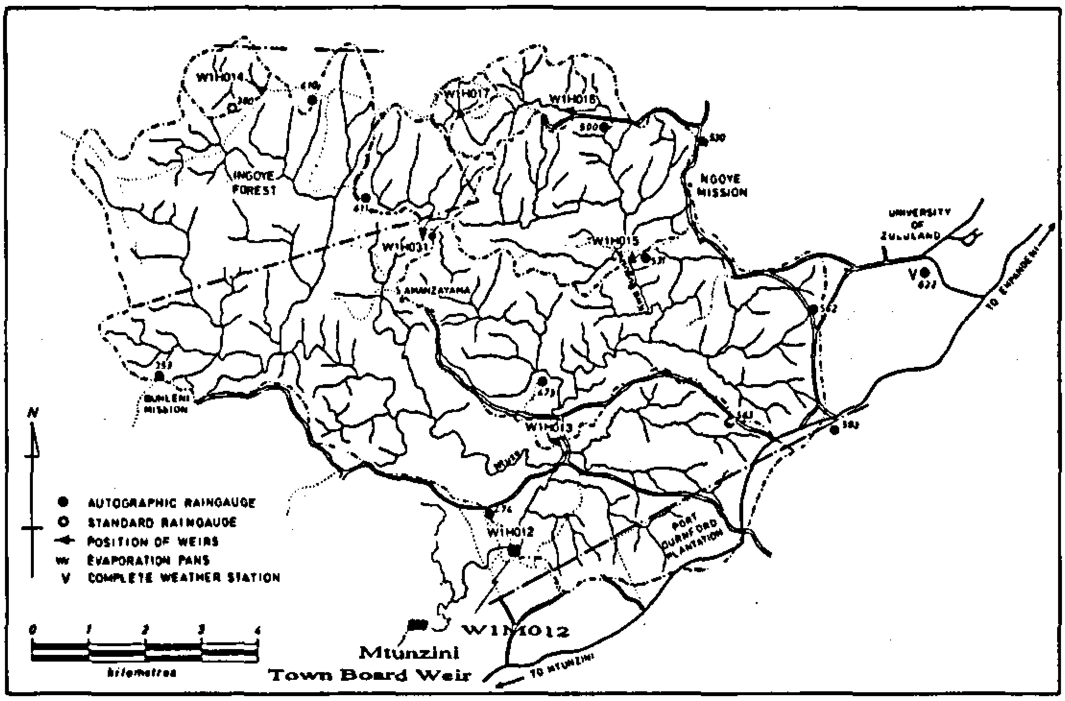


Figure 3.2 University of Zululand research catchment boundaries and instrument locations. Also shown is the Ngoye Nature Reserve Boundary(-·-·-)

3.2 TOPOGRAPHY

Both of the research catchments used in this study are situated in fairly hilly terrain (Figure 3.3 and Figure 3.4) and they form the headwaters of the Ntuze River. Their drainage areas upstream of the monitoring weirs at W1H016 and W1H031 are approximately 3.2 km^2.

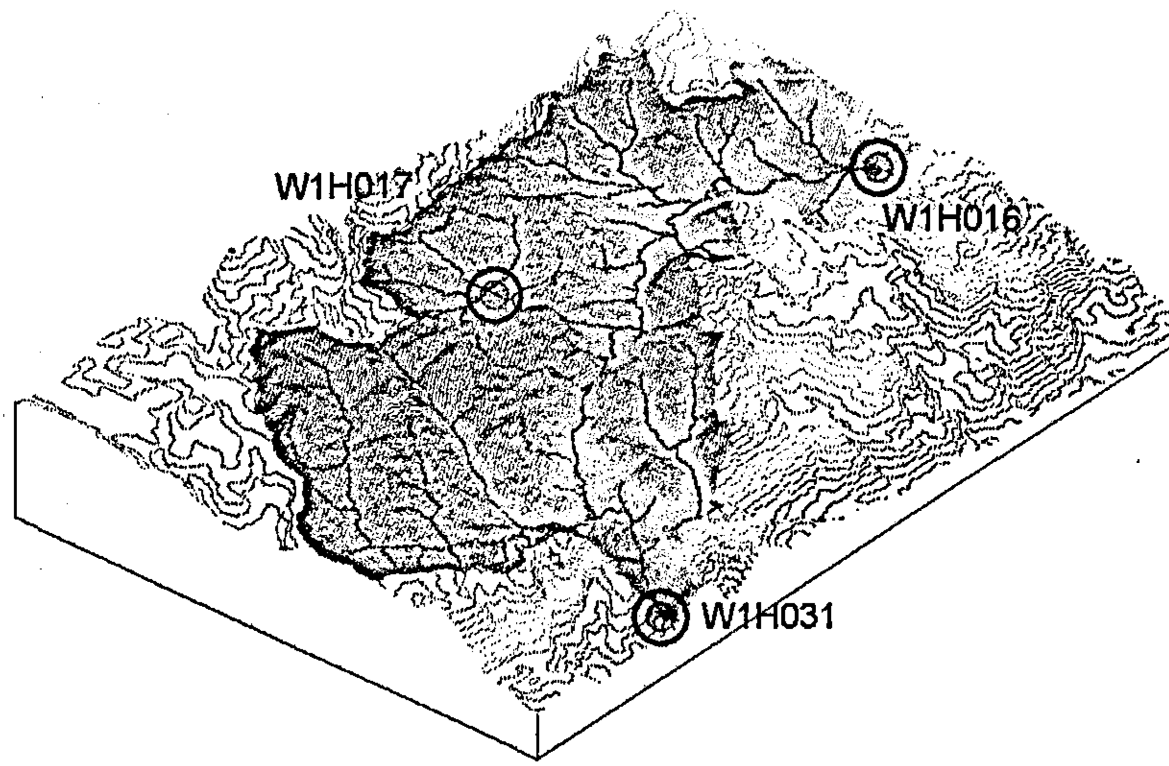


Figure 3.3 3-D view of catchment topography and streams with location of weirs

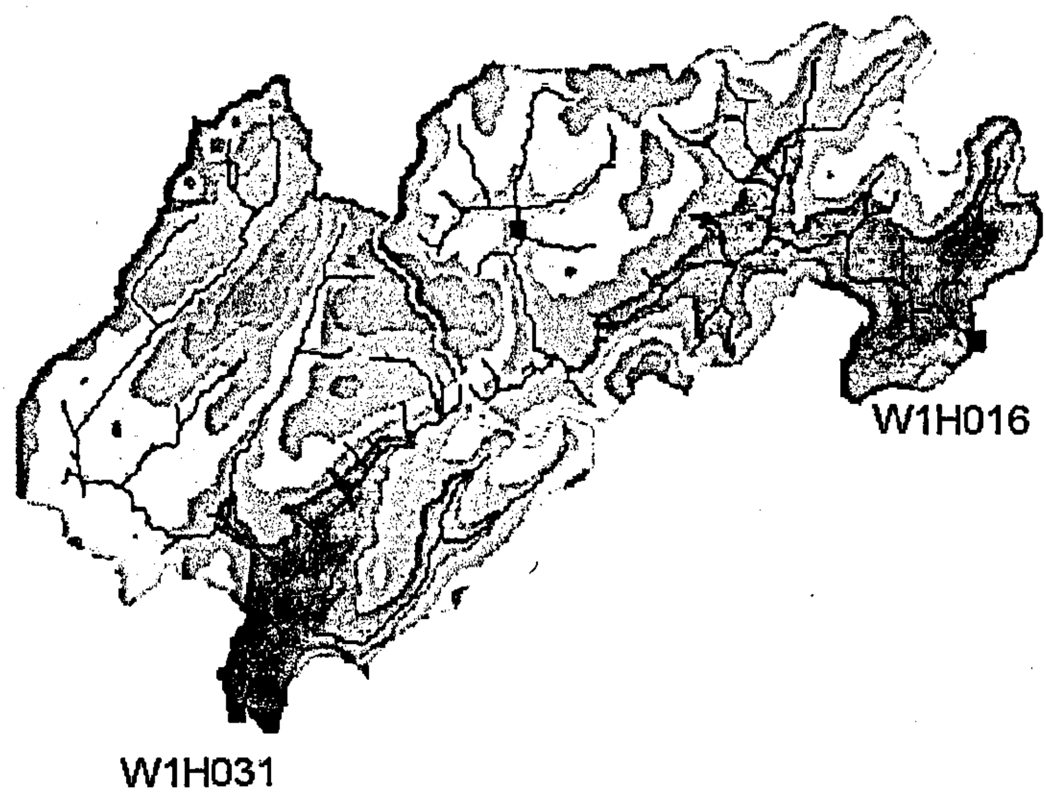


Figure 3.4 Topographical map with catchment boundaries and streams.

The western boundaries of the catchments coincide with the ridge of the Ngoye Hills and the divide with the Mhlatuze catchment. Both catchments also share a common divide of about 2 km.

3.3 SLOPE AND VARIABLE SOURCE AREAS

Studies by Mulder (1988) on deep, midslope, Glenrosa soils with grass cover on a runoff plot at the University of Zululand campus have shown that there is little or no significant surface flow on the mid-slopes. Nearly all the storm flow component from these plots were derived from surface runoff associated with bottom land (footslopes) variable source areas.

The possible range of variable source areas were estimated from topographical maps of the catchment areas between the stream and an arbitrary contour elevated some metres above the stream bed which is assumed to represent the flood plain. Flow-lines derived by Kelbe *et al* (1996) for W1H016, provided the means for estimating the catchment area contributing to runoff at various distances from the outlet (weir). Since each flow-path originates from a known pixel area, the frequency of flow-lines (Figure 3.5) also represents the catchment area contributing to runoff at the indicated distance. The total

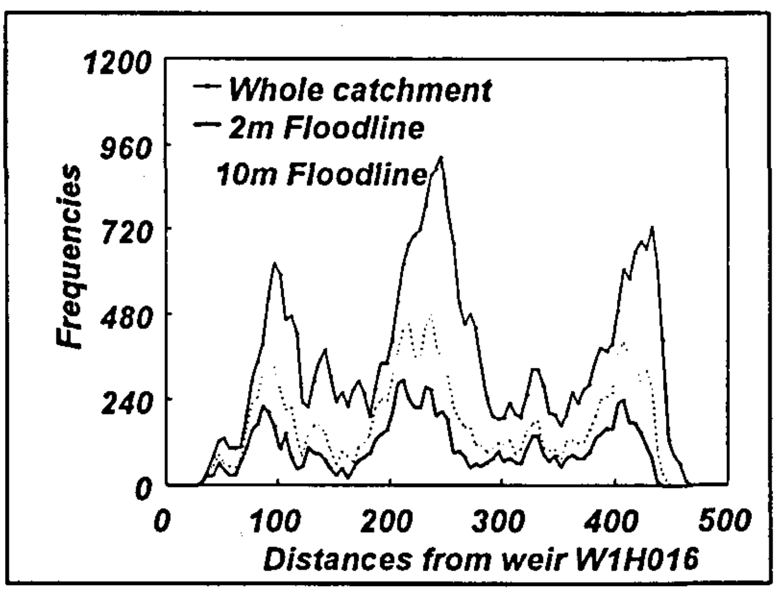


Figure 3.5 The relative area (frequency of 0.01 ha cells) upstream of weir W1H016 of the floodplain represented by the 2 & 10 m contours above the stream bed. The upper curve is for the entire contributing area (after Kelbe *et al*, 1998).

contributing area is shown by the upper curve in Figure 3.5. The corresponding areas for the flood-plain on either side of the stream was estimated from the contour of the bank elevations above the stream bed. These were derived for 2 and 10 m contours (defined above the stream bed) and their frequencies (areas) presented in Figure 3.5.

The cumulative frequencies (areas) upstream of W1H016 are shown in Figure 3.6. For a 2 m flood-plain, the "variable source area" contributing to overland-flow represents about 25% of the catchment area. This area is assumed to be the portion of the catchment which is responsible for the predominance of the surface runoff contribution to the discharge hydrographs discussed in later sections of this report.

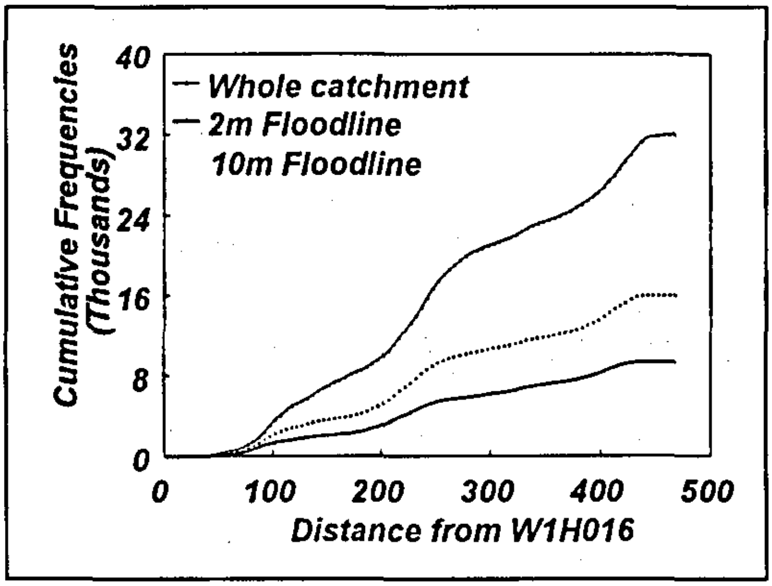


Figure 3.6 Cumulative area of the flood-plain upstream from W1H016 for two assumed elevations of 2 & 10 m. above stream-bed. The upper curve represents the area for the entire catchment.

3.4 SOILS

The soils of the research catchment are shown in Figure 3.7. These soils have a significant role in the hydrological response of the catchment. Deep sandy Glenrosa soils with a high infiltration rate will tend to induce greater attenuation of catchment peak discharge rates than the less permeable clay soils. Soil types will also have an influence on the sediment load and suspended solids derived from the catchments. Soil characteristics are also needed for deriving specific

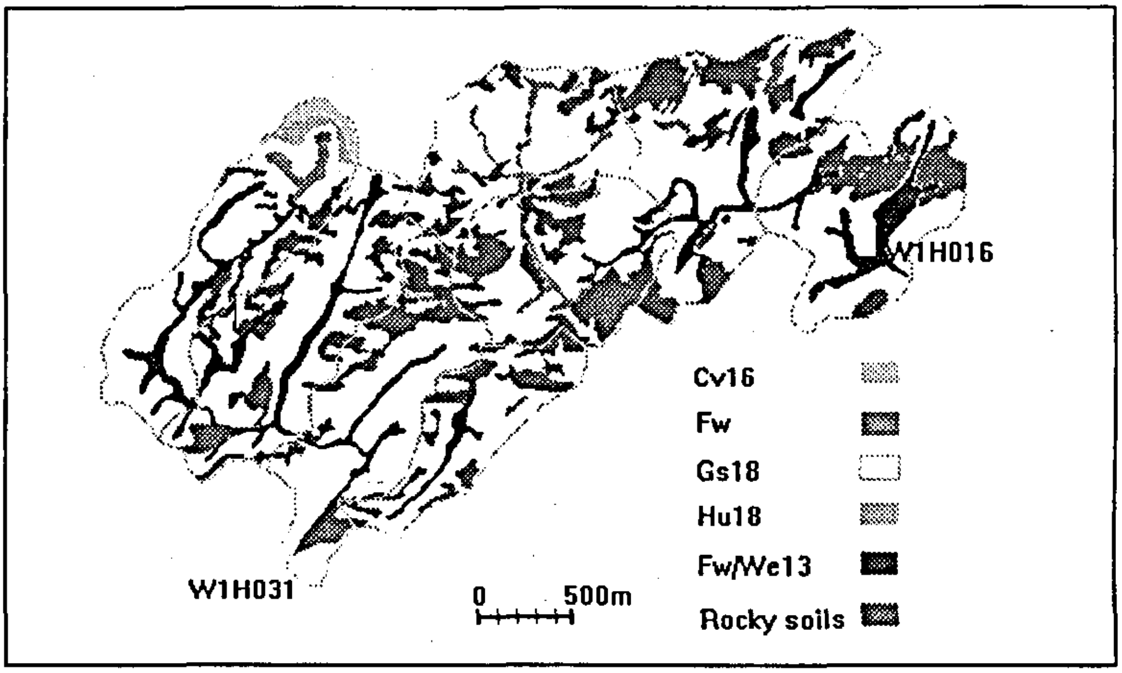


Figure 3.7 Soils for W1H016 and W1H031 catchments (after Mulder and Kelbe, 1992)

parameters in hydrological modelling (Mulder and Kelbe, 1991). Consequently a detailed soils map was derived for both catchments from core and pit profiles at strategic locations. Soil samples were analysed by the South African Sugar Association Experiment Station (SASAES) at Mount Edgecombe. The soil samples were analysed for bulk density, total and air filled porosity, moisture content at saturated capacity, field capacity, and wilting point. These values are discussed in detail by Kelbe *et al* (1996).

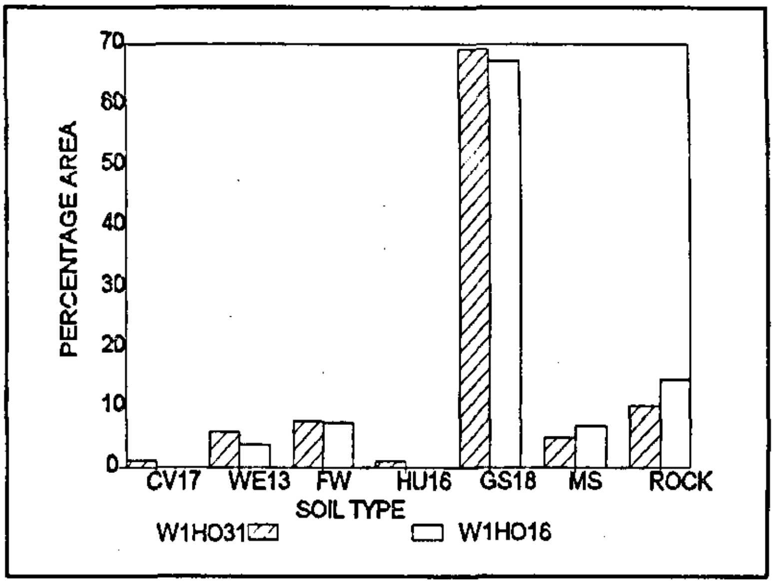


Figure 3.8 The relative difference in areas of the various soil classifications for W1H016 and W1H031.

The relative area of all the main soil types for both catchments is shown in Figure 3.8. With the exception of very small areas of

Clovelly (Oatsdale) and Hutton forms in the upper reaches of W1H031, both catchments have similar soils and approximately the same percentage of rock outcrops. Nearly 70% of both catchments are covered by fairly deep Glenrosa form (Robmore series) soils. Consequently the Robmore soil series should have the most significant effect on selected characteristics of the water quality.

3.5 STREAM CHANNEL

Soil samples were collected from the surface of the ground at 100 m intervals up the river from W1H016 to determine the composition of the soil surface most likely to be eroded with the initial storm runoff. Samples were collected at five points across the stream channel. These were taken from within the stream channel (1) , from either side of the immediate stream bank (2&3) and from a point (4&5) further up the bank on either side of the stream channel. The soil samples were taken from the immediate surface of the ground without disturbing the underlying soil. These samples were analysed in the laboratory for grain size and organic matter content in order to determine the potential source of sediment from surface runoff.

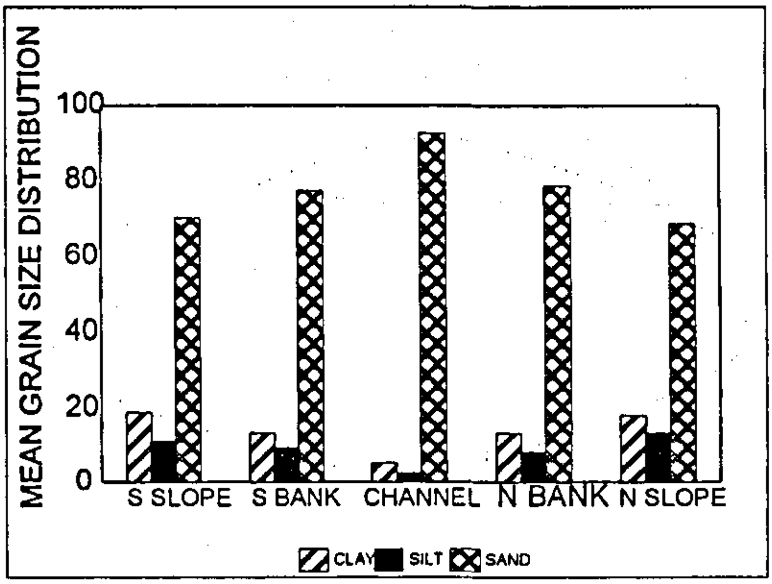


Figure 3.9 Frequency of soil composition across river banks and channel (S=south, N=north)

The relative frequency of the sand, silt and clay composition across the stream banks is shown in Figure 3.9. The clay and silt contents are between 10 and 20% on the foot-slope areas but this decreases to less than 5% in the river channel. There is a compensating increase in the sand content when going from the banks to the river channel.

The soil samples were ashed (@400°C) to give an indication of the organic content across the stream transect (Figure 3.10). There is a small difference between the north and south banks but a significantly lower organic content in the main stream channel.

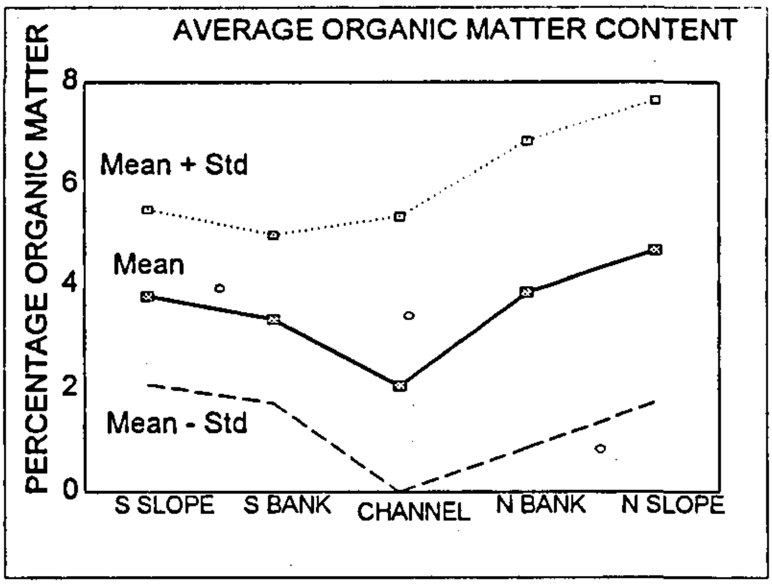


Figure 3.10 Organic content of soil samples from the stream channel and adjacent bank upstream of W1H016.

The sand and clay content of soil samples taken at regular intervals along the stream channel from W1H016 past W1H017 is shown in Figure 3.11. The sand content is fairly regular until W1H017 (sample point 21) where it decreases significantly. Similarly, there is a corresponding increase in clay content in this catchment above point 21 in comparison to the stream sections between W1H017 and W1H016. The stream banks and foot slopes show the opposite

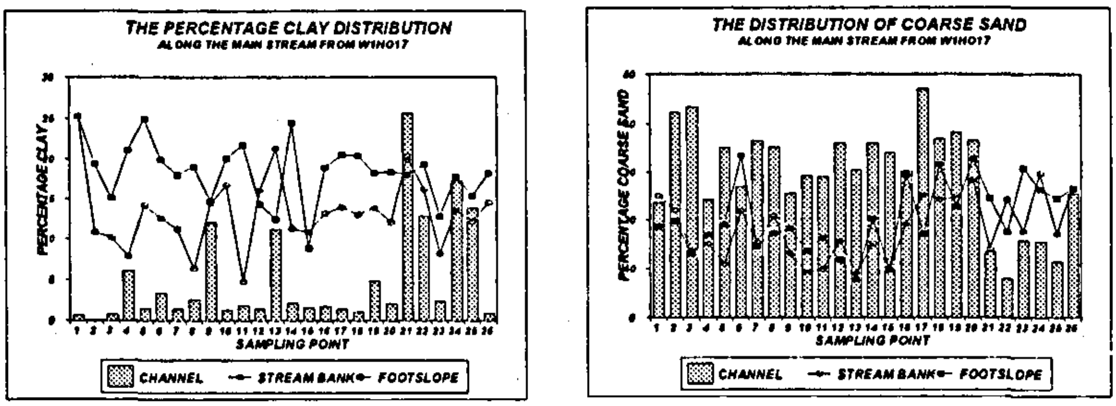


Figure 3.11 Soil surface composition upstream of W1H016.

trends for sand content although the difference does not coincide with the stream bed but changes at about half the distance between the two weirs.

There is a fairly uniform organic content in the surface soil of between 2 and 4% on the stream bank along the entire river course (Figure 3.12) with an occasional high value of 10%. The banks and foot slopes along the upper half of the river valley are usually higher in organic content (~4%) than the areas closer to weir W1H016.

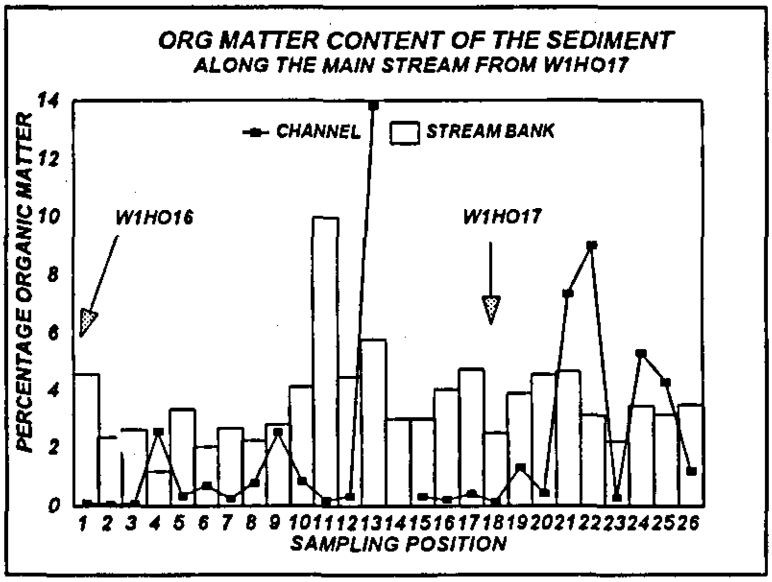


Figure 3.12 Organic content of soil profiles upstream of W1H016

The change in the particle size and the composition of organic material in the *runoff during storm events is discussed later. Similarly the difference in the* particle size composition of the bedload and the runoff is discussed by Kelbe *et al* (1998). There is a significant difference between the natural (W1H031) and the disturbed (W1H016) catchment in the volume of bedload cumulating in the streams as measured in the weir dam. The bedload in the disturbed system is more than four times the load in the natural system. This is also discussed in more detail by Kelbe *et al* (1998) where the sediment transport process is modelled for both landuses. With the exception of the slightly higher clay content in W1H017, the soil surface composition is consistent along the stream channel and adjacent banks for most of the length sampled.

3.6 LAND USE

The existence of the protected nature reserve in the research catchments (see Figure 3.2) provided the opportunity to compare two similar sized catchments with different land use practices while investigating the relationship between water quality characteristics and hydrological processes.

3.6.1 NATURAL CATCHMENT : W1H031

The Ngoye Nature Reserve, controlled by the Department of Nature Conservation of KwaZulu/Natal (now part of KwaZulu Nature Conservation), is a small forest reserve that was scheduled for re-fencing and stocking with indigenous fauna during 1988. This has not been achieved and the area is still used for controlled grazing by the local inhabitants surrounding the reserve. The grazing by a limited number of cattle is unlikely to exceed the utilization of fodder by indigenous fauna in a natural ecosystem except in the immediate vicinity of the access gates where excessive degradation is likely to occur. With the exception of the area around the access "gates" there has been no visible sign of overgrazing throughout the duration of this project.

Table 3.1 Land use area (ha) for W1H031 and W1H016

Land use Feature	W31	W1H016			
	1988	1978	1988	1993	1995
Forest	28	4	5	11	9
Gums	0	4	7	7	7
Cultivate	0	3	3	7	1
Sugar	0	0	2	7	16
Grass & Rocks	72	89	83	68	67

The areas of the various classes of land use types in the undisturbed natural catchment are shown in Table 3.1. The indigenous forest which are generally found along the streams contribute 28% of the catchment area, while the natural grasslands with some exposed rocky outcrops make up the remaining 72%. No significant changes have been identified in this catchment since 1988.

3.6.2 DISTURBED CATCHMENT : W1H016

The land use characteristics up to 1988 were presented by Kelbe *at al* (1992) and are summarized by class types in Table 3.1. This previous study also described the demographics and the cultivation practices in these research catchments as well as their changes over the three years of observations. The catchments were surveyed again in 1993 and 1995 using aerial photography. There have been significant changes in the land use practice in the W1H016 catchment. The present land use map derived from an aerial photograph flown in 1995 is shown in Figure 3.13 and the estimated changes in the area of each land use are given in Table 3.1. The major development has been the increase in sugar cane production which has increased from 2% of the catchment (6 ha) in 1988 to the present 16% (50 ha) in 1995 which is shown in Figure 3.14. The sugar cane has generally replaced the traditional cultivated crops such as maize.

Stock farming in this area is generally used for commercial, subsistence and traditional purposes. A survey by Kelbe *et al* (1992) indicated that 45% of the kraals had no cattle while none of the kraals exceeded 20 animals. A twice weekly government dipping program at a dip (Gugushe - 705) just upstream of weir W1H016 shows that the number of cattle declined from ±2700 to 2000 since 1987. The present number of owners amount to 356, giving an average of 5.6 head of cattle per owner, which is close to the value obtained by the survey.

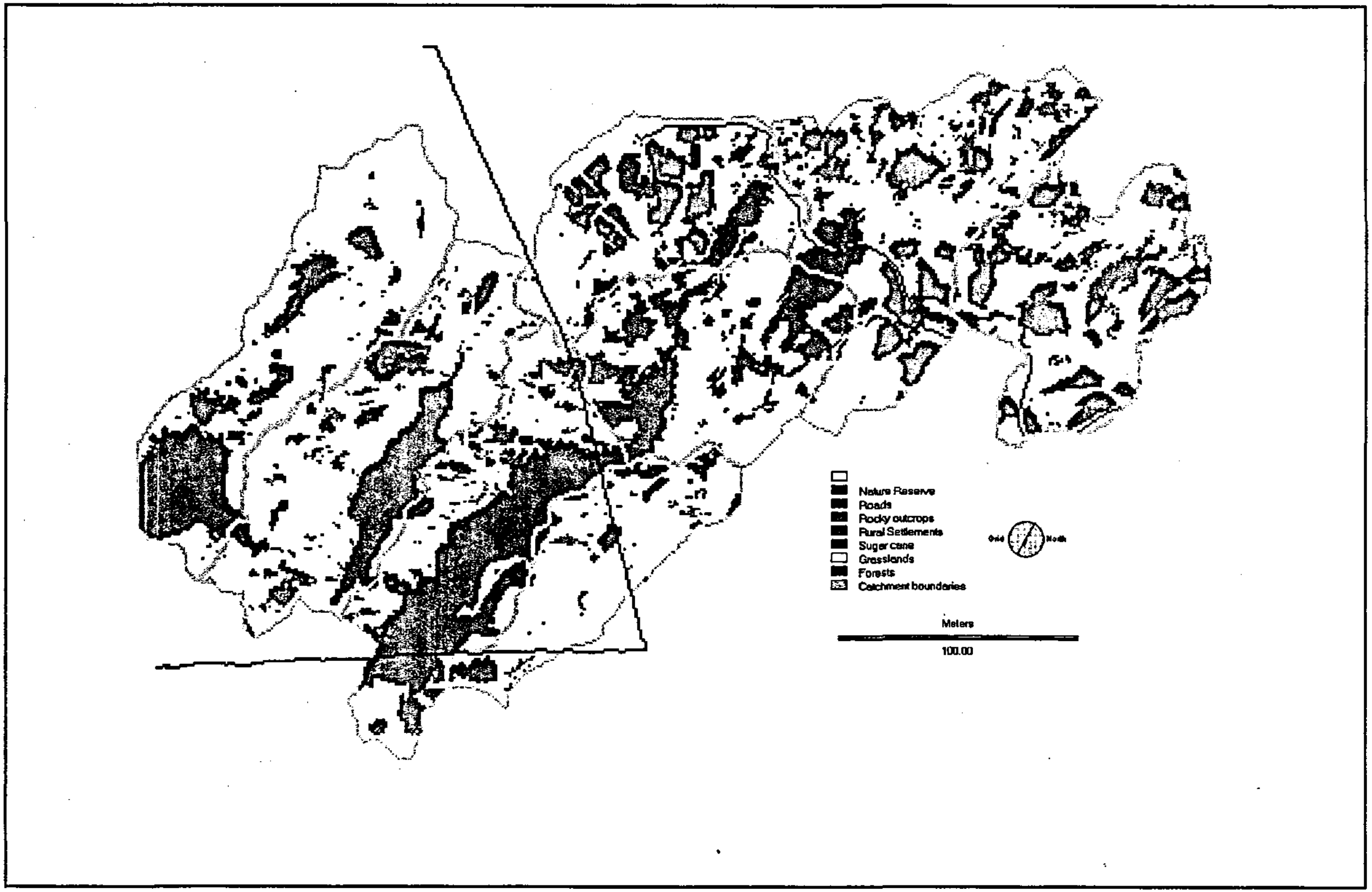


Figure 3.13 Land use for research catchments derived from 1995 aerial photograph.

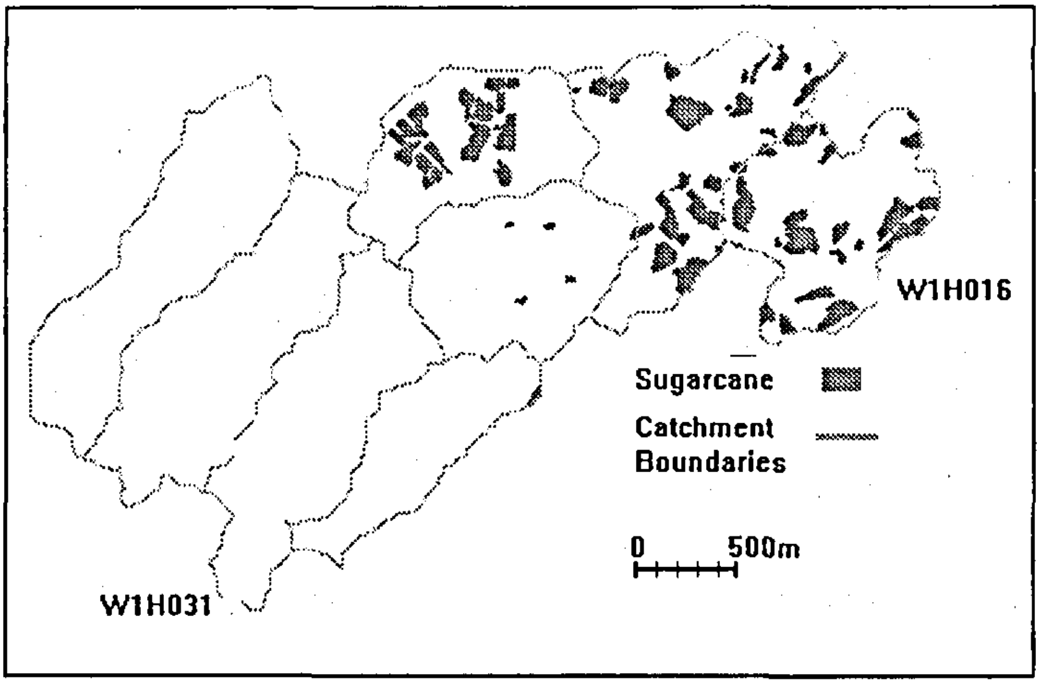


Figure 3.14 Areas under sugarcane production in 1995.

The present grazing density amounts to one hectare / large stock unit/ annum if one considers only the 2350ha of grassland (1988 land use survey) in the disturbed catchment only. This exceeds the recommended average carrying capacity of three hectares/ large stock unit/ annum (Tainton, 1980). The grassland within the Ngoye reserve is also being utilised to a large extent and it is therefore virtually impossible to ascertain the actual load. The higher density and quality of the grassland within the reserve compared to the disturbed catchment does indicate, however, a higher concentration of animals within the latter area.

The rapidly changing land use patterns and increasing population pressure on the area surrounding the forest reserve has an adverse effect on the natural environment. It is therefore important to predict the effect of these changes on runoff and its water quality for future planning purposes.

4 INSTRUMENTATION

The physical and chemical nature of the runoff from a catchment reflects the pathways and processes of a particle during its journey from precipitation to discharge at the point of sampling. While some processes lead to an accumulation of constituents in the runoff which culminates in a state of equilibrium, others act as sources or sinks while the discharge progresses from one equilibrium state to another. Based on previous studies by Kelbe *et al* (1992), it is difficult to attribute the observed character of the water quality in these catchments to any specific effect. However, these previous studies observed several differences between catchments in certain water quality parameters which may provide a guide in these investigations. Since the samples from both catchments were not always taken at exactly the same time or stage of discharge it was difficult to attribute a significance level to the comparison. Nevertheless, there was a definite relationship between discharge and certain water quality variables which requires further investigation.

Kelbe *et al* (1992) found that the turbidity and total phosphate were related in someway to suspended solids which also tended to increase with increasing discharge. However, the other water quality measurements did not show such a good relationship with either suspended solids or discharge. Nevertheless, all water quality measurements were considered to vary with discharge and were therefore classified according to the hydrographic stage of the discharge during the sample collection. In this previous study, four flow regimes were subjectively defined by - (1) the rising limb, (2) the peak flow, (3) the recession limb, and (4) the base flow. The water quality measurements from both catchments for each flow state were then compared during the sample period. The results suggest that there may be some seasonality in the pH, conductivity, and suspended solids which could be related to the seasonal trends in discharge (rainfall) volume. The increased runoff during summer is considered to promote a dilution of dissolved solids and an enhanced detachment and transport of soil particles.

The seasonality, however, was not always clear because of the number of samples, but it could be inferred from relationships with either the dissolved or suspended loads. The comparison between the catchments in the water quality measurements for the various storm hydrograph stages showed large differences for most variables, although the magnitudes varied with parameter.

The water quality parameters which were found to show the greatest response to land management practises (Kelbe *et al*, 1992) and which would be investigated in this project were the physical characteristics and the nutrient composition of the discharge in the form of nitrates and phosphates. Those chemical and physical constituents which show little variation within and between these research catchments in Zululand were not considered in this study for evaluating the relationship to hydrological processes. However, in other catchments these constituents may be extremely important.

The previous studies suggest that this investigation into the water quality response to hydrological processes would require information at a high temporal resolution which would have to be sufficiently short to detect changes within the hydrograph. A typical hydrograph with its characteristic components for one of the catchments used in this study is shown in Figure 4.1. The average time to peak for these storms is typically 1-2 hours. The quick-flow, often referred to as the overland-flow or surface-flow, generally takes several hours to reach its peak and may last for several hours. It may take up to 10 hours for the base-flow to reach its peak rates. This implies that the temporal resolution for water quality studies in these catchments has to capture these events and would need to be at least hourly or preferably shorter.

Commercial instruments for measuring water quality in the laboratory are very advanced and they have been designed for a full range of constituents and concentrations. Very few instruments, however, had been designed specifically for continuous field monitoring system where low power consumption is essential. This is particularly a problem for techniques which use an optical system requiring a light source. The system also requires minimal maintenance and calibration in the field.

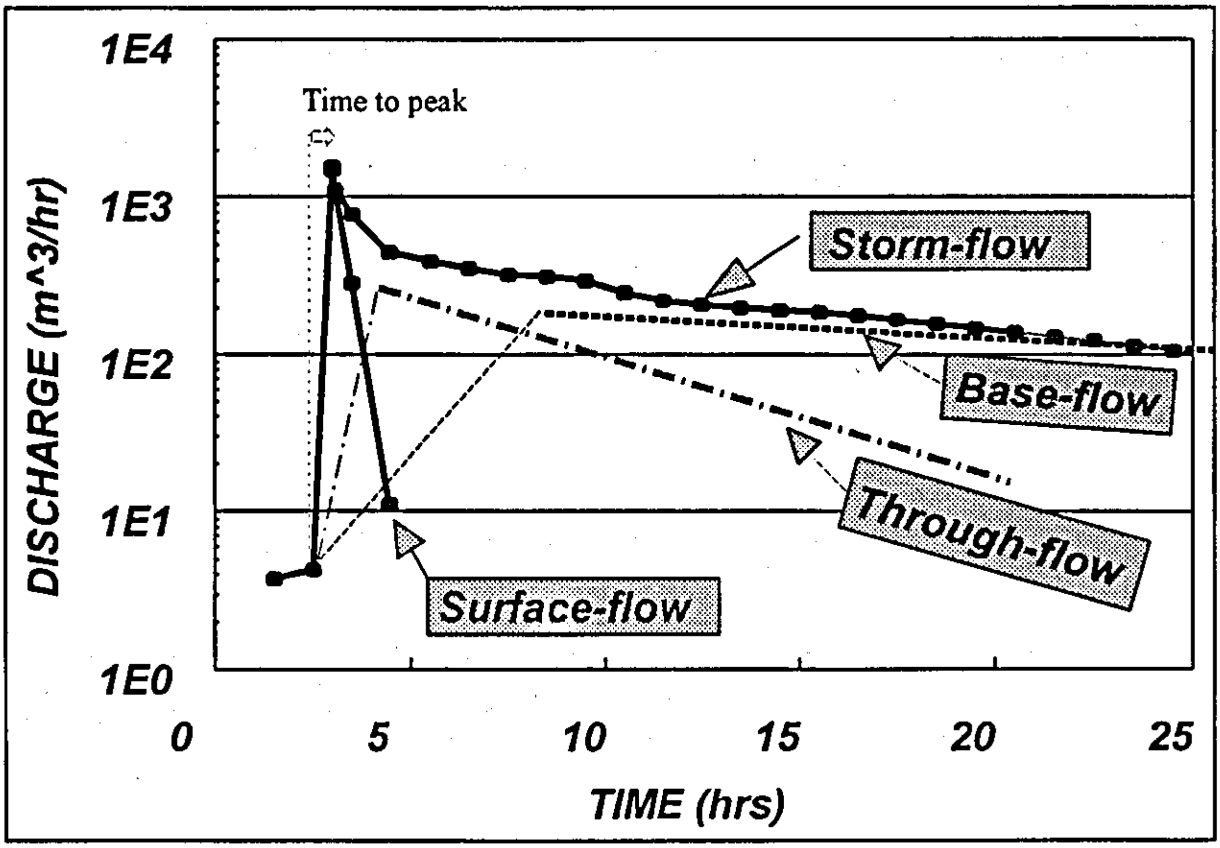


Figure 4.1 Typical hydrograph components for a short duration high intensity storm event..

There were no suitable systems available on the market, when the project started in 1991, for measuring flow and water quality conditions in the field where there was no electrical mains supply. However, programmable dataloggers had been installed in the catchments for measuring flow conditions (Kelbe *et al*, 1992) and these were adapted to measure selected water quality factors with the addition of suitable sensors. The system was also adapted for initiating grab type flow-related water samples for manual collection and further analyses in the laboratory. The grab samples were also used for quality checks on the continuous monitoring system as described later.

4.1 SYSTEM COMPONENTS

The system which was developed in this project is composed of a Campbell CR10 programmable datalogger with sensors for stage, temperature,

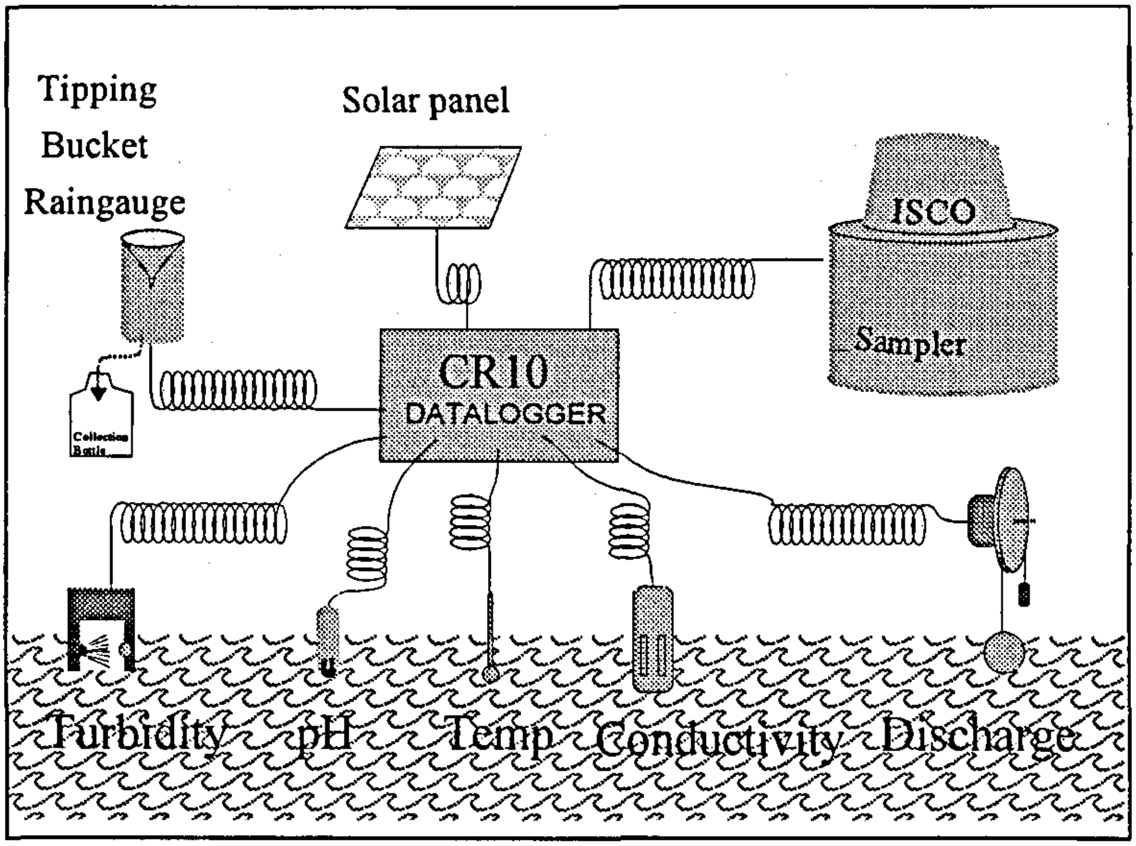


Figure 4.2 Schematic diagram of the water quantity and quality monitoring system

conductivity, pH, turbidity and rainfall (Figure 4.2). Details of the programme and layout are given in Kelbe *et al* (1992). The measured conditions at each site include the following:

① The **stage** is measured using either or both of :-

- a ten-turn potentiometer attached directly to the cable of the autographic stage recorder and configured as a half Wheatstone bridge with 2.5V excitation.

- a Geokon© vibrating wire pressure transducer (piezometer), vented directly to the atmosphere, producing a resonance frequency detectable by the datalogger. This sensor measures water temperature (at depth) for density compensation in estimating the water depth.

② The **temperature** is measured using either a standard thermistor or platinum resistance thermometer.

③ The **conductivity** is measured using a platinum electrode sensor taken from a Hach© laboratory conductivity metre.

④ The **pH** is measured using an AmpHel™ which comprises a twin compartment double junction reference electrode with a built in amplifier.

⑤ The **turbidity** is measured using a Partech© Active Head Suspended Solids infra-red Sensor which measures the transmission attenuation (loss).

⑥ **Rainfall** *is measured using a ECO© tipping bucket (0.2mm/tip) raingauge* on the roof of the weir instrument housing. The rainfall passing through the raingauge is fed directly into a large glass container to provide a check on the tipping bucket data and to provide rainfall samples for chemical and physical analyses in the laboratory.

⑦ The stage measurements are converted to **flow** using two rating curves for (1) the 90° sharp crested V-notch (0 to 0.4m stage) and (2) the compound sharp crested rectangular notch above the 0,4 m stage level. These rating curves were programmed into the datalogger as two 5-term linear regression equations. The flow rate (m^3/s) was integrated over time and programmed to activate an I/O port which switched on an ISCO© 24 bottle water sampler for collection, laboratory analyses and system calibration.

⑧ The system is powered by one or two 12 Volt lead-acid batteries charged by a small 5W solar panel.

4.2 LABORATORY CALIBRATION

A scaled down version of the system was constructed in the laboratory and used for testing and calibration with recognized standards.

① The calibration curves for the Hanna conductivity probe connected to the CR10 are given in Figure 4.3. The calibration curves are not quite straight but the linear calibration equation used (mS/m = 43*mV) is considered accurate to within 10%. This is considered acceptable for this study when compared to other sources of errors in the measurement system discussed below. Temperature compensation was determined through a series of calibrations under a range of temperatures on an agitated hot-plate.

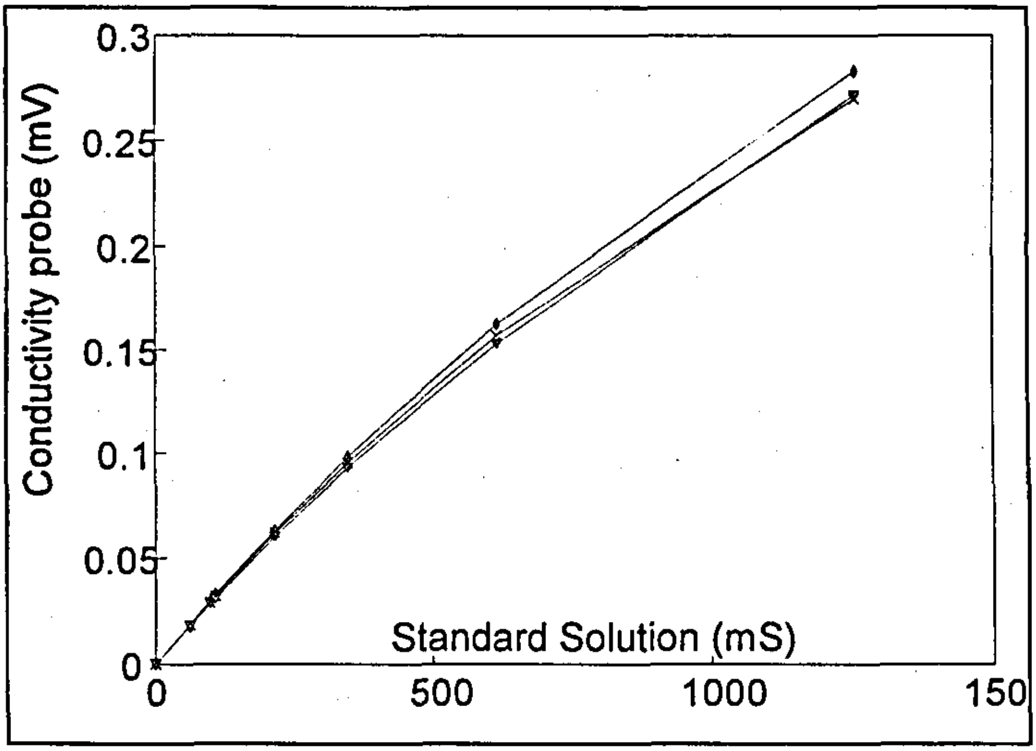


Figure 4.3 Laboratory calibration of the Hanna platinum resistance conductivity probes on the CR10 datalogger.

② The temperature was calibrated using standard thermometers in an ice/water bath and a boiling water bath and checked on an *ad hoc* basis in the field with a range of water temperatures.

③ The pH probe used in this study was a commercial AmpHel™ (Amplifier electrode for process application) which incorporates a built in amplifier. The amplifier provides an extremely low output impedance (typically 10 kΩ) which provides a high immunity to noise and humidity. This allows the use of long unshielded cables. The AmpHel™ was calibrated in the laboratory using standard buffers. Figure 4.4 shows a typical calibration curve which conformed very closely to the manufacturers specifications. Temperature compensation was not necessary within the range of pH experienced in the field.

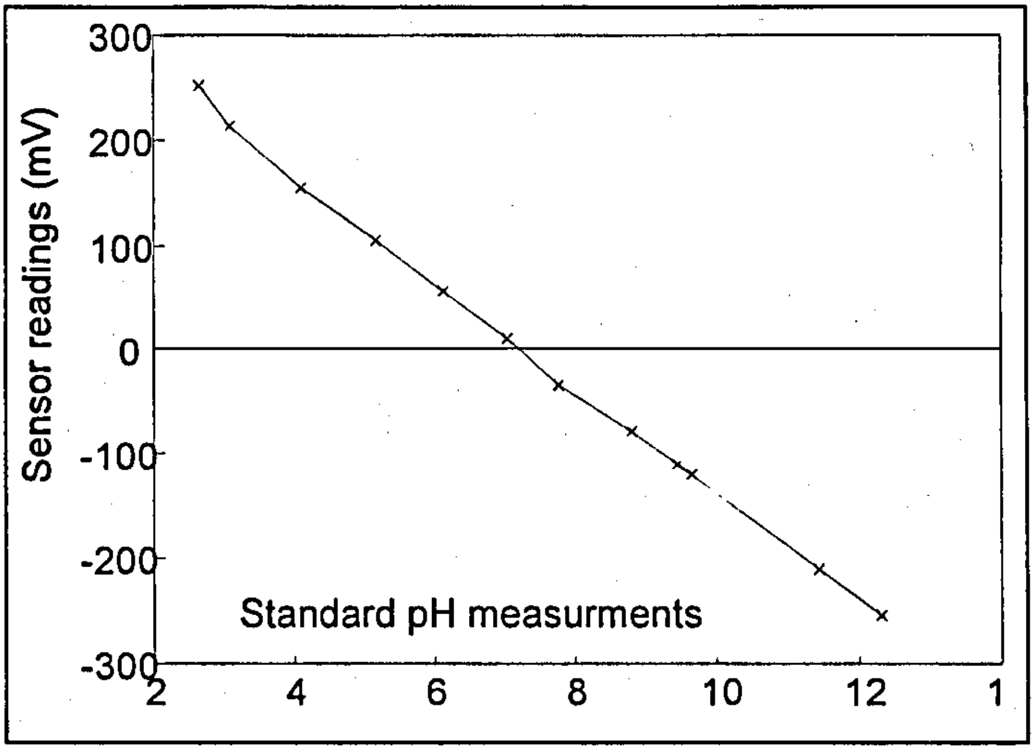


Figure 4.4 Calibration curve for pH sensors attached to CR10.

The pH measurements are extremely susceptible to large variability between individual probe precision and their accuracy in very dilute solutions (Stapanian and Metcalf, 1990). Hoenicke *et al* (1991) have also shown that errors in measurement for very dilute solutions can be more than one pH unit for some instruments in the laboratory. Consequently, these sensors were used principally to assess the change in pH rather than the absolute value.

④ The Partech infra-red turbidity sensors used in this study consist of a solid state light emitting diode source and detector which measure the attenuation of infra-red radiation over a distance of 1 cm. The sensors were calibrated in the laboratory using **nephelometry standards** (Figure 4.5). The "s" shape calibration curve conforms to the manufacturers specifications but is assumed to be linear for this study. Each sensor has a different curve (Figure 4.5) and calibration equation.

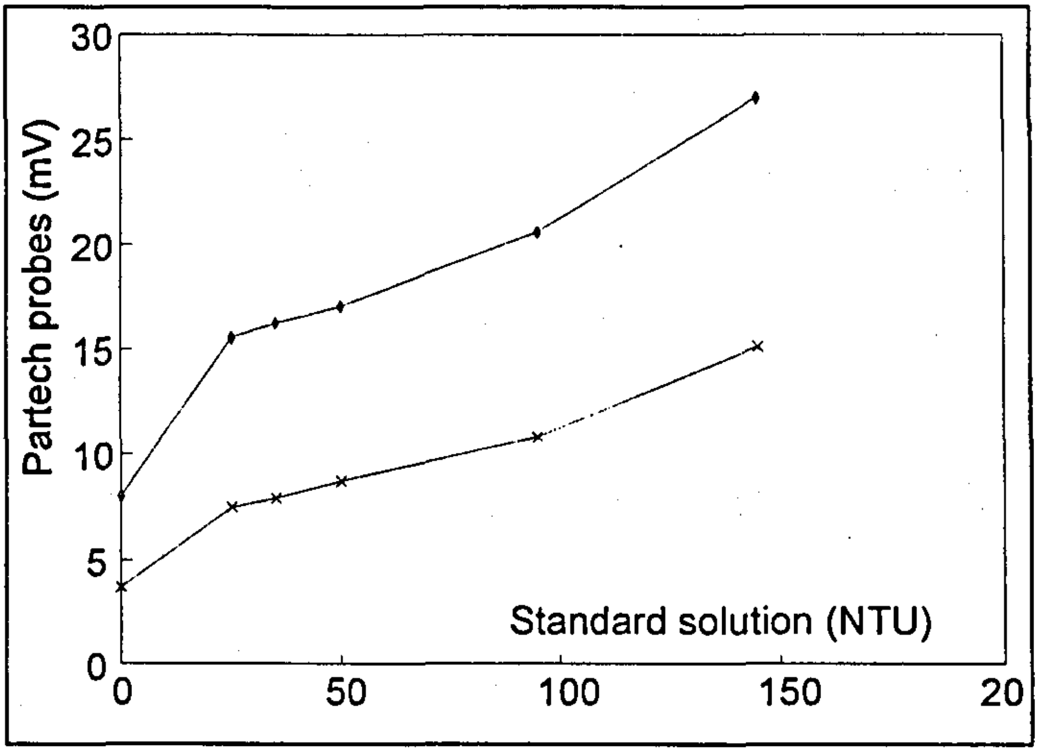


Figure 4.5 Calibration curves for the Partech infra-red turbidity sensors.

Since the direct transmission and scattering characteristics of turbid water depends on the particle size and dissolved substances, it is not certain that the Partech-CR10 system will give comparable results to the laboratory Turbidimeter instrument which also compensates for discolouration by utilizing forward scattered light and direct transmission through the sample for stability and comparison. Details of the comparison between field measurements and the laboratory samples are presented in subsequent sections.

4.3 FIELD CALIBRATIONS

The CR10-system sensors were calibrated in the field on an *ad hoc* basis throughout the study period. The field readings were also checked against samples taken at regular intervals throughout the study period. Unfortunately, the comparisons between the CR10 measurements and the laboratory measurements of the samples were not as good as expected. However, the many sources of errors in the sampling procedure and inconsistencies in the measurements systems are considered the main cause of the poor correlations between the field and laboratory measurements. These are outlined here as part of the general description of the field measurement system.

The continuous field observations of temperature, turbidity, pH and conductivity are measured in a remote box attached to the weir housing which is fed from a perforated pipe under the weir outlet (Figure 4.6). The grab samples are taken from inside the impoundment just upstream of the V-notch. These different sampling locations, their different potential contamination sources in the field, as well as the different optical measurement systems in the instruments and the time between sampling in the field and measurement in the laboratory are all possible causes of discrepancy between field and laboratory observations. Some discrepancies between field and laboratory turbidity observations were identified as algal growth on the inlet pipe to the grab sampler which were disturbed by the purging action of the ISCO sampler during the process of sampling and sediment deposition in the instrument housing.

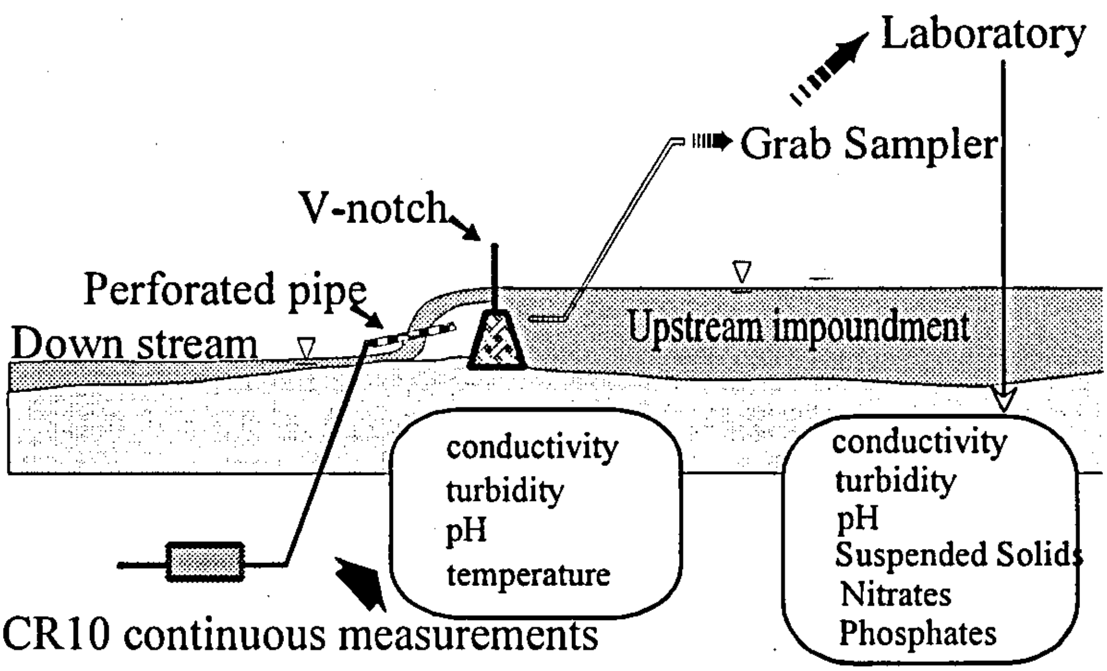


Figure 4.6 Schematic diagram of field observation system.

The ISCO takes samples from a partially stagnant water body while the CR10 monitors a constantly flowing water sample which passes through a small housing that may become contaminated. Algal growth and sediment deposition on the inlet of the ISCO sampler pipe can contrast with the bubbles, sediment/debris, blocked flow and other sources of error in the CR10 system which will lead to the creation of differences between the field and laboratory observations. Consequently, there are expected to be some differences in the comparisons (calibrations) of the two different sampling methods.

4.3.1 CONDUCTIVITY AND TEMPERATURE

Field calibrations were conducted in the field on an *ad hoc* basis throughout the year using laboratory standards. The relationships derived by inserting the relevant probes into standard solutions in the field are given in Table 4.1. A direct comparison between instantaneous field measurements and laboratory analyses of grab samples gave acceptable results for conductivity.

Table 4.1 Field calibration equations

TDS (mg/l)	= CR10 conductivity (mV)* 0.1515
pH	= CR10 pH (mV)/60 + 7.0
Temp ©	= CR10 temperature (mV) * 0.07357
Turbidity (NTU)	= CR10 turb(mV)*0.607+25.91

4.3.2 pH

The laboratory evaluation of the pH measurement system gave good calibrations using standard buffer solutions. However, the field observations showed very large variability and poor agreement with the grab samples analysed in the laboratory. Hoenicke *et al* (1991) found, in field trials of three different pH sensors which performed similarly in the laboratory, that they could deviate by as much as 2.5 - 3.0 pH units in the field during a 10 day period. The errors were found to increase with decreasing ionic strength of the water. Because the pH measurements in this study showed similar variability, the measurements have been presented and used **only for comparative purposes** over short periods during specific storm events. However, they may be in serious error over longer periods due to the multitude of possible errors described by Hoenicke *et al* (1991).

4.3.3 TURBIDITY

Considerable effort has gone into calibrating the turbidity sensors and establishing a relationship between suspended solids and turbidity but it proved difficult to achieve because of the numerous sources of error in both the field and laboratory observations. Grippel (1989) has shown that the Turbidity of standing samples can decrease by 2-3 NTU over 2-3 days due to flocculation and that any linear relationship is site specific. He presented correlations of between 0.475 to 0.943 for 7 Australian catchments. During this project an attempt was made to relate suspended solids measurements to turbidity and to establish a relationship between the laboratory and field measurements.

(a) Turbidity comparisons between instruments (field vs lab).

Peaks in turbidity are highly correlated to flood peaks and consequently there were few samples with high turbidity obtained during this study period because of the sampling interval method. However, two examples from storm events provided sufficient data to show the difficulty in calibrating field instruments because of strong hysteresis effects (Figure 4.7 and Figure 4.8). In the first example (Figure 4.7) the rising turbidity shows a reasonable relationship (with a slope of 0.64) between the field (CR10) and laboratory (grab samples) which is significantly different to the relationship for the falling turbidity (where the slope is 1.86).

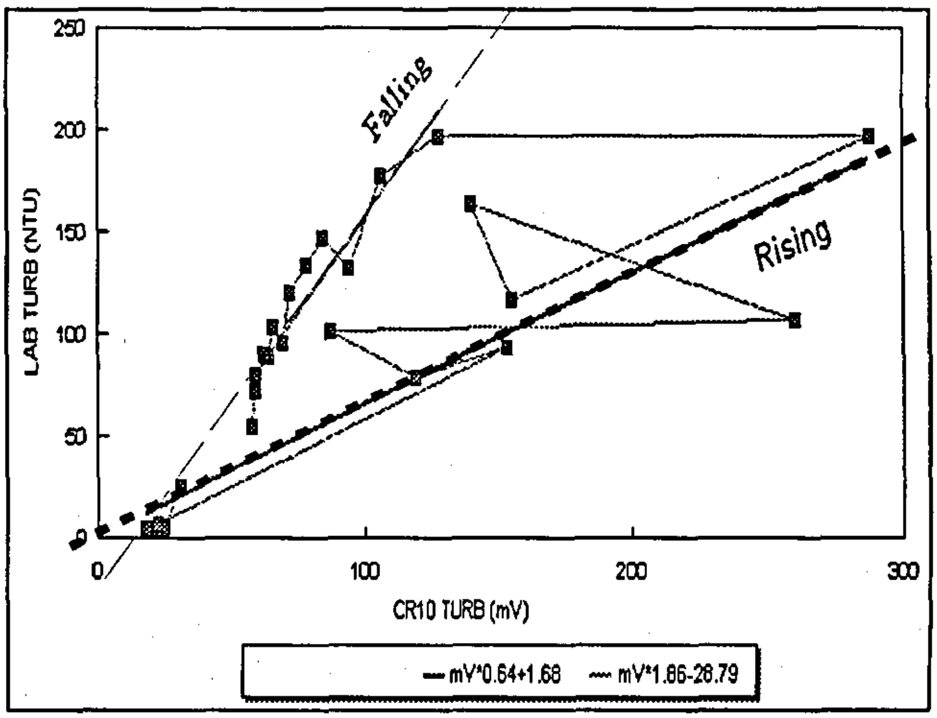


Figure 4.7 Hysteresis in turbidity field calibrations.

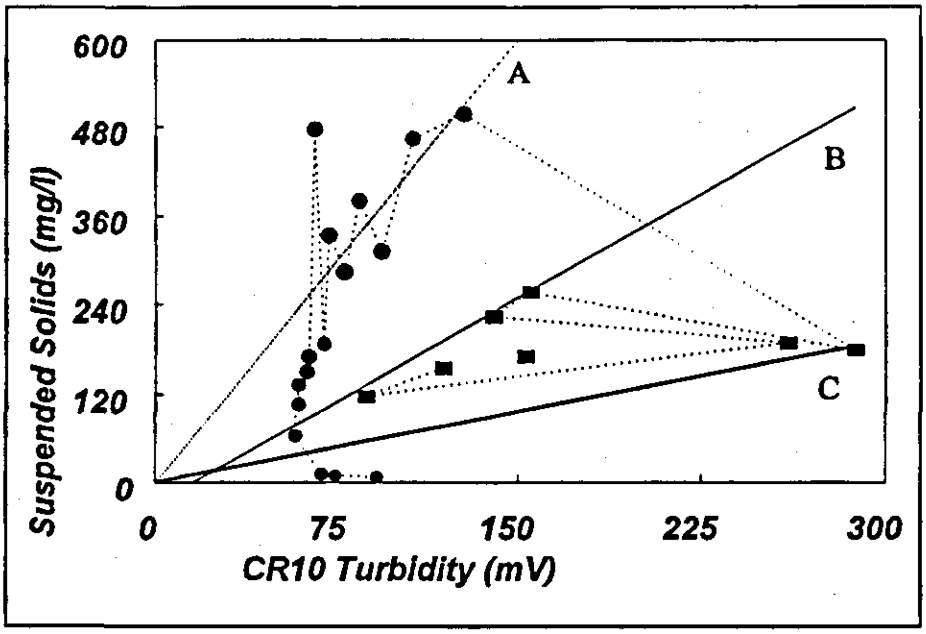


Figure 4.8 Hysteresis in turbidity field calibrations for storm on DOY 100, 1995

These same two lines are plotted in the second example (Figure 4.8) as B & C. They span the range of values for the rising limb while the falling limb in this example (line A) has a slope of almost 4.0 (Figure 4.8). Clearly the hysteresis effect varies between storm events and there is no simple relationship

A scatter plot of over 600 sample points for 1993/95 is shown in Figure 4.9 together with the three lines shown above in Figure 4.7 & 4.8. The two examples above are discernable in the plotted points corresponding to the indicated lines. However, there is a group of data points which fall below the line labelled "C". Nearly all these points above 200 mV in Figure 4.9 are from two main storms which have very different relationship to the examples presented.

The marked difference in the composition of the sediment during a storm is shown in the series of sediment samples taken in sequence for a storm on DOY 100 and shown in Figure 4.10. The

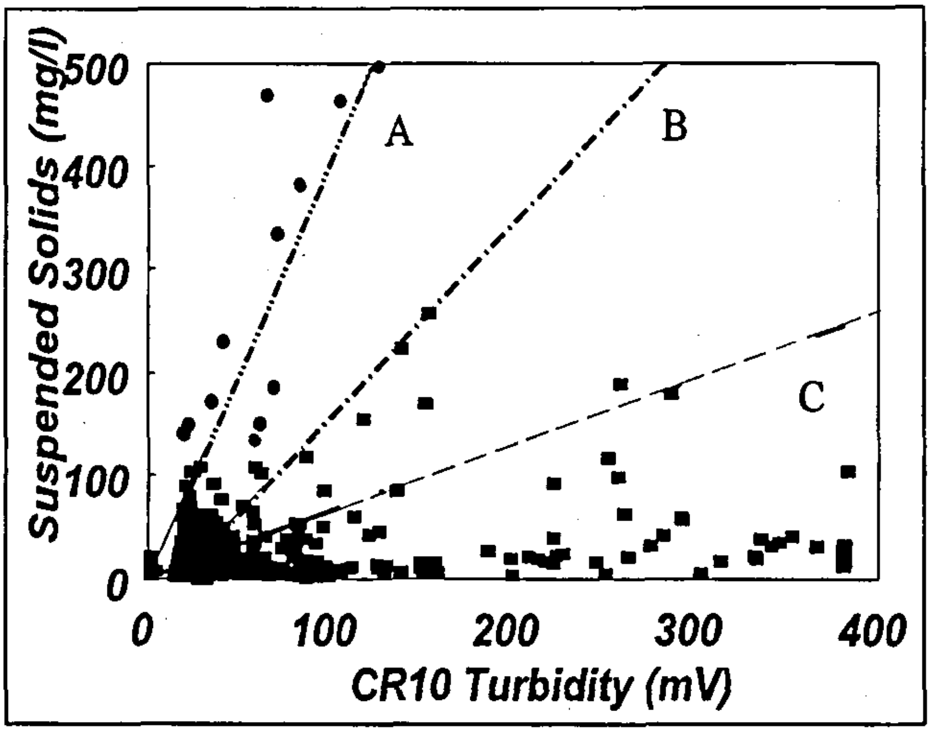


Figure 4.9 Scatterplot of field turbidity against sample suspended solids for all samples 1993-95.

sediment prior to the storm is a very light orange in colour. This changes very rapidly to a dark brown which then becomes progressively lighter as the storm recedes. This is a common feature of the sediment from storm samples for W1H016 and

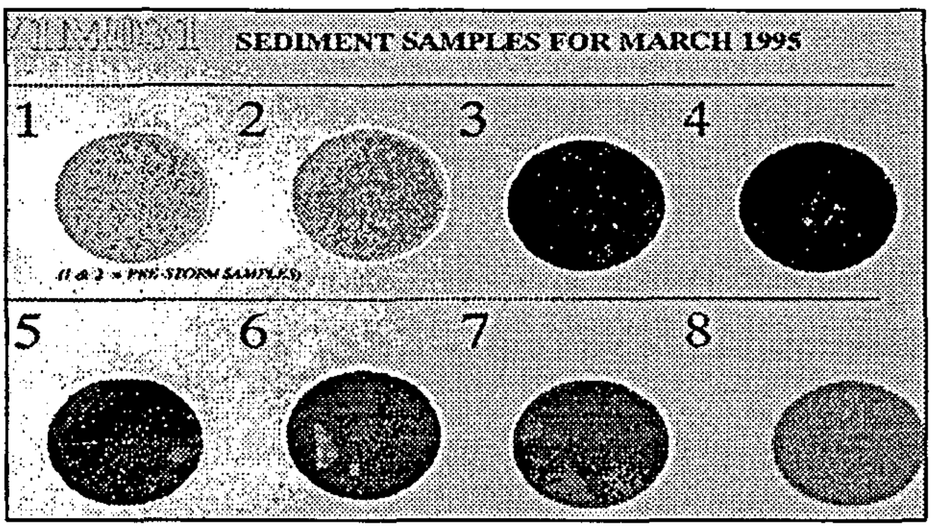


Figure 4.10 Photograph of the sediment residue from flow related water samples during a storm on DOY . The peak discharge occurred between samples 2 and 3 where there is a very significant change in composition (colour) of the sediment.

indicates a change in the composition of the sediment. The particle size distribution for several storms was measured and shows only slight variations which are discussed in the next sections.

In general, there was a large difference between field and laboratory measurements of turbidity. Besides the hysteresis effect, the significant difference between field and laboratory can be attributed to a combination of several factors which include the following-

❶ *INSTRUMENTATION* - The laboratory instrument measures transmitted and scattered light in the visible spectrum while the field instrument measures infra-red attenuation in transmitted light with no backscattering compensation. The visible radiation is more responsive to small particle size variations while scattered instruments are less sensitive to particle size. This effect of particle size is examined in a latter section.

❷ *SAMPLE AND MEASUREMENT LOCATION* - The laboratory sampling point is located in the stagnant weir impoundment where deposition and algal growth can cause measurement errors. The ISCO grab sampler expels all the "inline" water in the pipes before collecting a sample through suction. This can cause agitation at the sampling point that can resulted in ingestion of algal accumulations and any sediment that was deposited on the inlet pipe. This problem has been reduced through constant cleaning of the inlet section on a weekly basis.

❸ *BUBBLES AND DEBRIS* - The instrument box in the field has sufficient volume-to-flow ratio to reduce the effect of velocity and bubble formations but there is the possibility that debris and sediment could foul the turbidity sensor for indeterminate periods while passing though the system. However, the perforations on the inlet pipe (<3mm slits) are sufficient small to allow limited flow but restrict the large debris. The instrument housing was cleaned on a weekly basis once these problem became apparent.

❹ *STANDING TIME* - The programme required the samples to be collected once a week unless large storms had occurred when the samples were collected mid week. Consequently, some samples were in the field for as much as 7 days before analysis in the laboratory. However, the effect of the standing time on samples was checked by comparing the measurements of the set of two samples with a difference in standing time of approximately 7 days (last sample of first set - first sample of second set) under similar flow conditions. The results showed insignificant differences.

These potential sources of error are site specific and irregular. Consequently the relationship between the laboratory and field observations is tenuous and any direct association to suspended solids and nephelometric units (NTU) must be accepted with caution. Nevertheless, all CR10 data for both catchments have been converted to NTU using the relationships shown in Table 4.2.

Table 4.2 Calibration equations

W1H016	SS(mg/l) = mV*9.7-160.5
	NTU = mV*4.1- 58.2
W1H031	SS(mg/l) = mV*10.5-212.7

The hysteresis in the calibrations of field turbidity shown in Figure 4.7 suggests that there is a different particle composition (size) or change in the dissolved (colour) constituents which could indicate changing hydrological processes. Consequently, the two turbidity curves shown in Figure 4.7 were used to partition the data for investigating differences in other water quality factors and this is discussed in section 4.3.2(b) below.

(b) **Turbidity and particle size.**

Turbidity relates to the scattering or absorption (attenuation) of radiation by particles in suspension. Both absorption and scattering are dependent on the particle size and the incident radiation. Particle size analysis was conducted on a set of samples from both weirs covering a short duration high intensity storm. These samples were separated into sets representing the pre-storm, rising limb and falling limb conditions. The distribution of particle sizes for both weirs is shown in Figure 4.11 and Figure 4.12. For both these sample sets the particle size generally varies from < 1 µm to just over 20 µm. This gives a particle size-to-

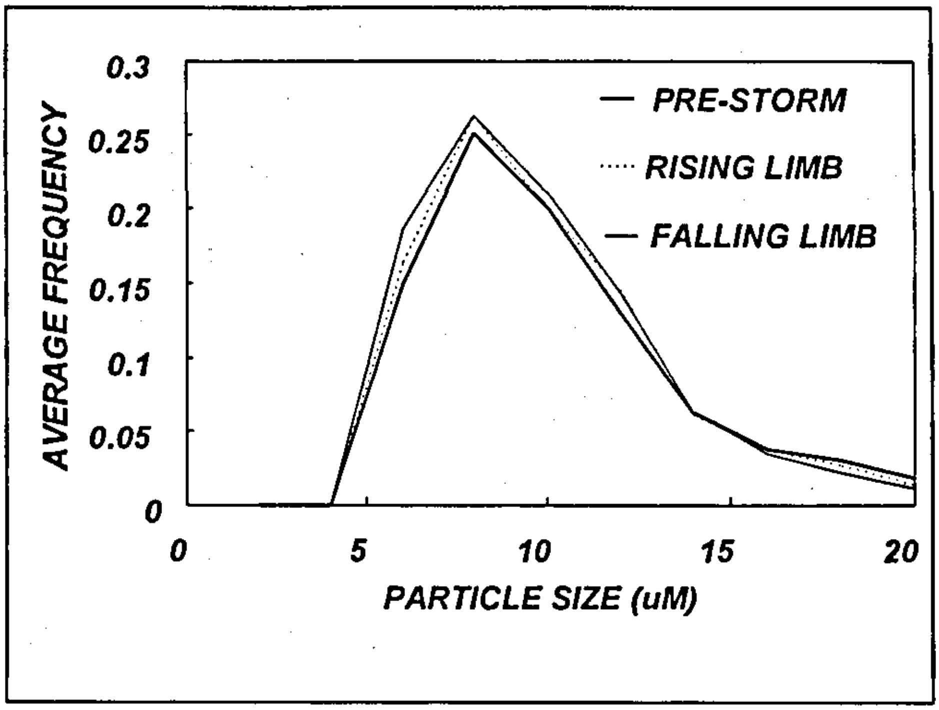


Figure 4.11 Frequency distribution for W1H031

wavelength ratio greater than one (>1) for the laboratory instrumentation and a ratio of generally less than one (<1) for the field sensor.

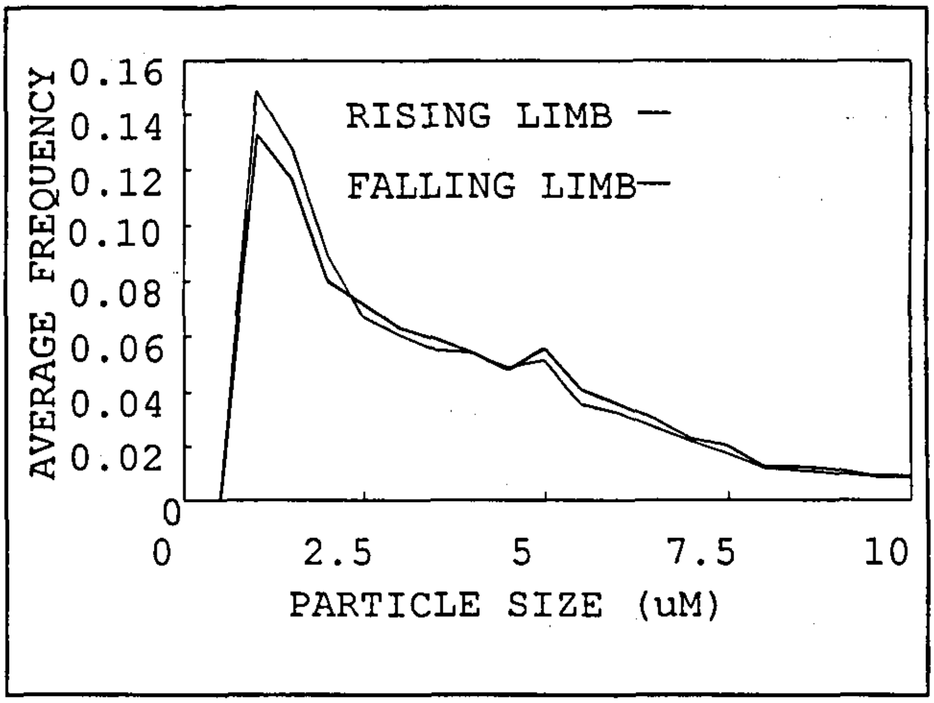


Figure 4.12 Frequency distribution for W1H016

These ratios may not be suitable for the application of radar theory to back-scattering concepts but it was investigated in an attempt to explain the difference between the laboratory and field instruments. In radar theory, the scattering of radiation is dependent on the sixth power of the particle size. This relationship was applied to estimate the scattering intensity for both laboratory and field turbidity measurements. One set of samples examined from W1H016 showed a linear relationships between the sixth power of particle size and turbidity with a correlation (r^2) of 0.47 which is not considered acceptable for application in this report but will be examined further.

Samples from several other storm events were kept after analysis and analysed for particle size at ALUSAF (Bayside). Examples are shown in Figure 4.11 and 4.12. Both graphs show almost no difference between the frequency distributions for the rising and falling limbs which is surprising considering the difference in appearance shown in Figure 4.10. However, there is generally a difference between storm events. The frequency distribution for a pre-storm, peak and receding storm samples is shown in Figure 4.12. It is not clear why the storms are different but all samples within the storm are almost identical at both weirs. This need to be examined further.

The hysteresis observed in the turbidity calibrations shown in Figure 4.8 and discussed in the previous sections was used to partition the samples into pre- and post- peak turbidity groups. This was done in order to determine differences in other water quality characteristics which could be used to explain the hysteresis in turbidity. The statistical results of two-sample analyses for all water quality factors for this event (Figure 4.8) are shown in Table 4.3. All differences are significant at better than the 95% confidence limits. The results show that there was a substantial increase in suspended solids (SS) when the turbidities were decreasing after the peak

Table 4.3 Flow separation analysis of water quality factors for W1H016 and W1H031. Ratio of ($^{pre}/_{post}$) turbidity peak values.

Factor	Diff in means	Sig(%)
pH	0.48	0.04
Cond (mS/m)	0.69	0.03
SS (mg/l)	**179.0**	**0.06**
NO_3 (mg/l)	0.082	<0.01
PO_4 (mg/l)	0.013	0.02
Particle size	Not available	

values. The laboratory turbidities show the same range of values but the CR10 turbidities indicate higher range of values for the rising turbidities when there were greater suspended solids. This is surprising and require further investigation. The other water quality factors also show significant difference (Table 4.3) but it is not clear how they could influence the hysteresis effect observed in turbidity calibrations.

4.3.4 INORGANIC CONTENT

All the laboratory samples were filtered to determine the suspended solids contents and then ashed at 400°C to measure the inorganic content. There is a strong relationship between the suspended solids and the ashed suspended solids (Figure 4.13) which indicates a very consistent organic content for both catchments. However, there is a significant difference between the two catchments in their ash/SS ratio. The ash content of the suspended solids for W1H016 is generally lower

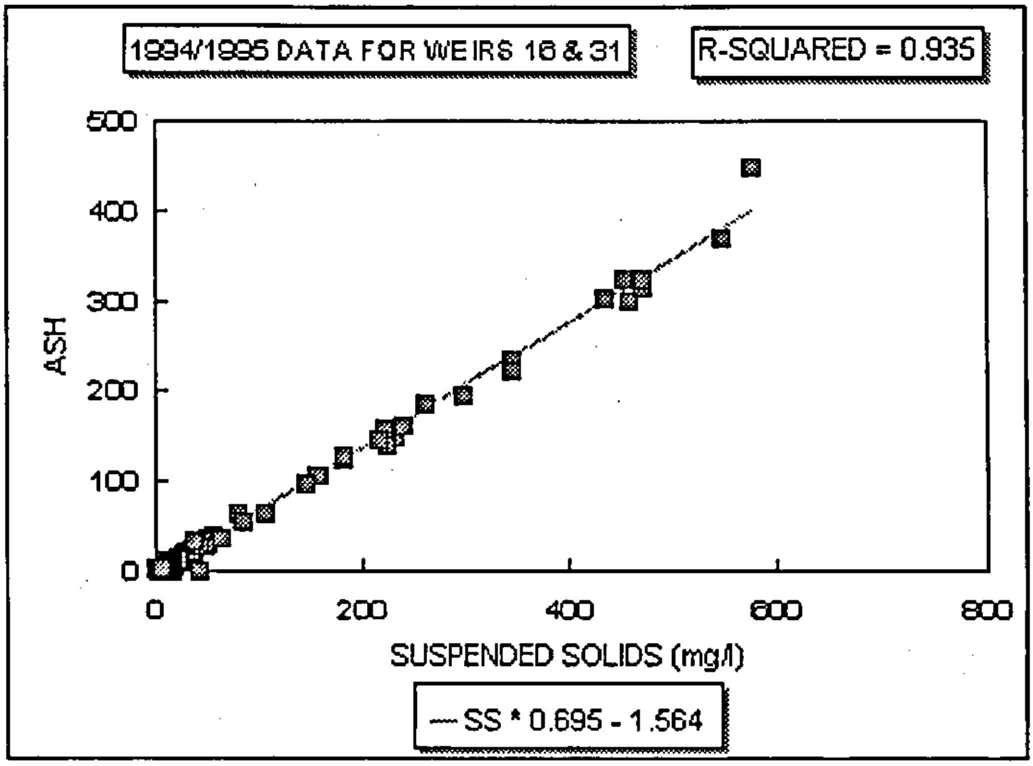


Figure 4.13 Inorganic (ash) content of suspended solids

than it is in W1H031 as shown by the frequency distribution in Figure 4.14.

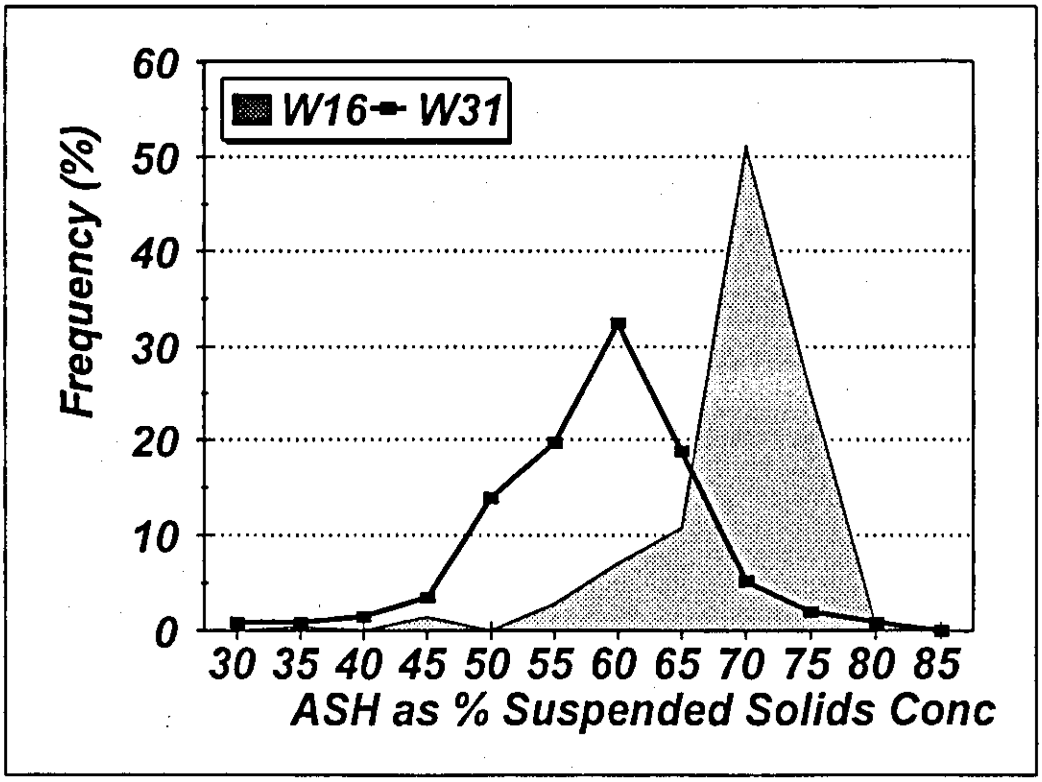


Figure 4.14 Relative frequency of ash content as a fraction (%) of the suspended sediment.

4.3.5 RAINFALL

The rainfall was measured at three sites across the catchments (W1H016, W1H017 and W1H031) using tipping bucket raingauges which passed the rainfall directly into collecting bottles for laboratory analysis. This rainfall was also measured for confirmation of total volume. Prior to 1995 the rainfall from W1H016 had unacceptably high NO_3 and PO_4 concentration which were attributed to contamination (birds). All the raingauges were fitted with anti-bird devices and have been cleaned on a more regular basis which appears to have reduced the problem of sample contamination. Analysis of the rainfall is presented in section 5.1

4.4 WEIR SURVEY

The continuous water quality measurement system provides estimates of the dissolved and suspended solids loads discharged from the catchments, but it gives no indication of the bed-load transported. In an effort to determine the bedload transported by the streams, both W1H016 and W1H031 were surveyed on an *ad hoc* basis from fixed survey pegs installed along the weir perimeter.

These survey estimates were also used to determine the flow residence time in the weir for water quality studies. The storage capacity of W1H016, when cleaned on August 10, 1990, was estimated to be 188 m^3. At a common peak discharge rate of 1000 m^3/hour, the residence time in this weir is about 11 minutes. Consequently, the weir has little effect on water quality measurements during major storm events because the volume would be turned over more than five times in an hour at these peak rates.

4.5 GENERAL VARIABILITY IN FIELD OBSERVATIONS.

The field instruments have been operational for several years and the changes in water quality values during individual storm events have been analysed and presented in the next chapters. The changes during specific storm events are examined for characteristic variation which can be attributed to hydrological processes. In order to evaluate the magnitude of these changes the general variability or background noise is examined here.

The data loggers were programmed to measure and record the standard deviation of measurements, conducted every 10 seconds. The relative frequencies of the standard deviations for one month are shown in Figure 4.15. The mode in these distributions is assumed to represent an upper limit to the background noise in each case. The variability above the mode would be due to the natural variability which is being monitored for analyses. If the mode is an indication of the background noise, then the approximate range of errors in the instrumentation is less than 0.02 mS/cm for conductivity. For the Turbidity, pH and Temperature it is less than 5 NTU, 0.1 pH units and 5°C respectively.

The general variability for conductivity, turbidity, pH and temperature together with the discharge for W1H016 can be gauged from the examples of hourly series for October 1994 shown in Figure 4.16. The early part of the month had extremely low discharge which is characterized by very large variability in all parameters. Following the good rains and substantial increase in discharge during storm events, the daily variability decreased substantially for some factors.

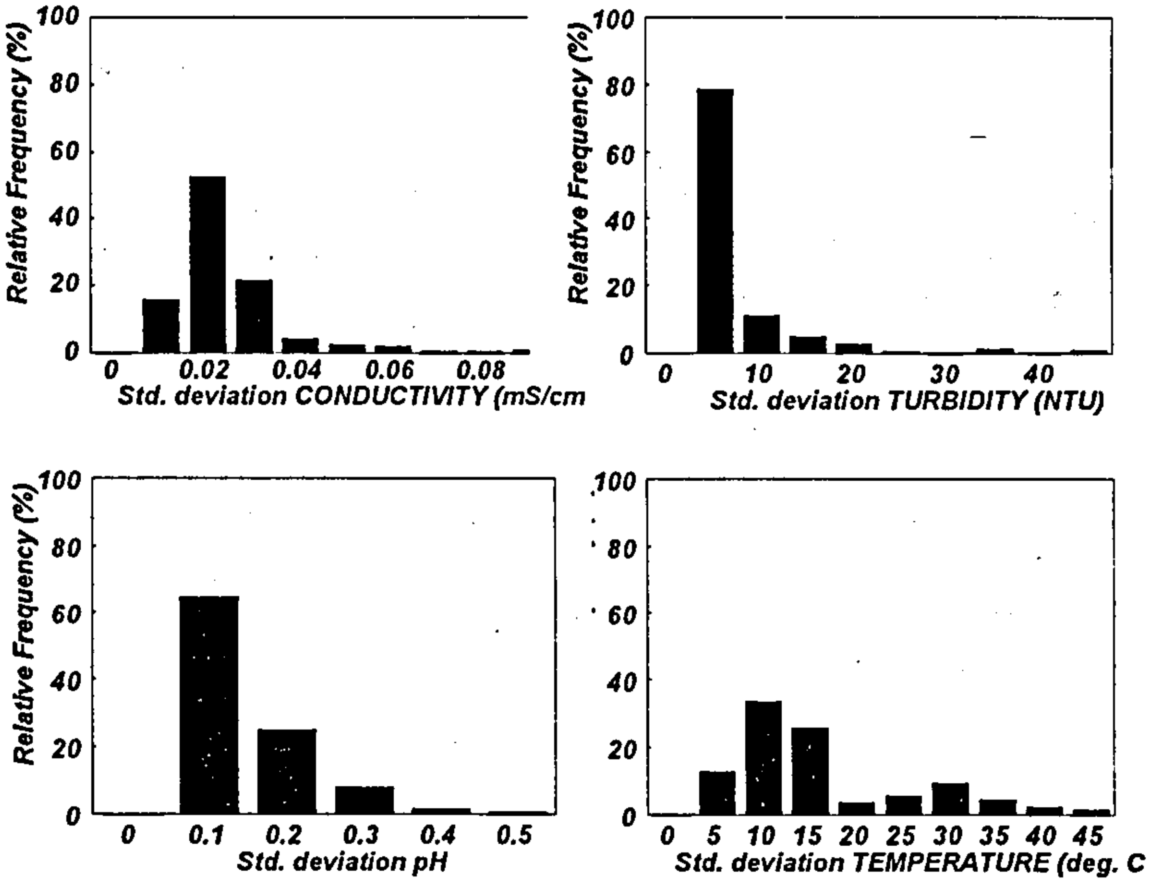
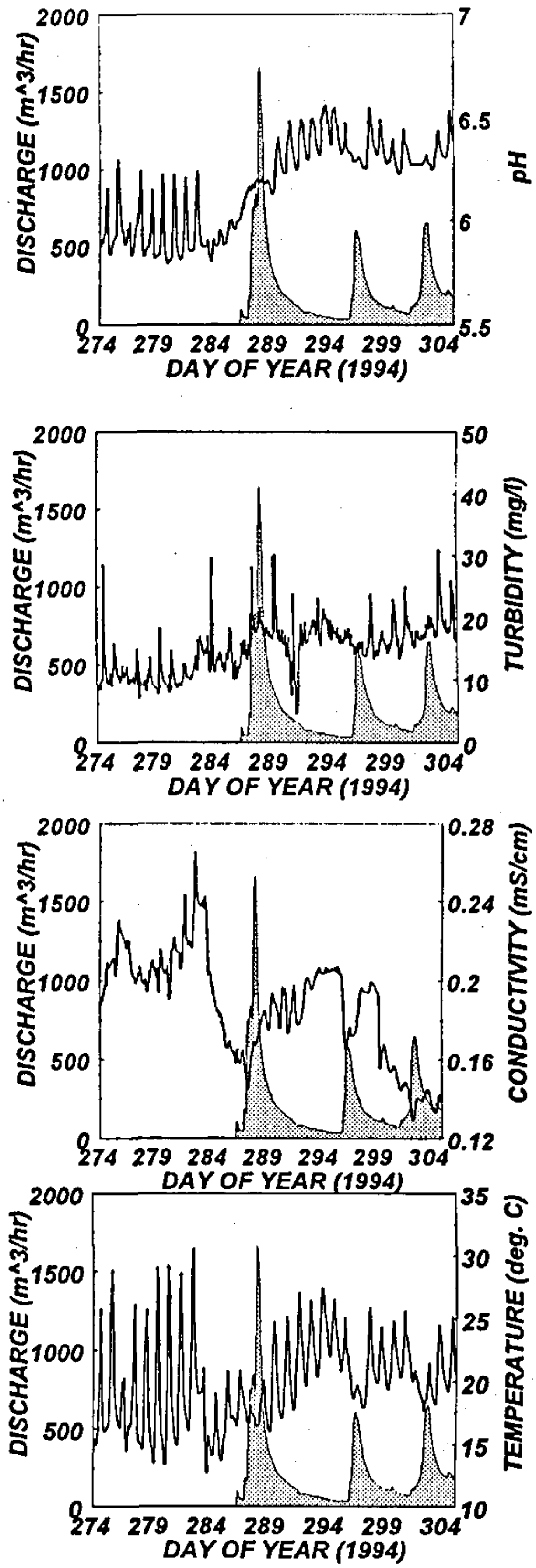


Figure 4.15 Relative frequencies of standard deviations for W1H016.

Figure 4.16 Variability in the conductivity, turbidity, pH and temperature measurements for W1H016 during October, 1994.



5 GENERAL WATER QUALITY

The primary objective of this study was to relate water quality characteristics to hydrological processes in order to understand the effects of land use on the hydrological response in the small Zululand research catchments. Three research catchments have been investigated which cover two similar geomorphic basins of almost equal size and one smaller sized nested catchment. The study concentrated on short duration, high intensity storms because it needed to differentiate between surface and subsurface hydrological processes. However, in order to compare storm events within and between catchments, the general features of the hydrological variables driving the system response must be quantified. In this section, the general features of the rainfall are examined as the primary driving force which result in the hydrological response from the different catchments. The hydrological response is also examined for general trends in order to identify any significant differences which could indicate different hydrological responses to the incident rainfall.

Annual cumulative series are used for comparative purposes. The cumulative rainfall, discharge and water quality factors from the three research catchments (weirs W1H016, W1H017 and W1H031) for the 1993/94 and 1994/95 seasons were derived by interpolating the daily series for each station using information at the other sites when there was missing data. When flow related grab samples are compared, missing sample information was interpolated between the observed sample measurements by using the average of the two known values (last and first values spaning the missing series). This has an impact on some comparison and is discussed in the text. The analysis has been primarily restricted to the 1993/94 and 1994/95 seasons because these seasons started at a time when both the catchments were almost completely drained of all water reserves following major drought periods.

5.1 RAINFALL

The cumulative plot of hourly rainfall measurements at the three weirs located on the eastern extremity (W1H016), at a central location (W1H017) and on the southwestern section (W1H031) are shown in Figure 5.1 and Figure 5.2 for the two different hydrological years. The missing rainfall data for these series was interpolated from nearby autographic rainfall stations (see Figure 3.2). There are only small differences between the cumulative curves for the three locations which indicates that the catchments received sufficiently similar rainfall for comparative purposes. This also indicates similar antecedent rainfall conditions at the different catchments for the individual case studies of selected storm events presented in the next sections.

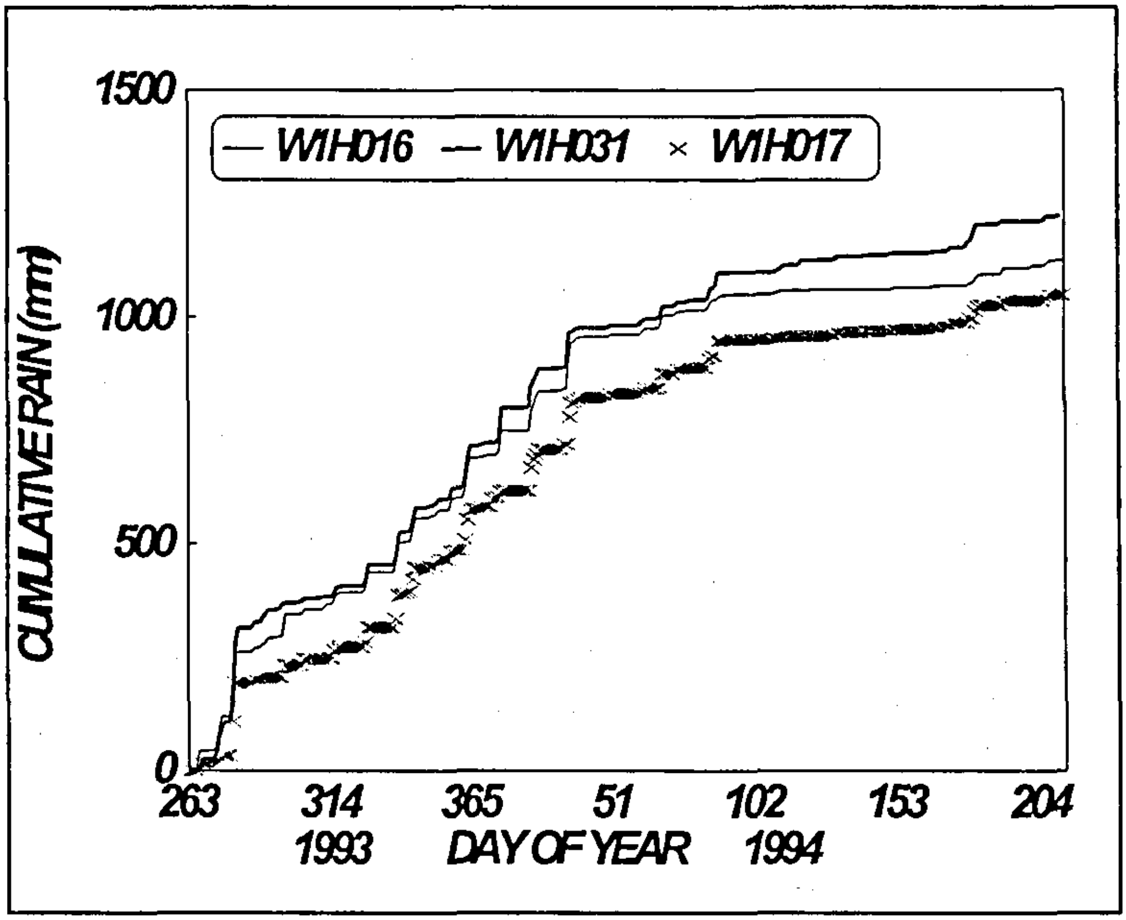


Figure 5.1 Cumulative rainfall for tipping bucket rain gauges at W1H016, W1H017 and W1H031 for the 1993/94 hydrological year.

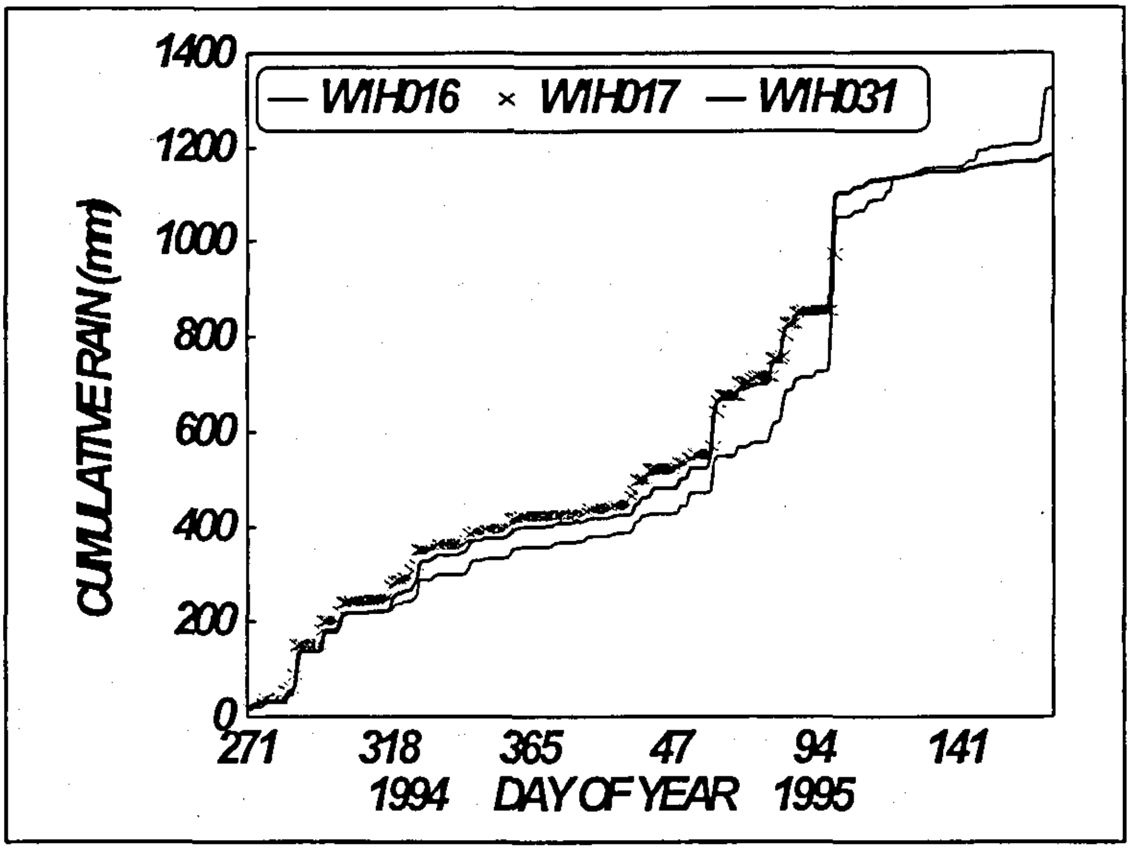


Figure 5.2 Cumulative rainfall for the three rain gauges at W1H016, W1H017 and W1H031 for the 1994/95 hydrological year.

The chemical and physical characteristics of the rainfall indicate the level of nutrient loading for the research catchments and highlight any differences which may be expected in comparisons with other regions. Rainfall observational analyses in previous studies by Kelbe *et al* (1992) are summarized in Table 5.1. The rainfall analyses in this study have been restricted to the constituents given in Table 5.2 and were derived from 15 samples at both W1H016 and W1H031 but there were only 7 samples from W1H017.

Table 5.1 Water quality for rain samples at the University of Zululand (Kelbe *et al* 1992)

Factor	pH	Conductivity (mS/m)	Tot PO_4 (µg/l)	NO_3 (µg/l)	NH_3 (µg/l)	KNF (µg/l)
Maximum	6.6	4.7	14	246	292	600
Mean	6.0	3.0	11	122	151	390
Minimum	5.3	1.7	3	19	26	83

Studies by Stednick (1987) indicate that it is necessary to obtain many more samples than those available in this study for characterizing the conductivity of rainfall but that the pH and phosphates sample size was adequate. However, the studies by Swank and Waide (1988) indicate that the Coefficient of Variation (CV) for weekly precipitation sample concentrations was extremely low (< 0.2) and that weekly sampling was adequate for estimating the bulk precipitation loads for nitrates but not necessarily for phosphates. It is assumed that the 15 samples summarized in Table 5.2 for W1H016 and W1H031 are sufficient to give an indication of general rainfall characteristics but that the W1H017 sample set may be too few.

Table 5.2 Water quality of rain samples during study period

Catchment Factor	pH	Conduct (mS/m)	Turbidity (NTU)	SS (mg/l)	Ash (µg/l)	Nitrate (µg/l)	Phosphate (µg/l)
W16-mean	5.7	5.24	3.37	N/A	0.06	250	80
W17-mean	5.5	6.71	3.03	N/A	0.10	350	40
W31-mean	6.2	4.79	1.90	N/A	0.03	260	20
Average	5.8	5.57	2.77		0.06	287	47

The rainfall during this study period has similar values for the physical factors but higher values for the nutrient loads than those observations in the previous study period. The more recent nitrate concentrations are more than double the previous values but they are still comparable to concentrations observed in other areas of KwaZulu/Natal region (Simpson, 1992). The latest phosphate concentrations are slightly higher than those observations of Simpson (1992) and Kelbe *et al* (1992). This might be due to some dry deposition during the week between sample collection, particularly for W1H016 which may have been affected by dust from the nearby road that is above the elevation of the raingauge and about 100 m away.

The nitrate concentrations are similar to those observed by Wanielista and Yousef (1993) for urban and rural areas as well as near roads, but are slightly higher than those found by Swank and Waide (1988) in other parts of the world.

5.2 DISCHARGE

The two hydrological years examined in this section were chosen because they started from extremely dry conditions when there was no flow through W1H016 and only very little flow through W1H031. The flow from W1H017, a sub-catchment of W1H016, stopped flowing at the same time as W1H016 on two occasions during the drought of 1993. However, W1H017 did continue to flow at all times during the drought in 1994 when W1H016 stopped flowing for 66 days between May and August. The stage in W1H017 was generally between 0.018 and 0.14 m during this period when W1H016 had stopped.

Examination of the rainfall during the drought periods in 1993/94, when flow at W1H016 stopped, is shown in Table 5.3 and indicates that there was some rainfall in each month during 1994 but virtually none during 1993. It is possible that the small regular rainfall events during 1994 were sufficient to support some flow through W1H017 but not for the much larger catchment of W1H016. There has been suggestions by Schulze (pers comm) of ground water leakage from W1H016 which would account for the failure of the discharge from W1H017 to reach the weir at W1H016. However, when there was no rainfall during 1993, the discharge from W1H017 stopped at almost the same hour that it stopped in W1H016.

Table 5.3 Rainfall during period when W1H016 stopped flowing. [bracket = partial period]

Month	1993	1994
May	[9.6]	[0]
June	5.6	19.2
July	0	39.0
August	0	[0]
September	[12.6]	

The cumulative discharge for 1993/94 and 1994/95 are shown for all three catchments in Figure 5.3 and figure 5.4. The cumulative discharge for 1992/93 exhibited the same trends (not shown) but even greater differences between W1H016 and W1H031 than those shown in Figures 5.5.

The discharge from the research catchments for both the 1993/94 and 1994/95 hydrological years are similar during the early part of the hydrological season (Figure 5.5) following the drought period. However, there are periods with significant differences between the two catchments. The difference during 1993/94 is sustained over several months from about DOY 360 (1993) to DOY 40 (1994) while the difference during 1994/95 occurs as several discrete event which appear to be associated with individual storms.

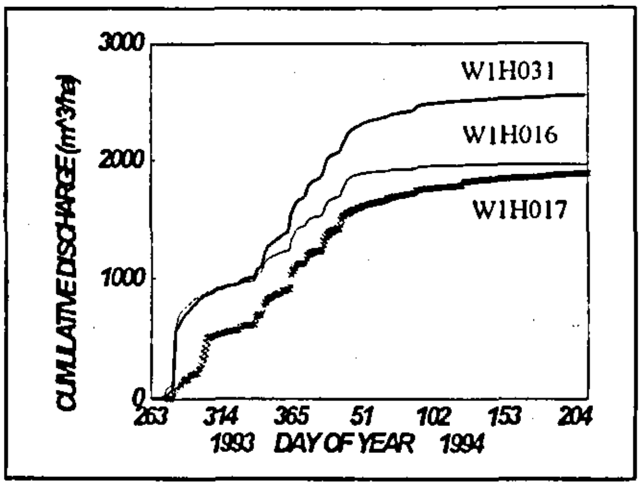


Figure 5.3 Cumulative discharge from the research catchments for 1993/94.

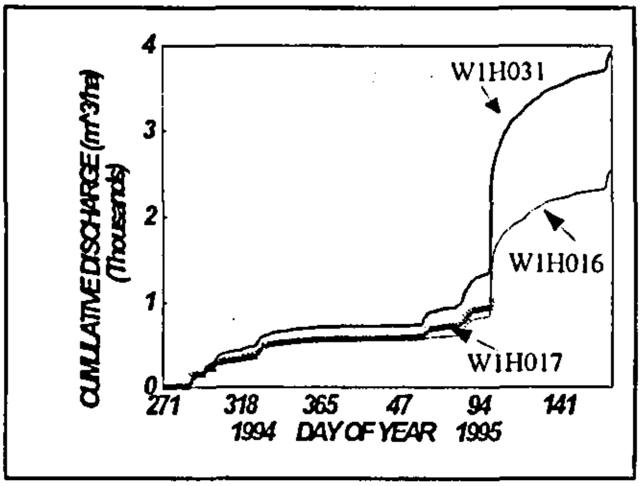


Figure 5.4 Cumulative discharge from the research catchments for 1994/95.

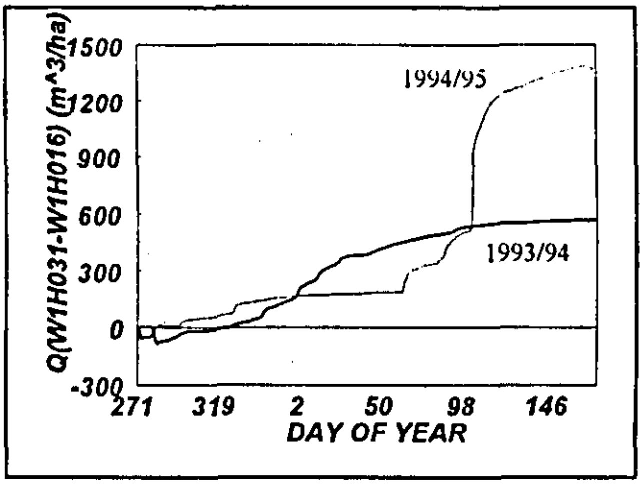


Figure 5.5 Difference between the cumulative discharge series of W1H016 and W1H031.

The ratio of hourly discharge (per hectare) from W1H017 and W1H016 (Q_{17}/Q_{16}) for 1993/94 season is shown in Figure 5.6. The ratio (Q_{17}/Q_{16}) generally reaches a minimum value of between ½ and 1 following a significant rainfall event (indicated by the vertical component of the cumulative rainfall curve). However, W1H017 has a much higher normalized runoff component between the rainfall events and it reaches levels which are more than five times those observed from W1H016 during dry periods that are depicted by flat regions in the cumulative rainfall curve of Figure 5.6.

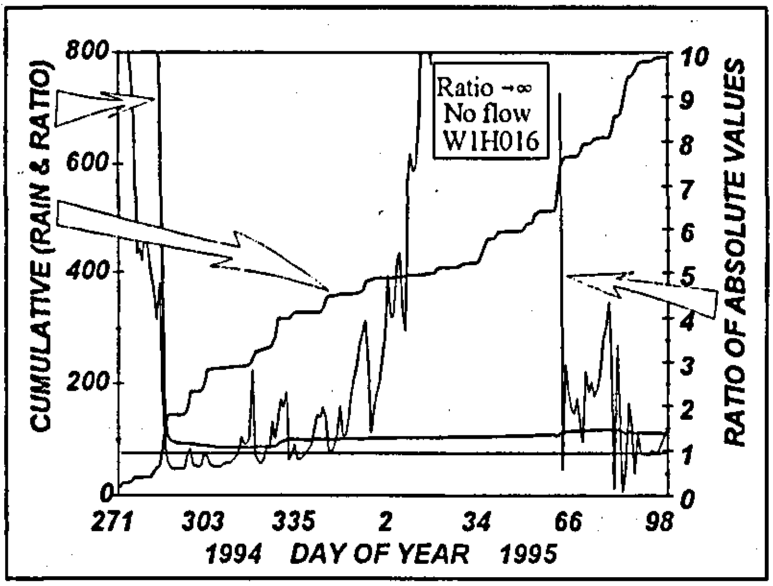


Figure 5.6 Ratio (%) of discharge from W1H017 to discharge from W1H016.

The general trend in the relative discharge rates throughout the 1993/94 and 1994/95 seasons are shown in Figure 5.7. The ratio of cumulative discharge rates increases consistently in each season. Cumulative ratios were used to smooth out the

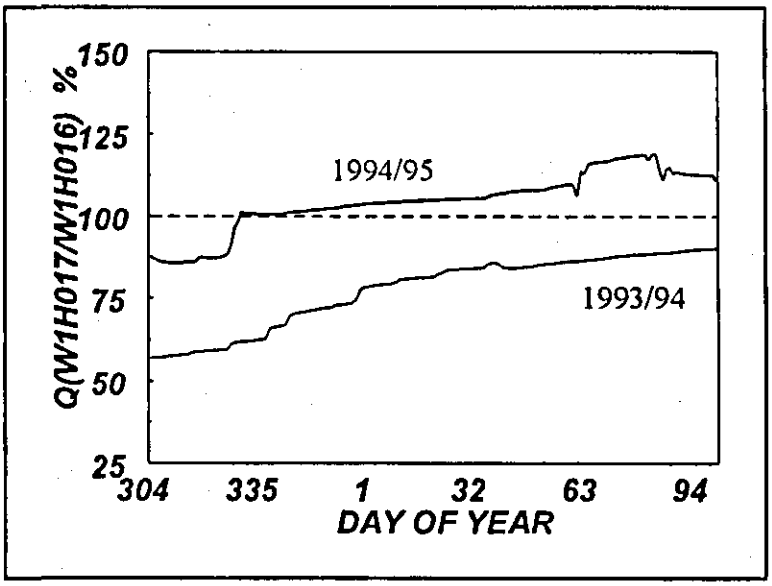


Figure 5.7 Seasonal trends in the ratio of cumulative discharge from W1H017 and W1H016.

very high values for very low flow conditions at one weir (shown in Figure 5.6). The gradient in these two curves indicates that there is consistently more runoff per unit area from W1H017 than there is from W1H016 except during significant rainfall events. The 1993/94 curves suggest that there is relatively more runoff from W1H016 than W1H017 at the start of both seasons but the gradient suggest that this decrease over the season.

5.3 BEDLOAD

The *ad hoc* measurements of bed-load since 1990 are shown as accumulated mass per hectare in Figure 5.8 for both catchments. There is a substantial difference in the cumulative volume of the bed-load between the two catchments. This difference is probably due to land use effects such as the extent and form of bare surfaces. Efforts to simulate the erosion process are presented in Kelbe *et al* (1996b).

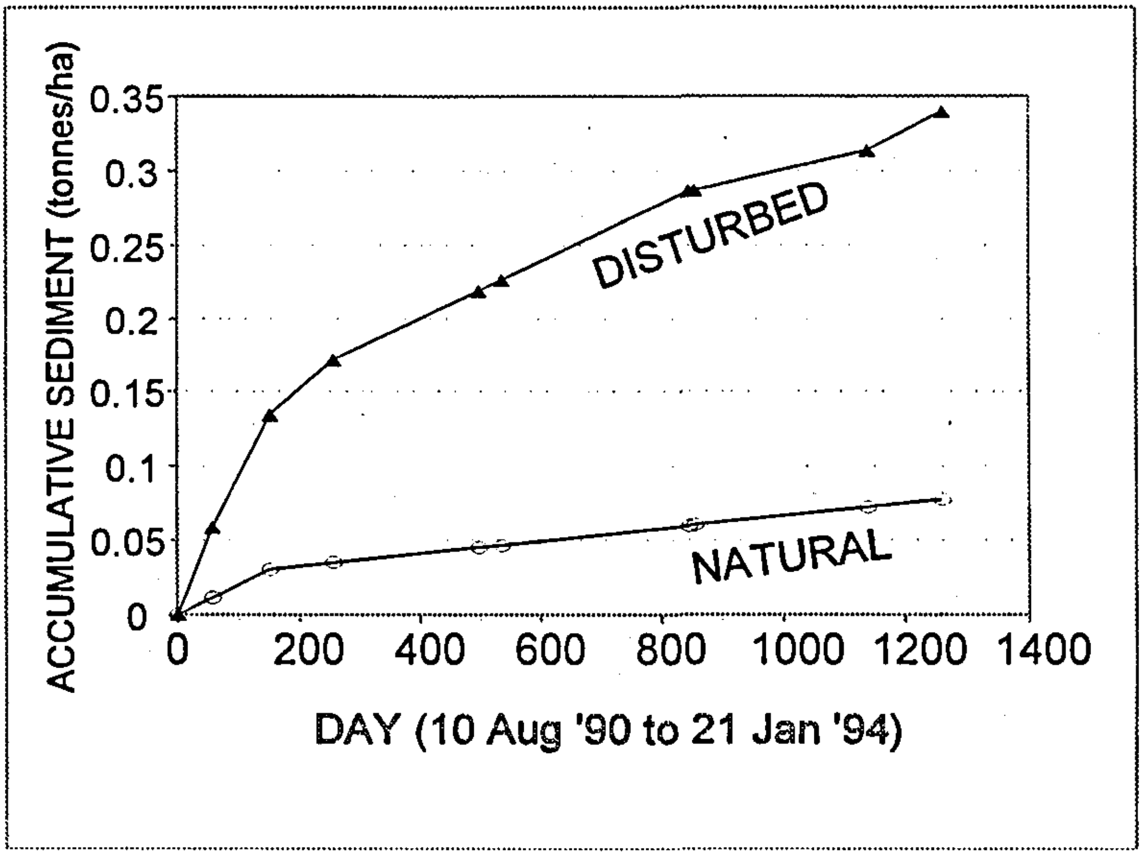


Figure 5.8 Cumulative bedload trapped in weirs W1H016 and W1H031.

For bare gravel roads, Swift (1988) has indicated that there is approximately 1.2 *tonne of soil loss for each hectare of roadbed for each 10mm rainfall.* The primary road network (Figure 5.9) covers approximately 1.1 ha (assuming a width of ~5m) while other open surface features cover about 0.5 ha for the pathways (assumed to be one metre wide) and 2,9 ha for the open area around the kraals. These exposed soil surfaces covers approximately 4,5 ha. If the annual estimate of storm (>10mm) rainfall is assumed to be 500mm then the Swift (1988) estimate of soil loss is about 1000 tonnes (or 270 tonne/ha/a) for the three and a half years of observations shown in Figure 5.8. This is considerably higher than the observed bed-load.

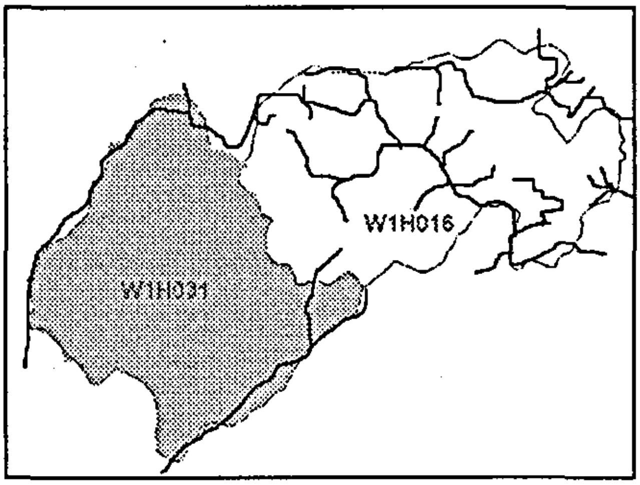


Figure 5.9 Roads, pathways and settlements derived from 1995 aerial photographs.

5.4 SUSPENDED SOLIDS

Cumulative estimates of the suspended solids export loads from the research catchments for the 1993/1994 and 1994/1995 seasons are examined for both the flow-related *grab samples* and the CR10 continuous *hourly* measurements of turbidity. Values of suspended solids export loads from measured (SS) and interpolated values of laboratory turbidity ($TURB_{Lab}$) were interpolated at hourly intervals using laboratory sample values. The hourly export loads for the continuous field measurements were **estimated** from the CR10 value of turbidity ($TURB_{CR10}$) using the calibration relationships shown earlier. Since there is some doubt about some of these relationships this analyses concentrates on the *difference between seasons and catchments rather than on the absolute export* loads.

5.4.1 EFFECT OF ESTIMATION METHOD

There is a big difference between the two estimates of suspended solids derived from the turbidity measurements and the measured SS values at W1H016. Cumulative curves for all three methods are shown in Figure 5.10 & 5.11 for W1H016 for both seasons. Similar cumulative plots of suspended solids derived estimates for W1H031 given in Figure 5.12 & 5.13 show a smaller difference during the 1993/94 season only.

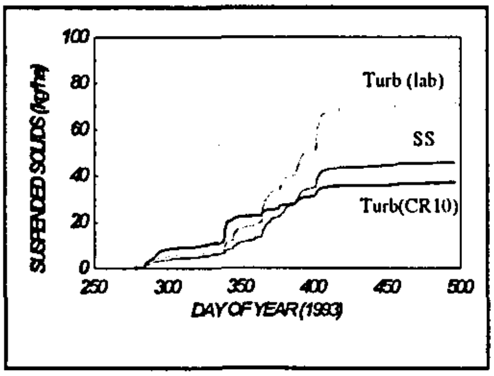


Figure 5.10 Cumulative plots of suspended solids for W1H016 from three different estimations for 1993/94.

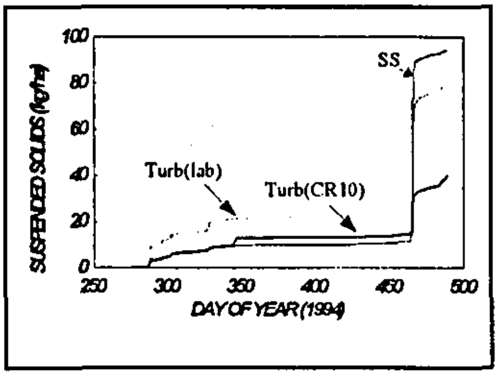


Figure 5.11 Cumulative plots of suspended solids for W1H016 from three different estimations for 1994/95

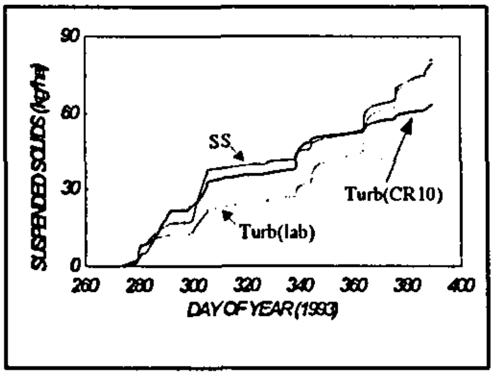


Figure 5.12 Cumulative plots of the suspended solids for W1H031 from three different estimations for 1993/94.

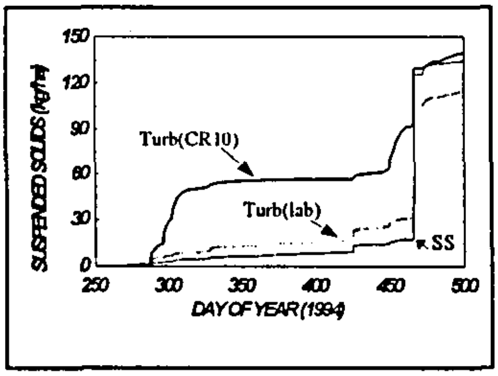


Figure 5.13 Cumulative plots of suspended solids for W1H031 from three different estimations for 1994/95.

The suspended solids estimate for W1H016 (SS_{W16}) is slightly lower than both of the turbidity estimates ($TURB_{lab}$ and $TURB_{CR10}$) for most of

1993/94 (Figure 5.11) but not for 1994/95 where the $TURB_{CR10}$ is less than both the other two estimated values (Figure 5.10). The cumulative values for all three estimation procedures are very similar for W1H031 during the 1993/94 season (Figure 5.12) but differ substantially from the $TURB_{CR10}$ estimates during most of the 1994/95 season (Figure 5.13). These differences may be partly due to the patching method for missing data values and to the empirical relationships derived earlier.

There were several missing sample values for both SS and $TURB_{LAB}$ in most of the series for both weirs which were interpolated using the average of the previous and next known values. While this would not affect the comparison between the two sample series of SS and $TURB_{LAB}$ (both derived from grab samples) it would impact on the comparison between these two series and the $TURB_{CR10}$.

The largest discrepancy between the three estimation methods occurs with the individual storm events which is clearly evident at the end of the 1994/95 season shown in Figures 5.11 and 5.13. Consequently, errors in measurement during large storm events must have a profound impact on estimation of export loads.

The difference between the cumulative total of the three estimation methods for W1H016 and W1H031 for 1993/94 are given in Table 5.4. It is not clear if the discrepancies in the estimation methods are due to the measurement techniques described

Table 5.4 Annual export loads of suspended solids (kg/ha/a) derived from different estimation methods for 1993/94 and 1994/95 seasons.

Methods	W1H016		W1H031	
	93/4	94/5	93/4	94/5
Sus Solids	28	62	74	84
$TURB_{(Lab)}$	43	54	78	72
$TURB_{(CR10)}$	22	30	60	88

above or whether there is a large difference due to the missing samples or the sampling locations. However, the observations suggest that the largest difference occurs with individual storm events.

The cumulative export loads for both years is substantially lower than the export loads observed by Simpson (1992) who presented values almost one order of magnitude greater. This may be due to the much lower discharge during the drought conditions prevailing during these two seasons. If there had not been a very large storm during the early part of 1995, the export load for the 1994/95 season would have been much lower, probably half, the previous seasons values. These figures show the influence of individual storms on export loads and for the 1994/95 season they accounted for more than half the soil loss during the one event.

5.4.2 SPATIAL VARIABILITY

Flow-related Suspended Solids - The cumulative SS series derived from laboratory measurements of SS for W1H016 and W1H031 are shown in Figure 5.14 for 1993/94 season. The SS is significantly larger for W1H031 than W1H016 at the start of the season and during a large storm event around DOY 290. The differences are not particularly large during the middle of the season but deviate again during the later part of the season so that W1H016 has almost a 57% lower export load during the 1993/94 compared to W1H031. The 1994/95 season shows a similar trends for the season with a very large event on DOY 100, 1995 (Figure 5.15). This higher load for the natural catchment (W1H031) is in direct contrast to the bedload component which is considerably higher for W1H016. Clearly, the estimation of suspended solids export load derived from flow related samples is strongly related to individual rainfall events.

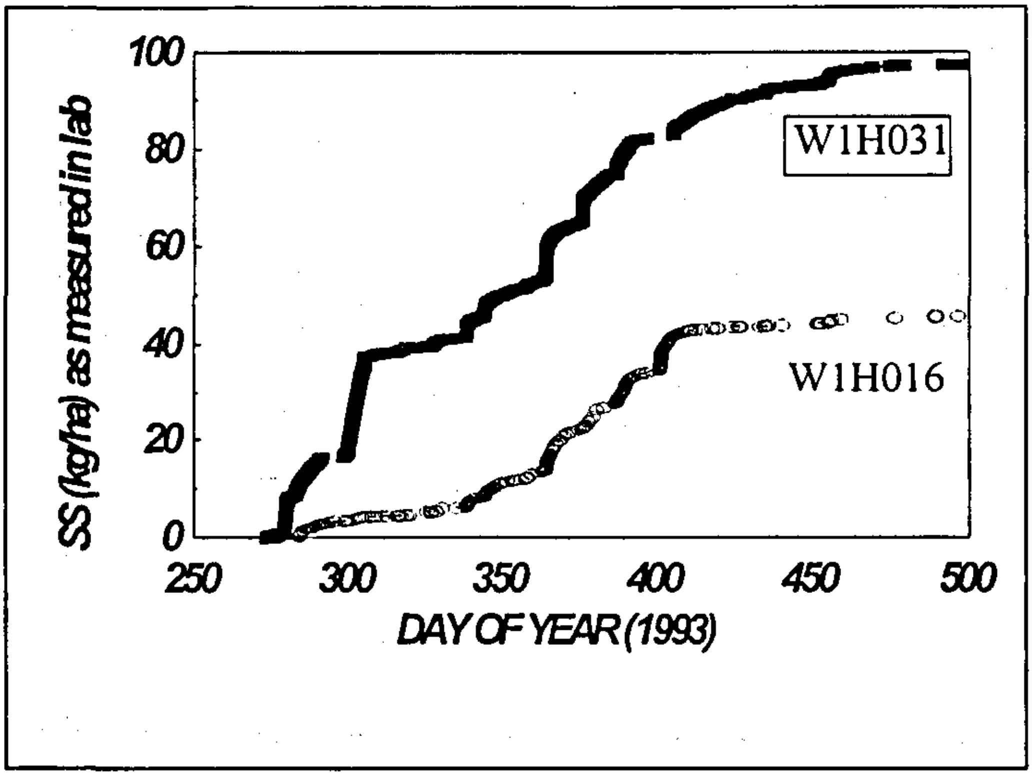


Figure 5.14 Cumulative SS for 1993/94 .

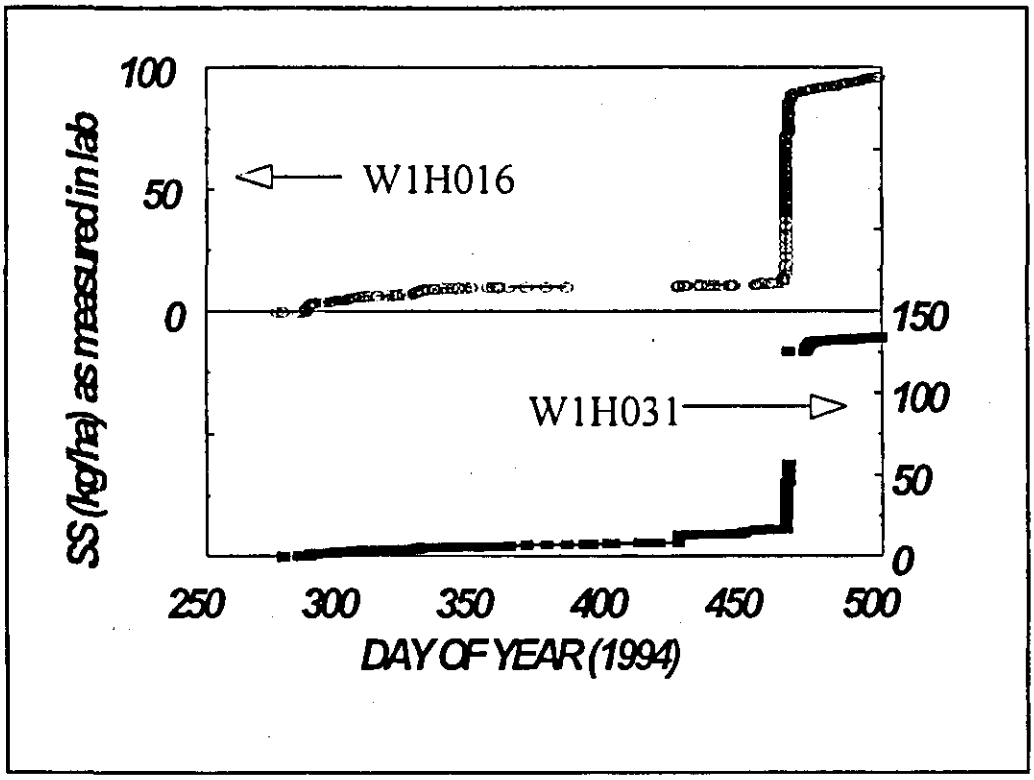


Figure 5.15 Cumulative SS for 1994/95 .

Flow-related Turbidity ($TURB_{LAB}$)

With the exception of one large event which had little effect on W1H016 during the early part of the season, the difference between W1H016 and W1H031 in the cumulative suspended solids derived from the turbidity measurements (in the laboratory) is very small for the first half of 1993/94 season (Figure 5.16). However, there is a small but consistent difference during the second half of this season when W1H031 increases more rapidly to have a total export load almost 1.8 times higher than W1H016. The two catchments have similar total loads during the 1994/95 season(Figure 5.17) until the storm around DOY 430 and the exceptional storm on DOY 465 (DOY 100 in 1995) which again produced increased export for W1H031. These increased export loads from W1H031 must be due to the greater discharge from this catchment during the exceptional drought conditions because the concentrations are generally lower.

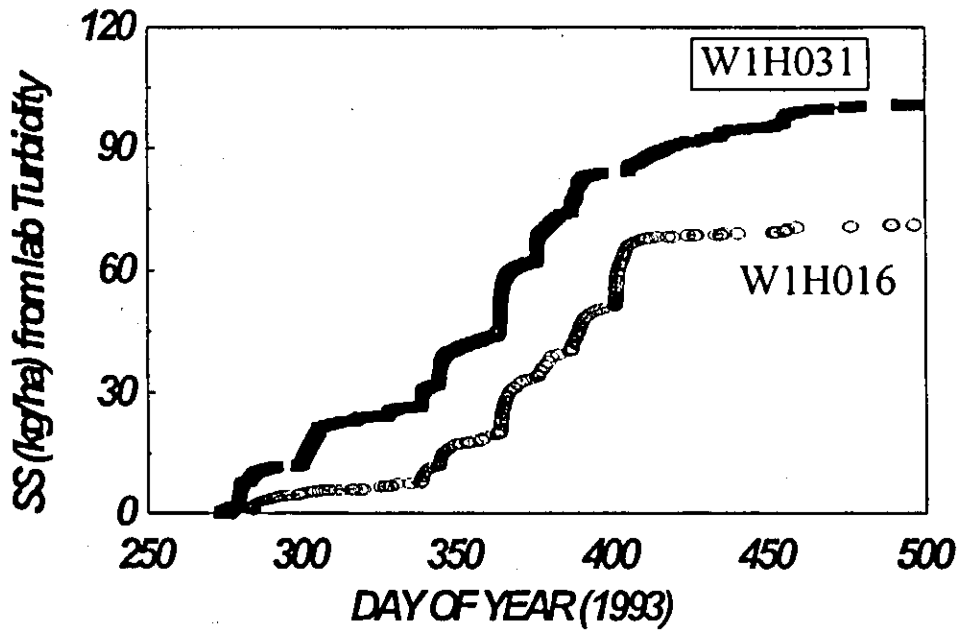


Figure 5.16 Cumulative $TURB_{LAB}$ for 1993/94

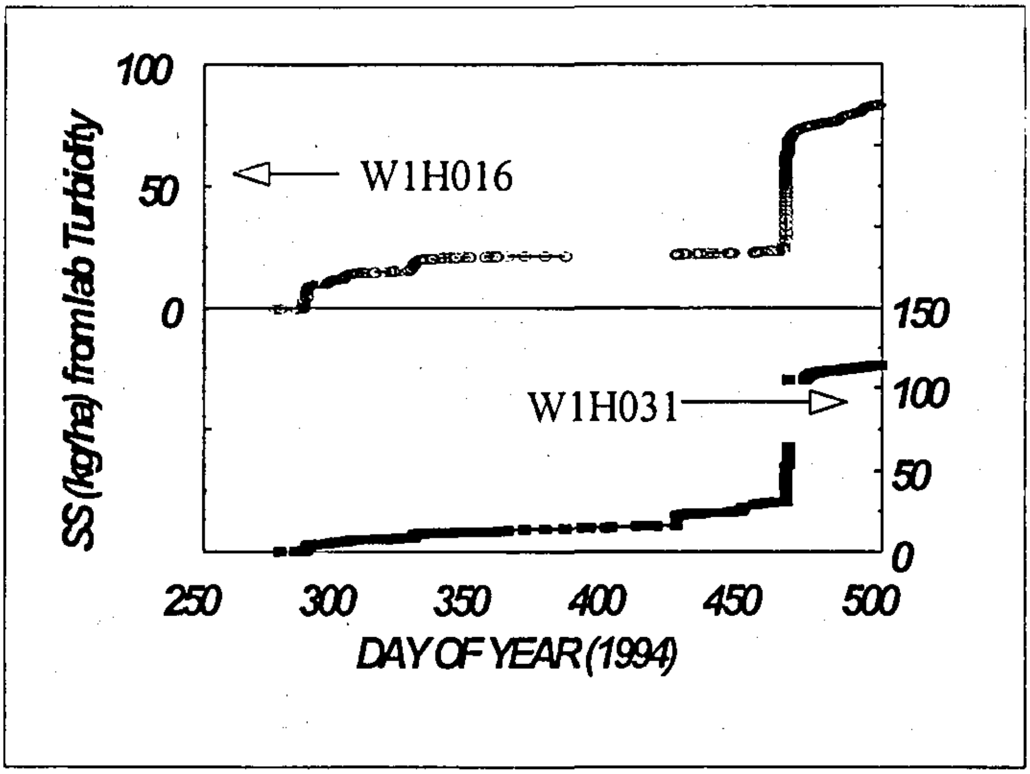


Figure 5.17 Cumulative $TURB_{LAB}$ for 1994/95

Field Turbidity derived SS ($TURB_{CR10}$) - There are some very large differences between the field estimates of suspended solids export load for the two catchments at W1H016 and W1H031 using $TURB_{CR10}$ (Figure 5.18 and Figure 5.19). These differences are generally due to substantial difference between individual storm events particularly during the early part of both seasons. The sediment load derived from these measurements indicates almost double the amount exported from the natural catchment (W1H031) compared to the disturbed catchment (W1H016). This is consistent for all three methods of estimation.

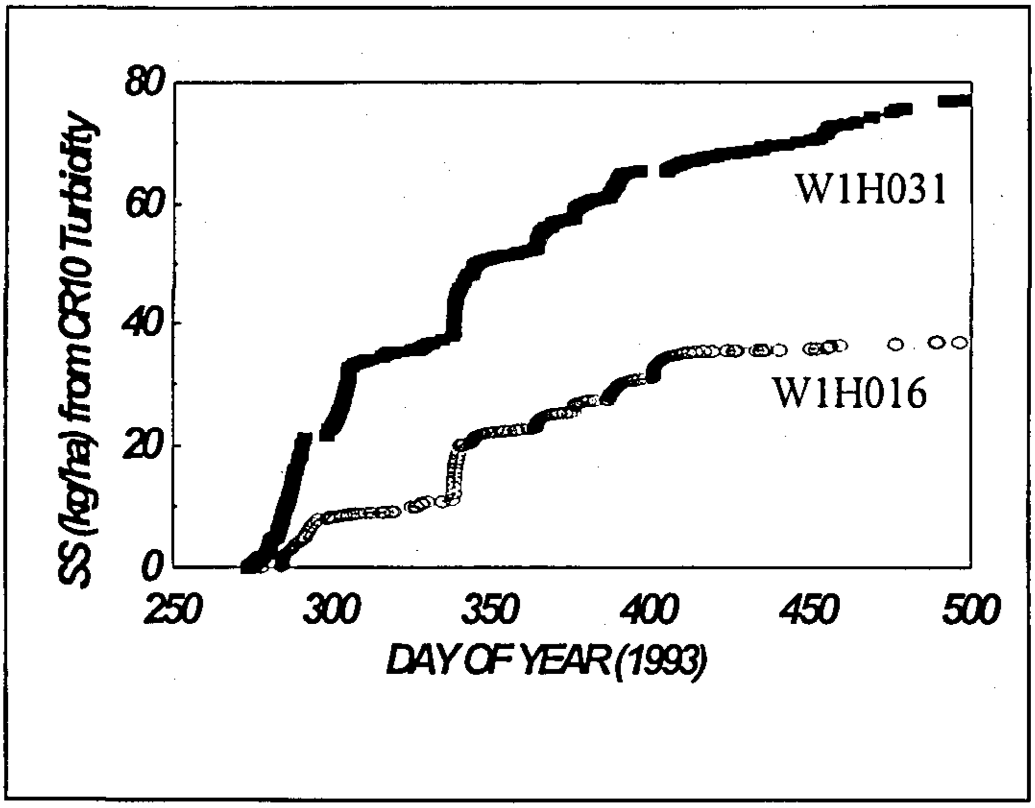


Figure 5.18 Cumulative $TURB_{CR10}$ for 1993/94.

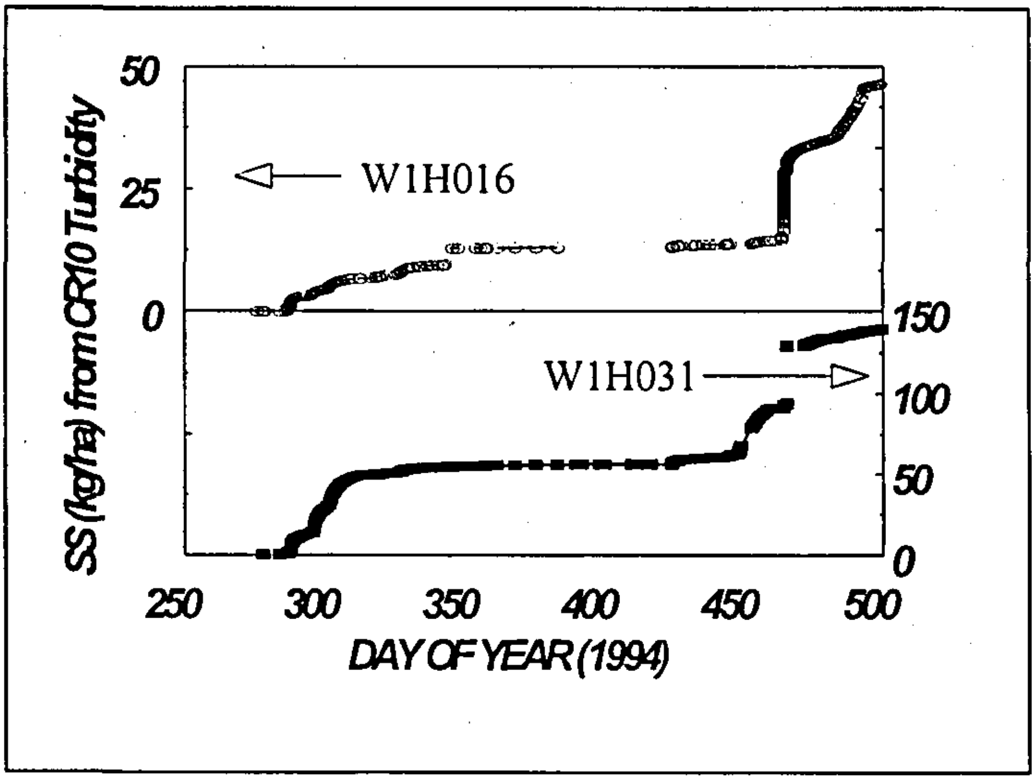


Figure 5.19 Cumulative $TURB_{CR10}$ for 1994/95

5.5 TOTAL DISSOLVED SOLIDS (TDS)

The cumulative discharge loads of total dissolved solids (TDS) for all three catchments using sample and hourly data were derived for all seasons. The export loads using hourly data for 1993/1994 and 1994/95 from all three catchments are shown in Figure 5.20 & 5.21 respectively. The total export of TDS from W1H017 (329 kg/ha/year) is slightly less than the other two catchments for the 1993/94 season (Figure 5.20). The other two catchments have very similar loads which agree closely with the export loads observed in earlier studies by Simpson (1992). However, there is a large difference between catchments in the 1994/95 year (Figure 5.21). W1H017 export load is higher than the export from W1H016 for much of 1994/95. This is due mainly to the lack of runoff in W1H016 for much of this period while W1H017 was still flowing. There is a very high export load for W1H031 in 1994/95 which is due mainly to the very large storms in early 1995 (Figure 5.21 & Table 5.5). Almost half the total export for 1995/95 occurred in the period during March and April, 1995 (Figure 5.21). However, the conductivity for W1H016 (~10mS/m) during this period was almost half the corresponding conductivity for W1H031 (19 mS/m). A case study during this period is discussed in more detail in section 8.4.

Table 5.5 Seasonal export of Total Dissolved Solids (kg/ha/yr)

Weir	1993/94	1994/95
W1H017	329	227
W1H016	493	134
W1H031	524	896

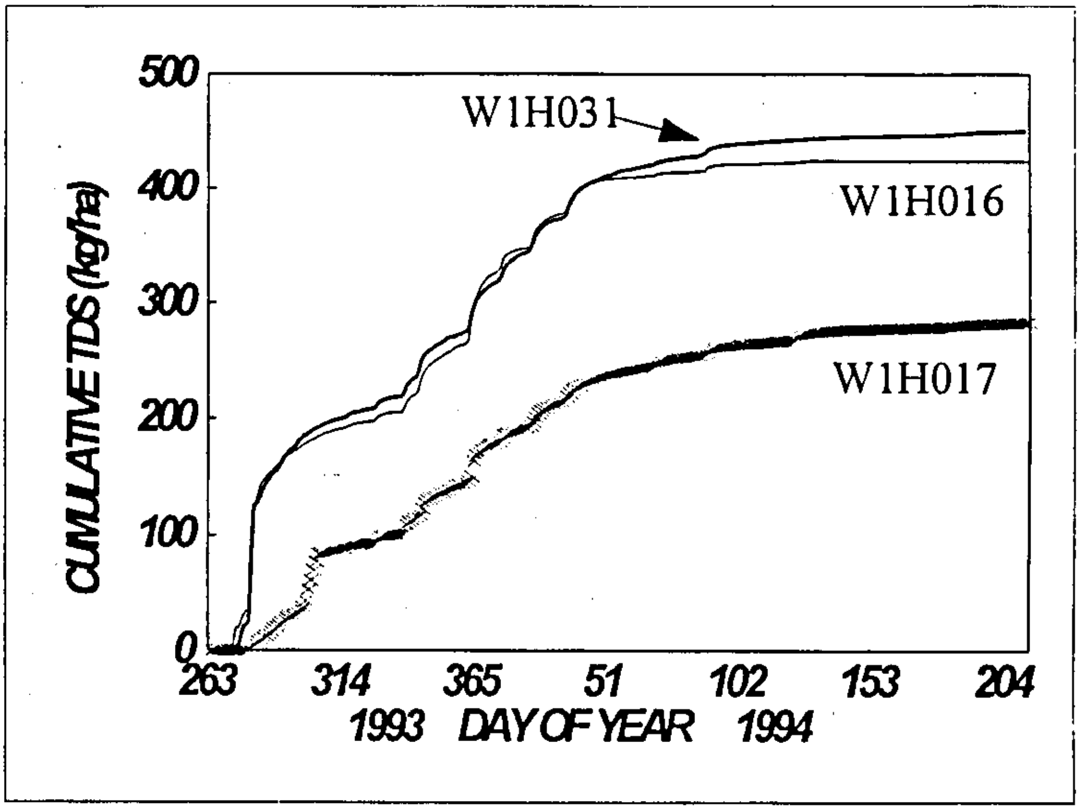


Figure 5.20 Cumulative TDS for 1993/94

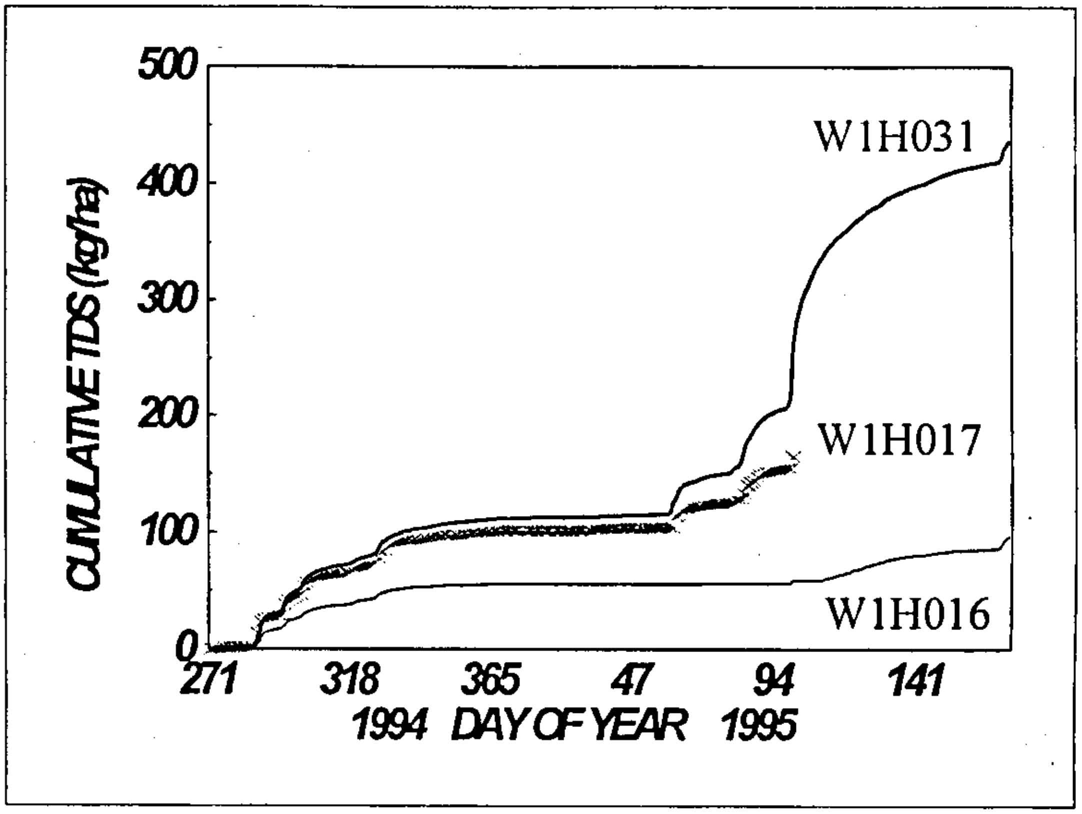


Figure 5.21 Cumulative TDS for 1994/95.

5.6 NITRATES

The cumulative export of nitrogen (as nitrate) from W1H016 and W1H031 are shown in Figure 5.22 for 1993/94 season and in Figure 5.23 for the 1994/95 season. The total nitrogen export for 1993/94 is 613 g/ha/year and 1322 g/ha/year for W1H031 and W1H016 respectively. Corresponding exports for 1994/95 are 740 g/ha/year and 895 g/ha/year.

There was a far smaller difference between the seasons for W1H031 (127 g/ha) compared to the large difference for the corresponding years in W1H016 (427 g/ha). The total input of nitrate from rainfall during 1993/94 seasons was estimated from the 15 samples. This estimate exceeded 1400 kg/ha/year (Figures 5.24 and Figure 5.25). The corresponding export of nitrates was ~13% and ~12% of the rainfall input into W1H031 and W1H016 respectively. The main difference between the import and export could be attributed to the individual storms which produced a large amount of nitrate but this never materialized directly in the runoff. Chapter 7 presents the nitrate response to individual storms and it is shown that the nitrate concentration generally rises substantially during storm events but does not exceeds the concentrations in rainfall by much except in the occasional storm (see figure 7.7). Consequently, this difference between the importation and exportation requires further investigation. It is possibly a result of the limited number of samples for both rainfall (15 samples) and grab sampling method for runoff.

The differences between catchments in the nitrate export also needs further investigation, particularly because of the rapid increase in sugar cane production during the last three years which must have been accompanied by a corresponding increase in fertilizer application.

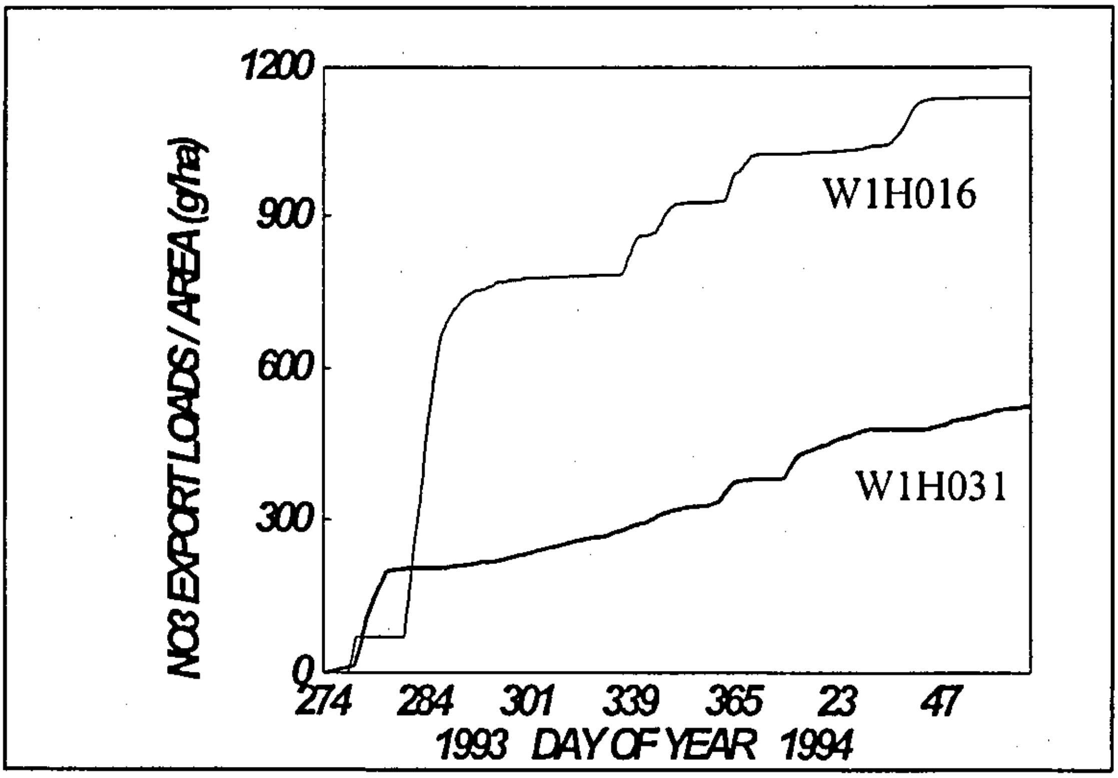


Figure 5.22 Nitrate (N) export for 1993/94.

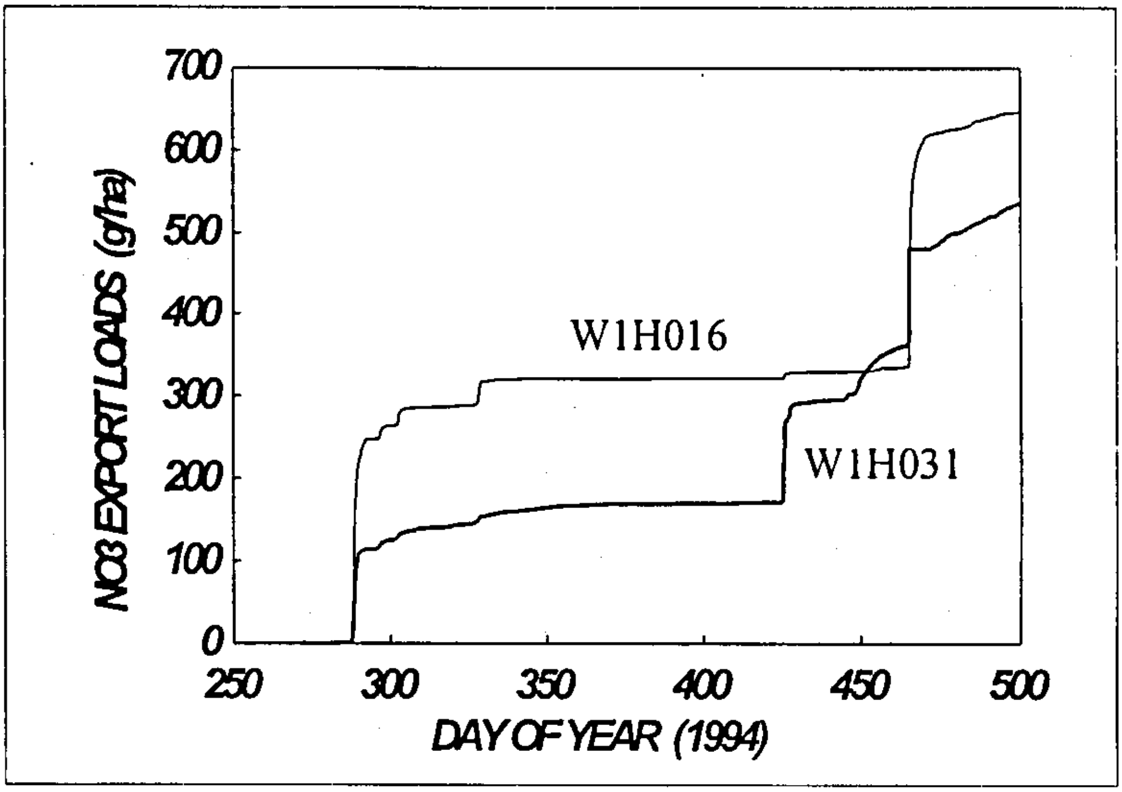


Figure 5.23 Nitrate (N) export for 1994/95.

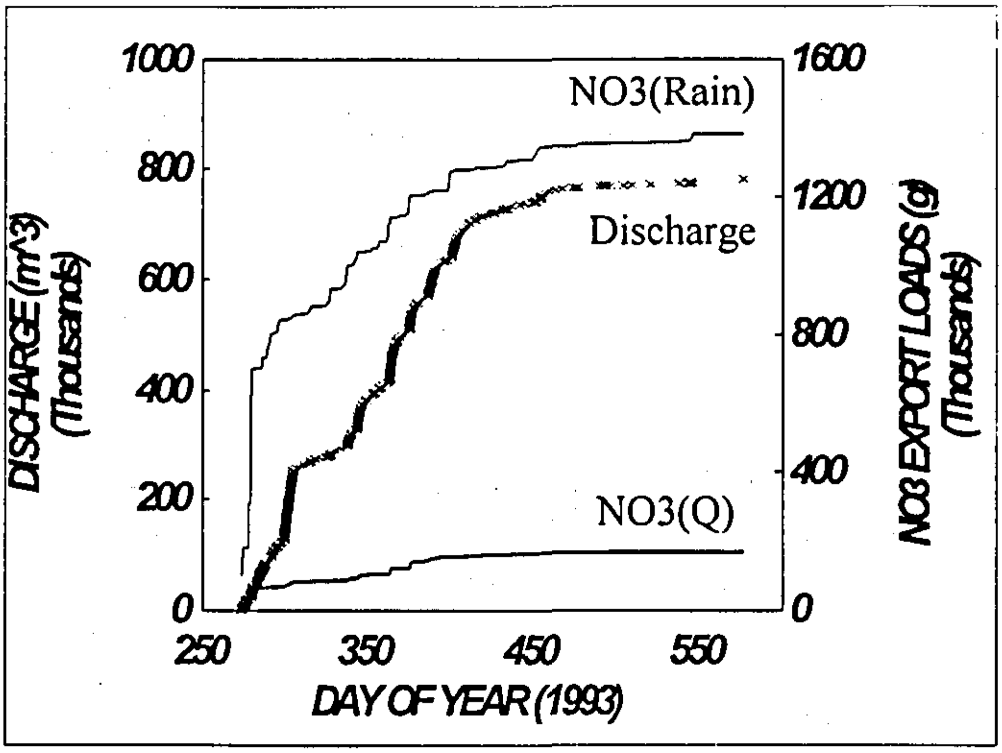


Figure 5.24 Nitrate (N) import & Exports from W1H031 for 1993/94.

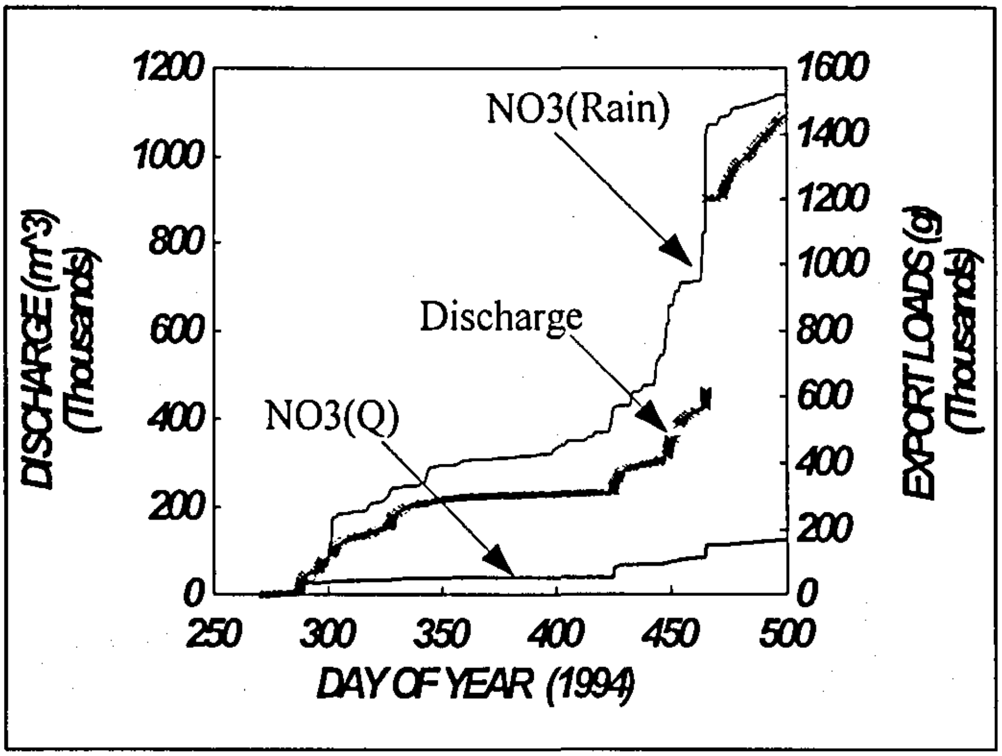


Figure 5.25 Nitrate (N) export for 1993/94 from flow related grab samples.

5.7 PHOSPHATES

The cumulative export of dissolved phosphate from W1H016 and W1H031 are shown in Figure 5.26 and 5.27 for the 1993/94 and 1994/95 seasons. W1H016 (55 g/ha/year) exported almost half the load of W1H031 (101 g/ha/year) for the 1993/94 season. During the 1994/95 season, W1H031 continued to export at almost the same rate (128 g/ha/year) but W1H016 export dropped to only 19 g/ha/year (or about 15%) of W1H031's export for the same period. This is surprising because of the increase in sugar cane in W1H016. Previous studies by Simpson (1992) show the opposite effect with W1H016 exporting about one and half times as much as W1H031. This requires more investigation.

5.8 GENERAL FEATURES

The research catchments are small enough to have very similar rainfall regimes. However, there are small differences in their response to the rainfall which are due to specific rainfall events. In spite of the continued discharge from W1H017 when the flow from W1H016 had stopped during very dry conditions, the proportion of run off from the sub catchment remains in proportion to the contributing area. Individual storm characteristics are described in the next sections where significant differences in hydrological responses are presented. In many cases it is these individual events which cause the major differences in water quality response in the catchments examined above.

The problems with estimation methods for suspended solids mask the response differences between the catchments. The grab sample analyses indicate that the suspended solids load from W1H016 is lower than the load from W1H031 while the turbidity observed estimates indicate that the load is higher from W1H016. The cumulative difference however remains relatively small for W1H031 but much more variable for W1H016.

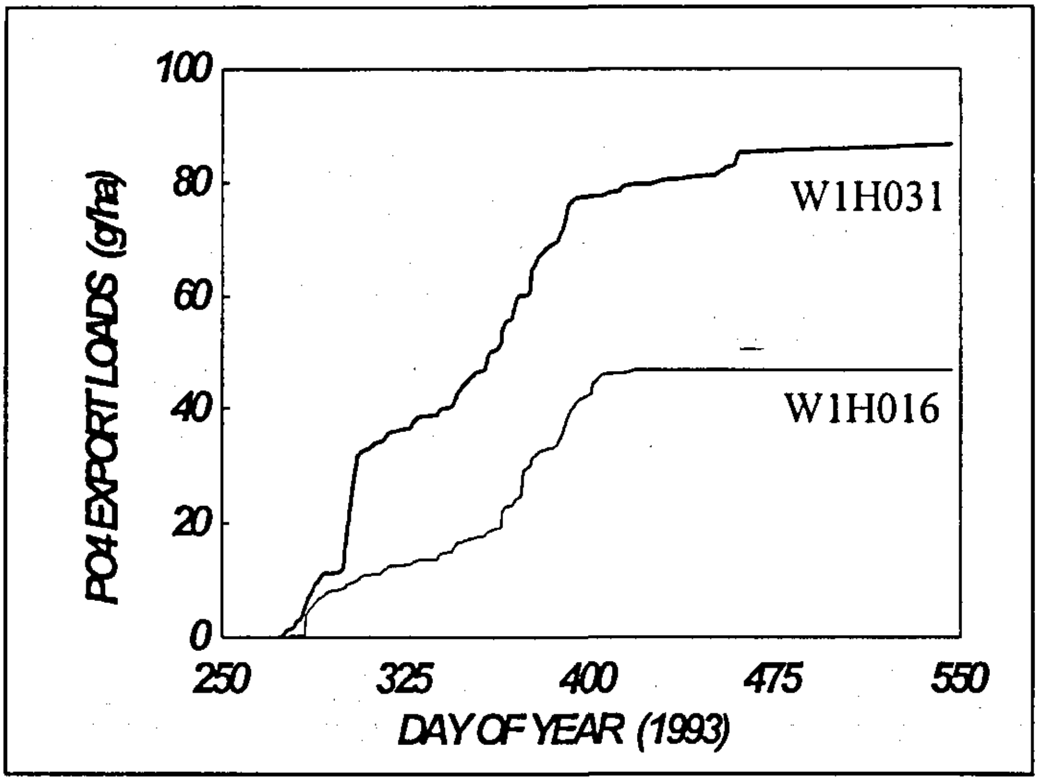


Figure 5.26 Phosphate (P) export for 1993/94 using flow-related grab samples.

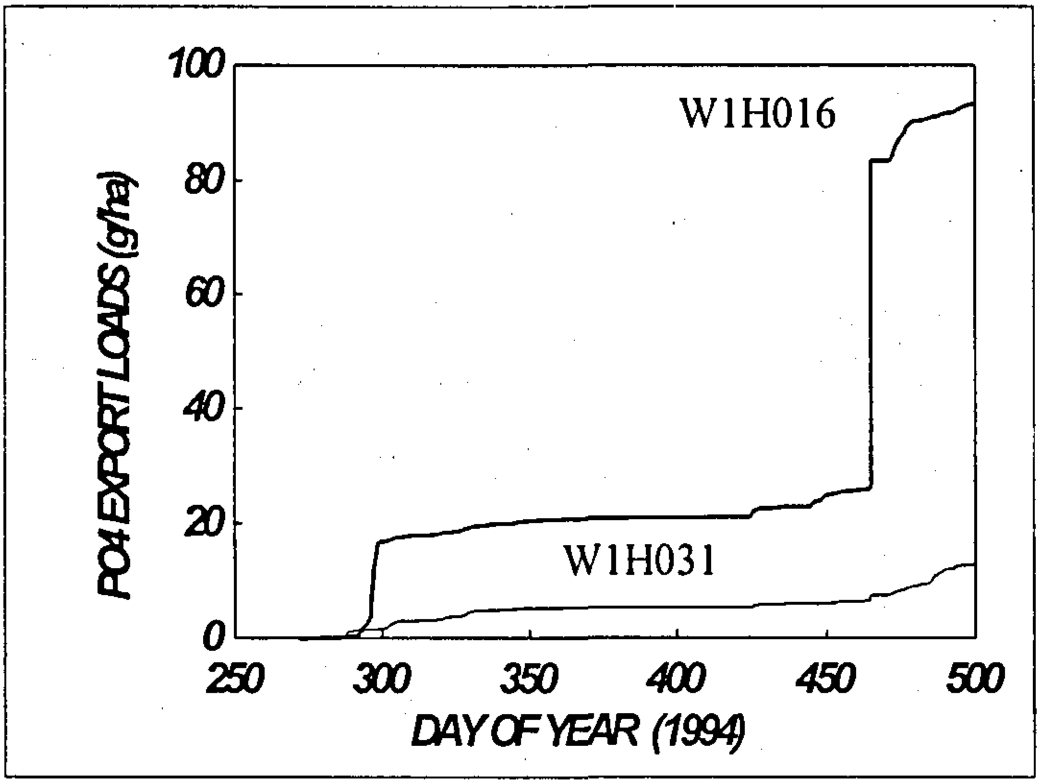


Figure 5.27 Phosphate (P) export for 1994/95 using flow related grab samples.

6 FLOW CHARACTERISTICS

The hydrograph emanating from a catchment reflects the integrated effects of all the hydrological processes operating in the catchment in response to a specific rainfall event. The discharge hydrographs from the research catchments have been analysed according to Chow *et al*, (1988) and Herrmann *et al* (1987) in order to identify aspects of the hydrological processes dominating the runoff from the small research catchments. Distinctly different unit hydrographs have been identified for the two research catchments representing the natural undisturbed system (W1H031) and a catchment with subsistence agricultural settlements (W1H016) which is considered to be typical of large sections of Zululand (Mulder and Kelbe, 1992). Typical discharge hydrographs from both catchments for a short duration high intensity storm in October 1995 are shown in Figure 6.1.

– W1H031 HYDROGRAPH

The 3.18 km^2 catchment draining through W1H031 has geomorphic features (Kelbe *et al*, 1992) that obey Horton's Laws of stream number and stream length (Chow *et al*, 1988). The main tributary is 4.00 km and the catchment has a perimeter of 8.57 km. The stream network can be divided into the four relatively equal sized sub-catchments shown in *Figure 6.2*. Each sub-

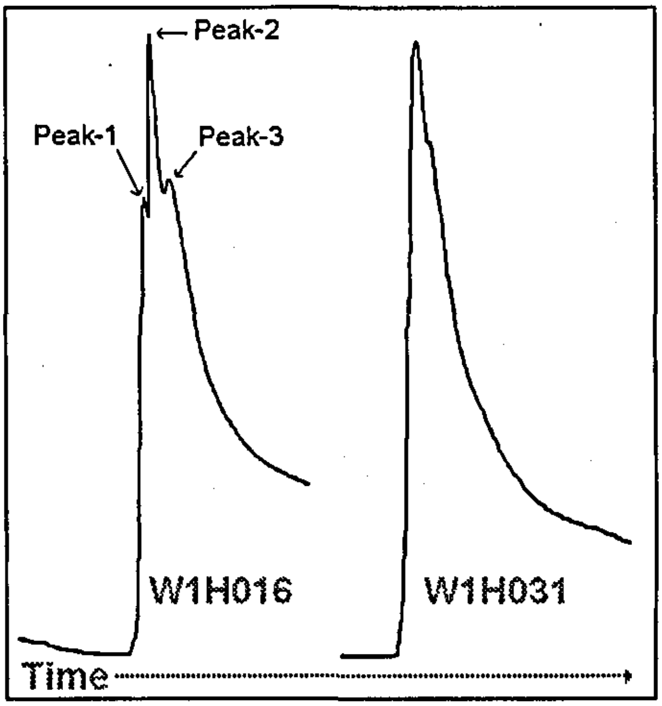


Figure 6.1 Typical discharge hydrograph forW1H016 and W1H031.

catchment is separated by a steam length of about 500 m that would have a very short response time so that the discharge from each sub-catchments are effectively routed in parallel. This would suggest that there would be little separation between the runoff hydrographs from each sub-catchment and that the hydrograph from W1H031 would normally exhibit a single sharp peak as shown in Figure 6.1.

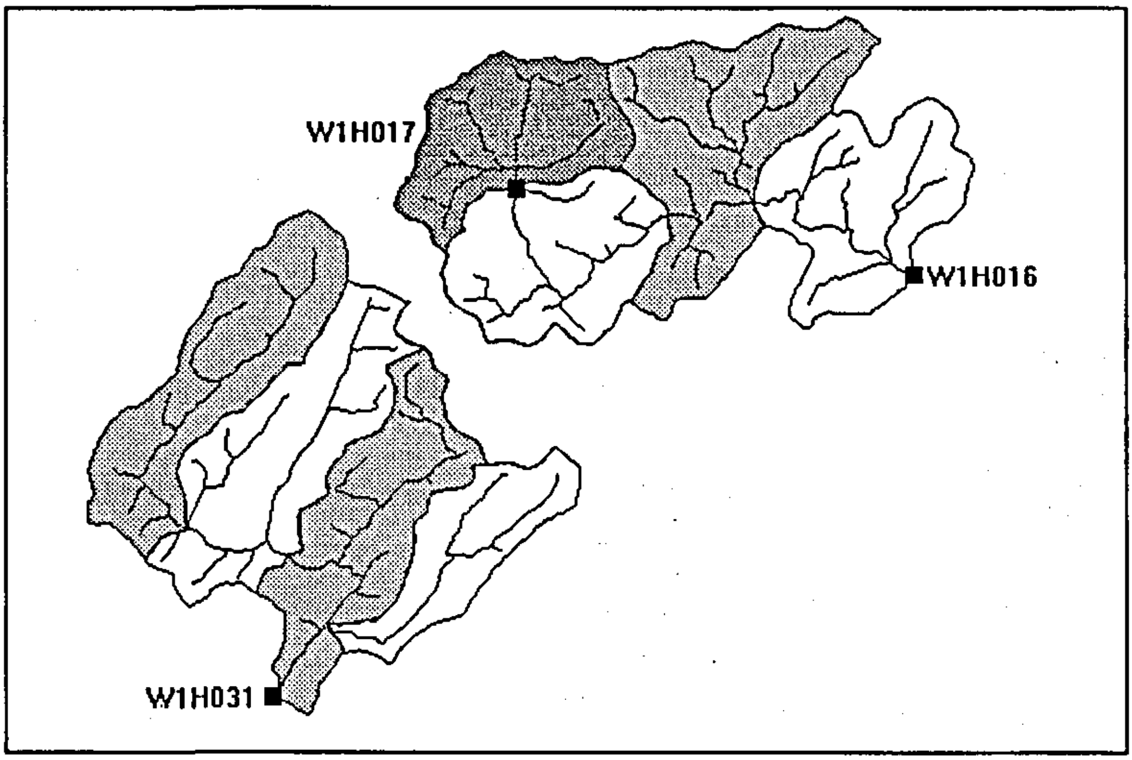


Figure 6.2 River networks and sub-catchments

– W1H016 HYDROGRAPH

W1H016 monitors a fourth order catchment with an area of 3.23 km^2 that has very similar Horton Numbers to W1H031 (Kelbe *et al*, 1992). The main tributary is 4.25 km and the perimeter is 9.55 km. However, the catchment shape is distinctly different to W1H031. In W1H016 there are also four basic sub-catchments shown in Figure 6.2 which route the discharge in series rather than in parallel as in W1H031. Consequently, the typical hydrographs from the disturbed catchment W1H016 for short duration high intensity storms generally show three distinct peaks (Figure 6.1) which are identified with the different contributing sub-catchments within W1H016.

The autographic records of five short duration, high intensity storm hydrographs were digitized specifically to determine the characteristic lag times of the three peaks for W1H016. A composite hydrograph was derived from these events through a determination of the mean stage and the mean time between discontinuities (peaks and trough). The peak and trough stages for the individual storms are given in Table 6.1. The composite (mean times) of all these individual storm hydrographs is shown in Figure 6.3 and was constructed by normalizing the discharge relative to the initial base flow conditions and setting the time relative to the start of each storm hydrograph. There is considerable variability of the peak flow between storm events which is due to the incident rainfall volume and the antecedent conditions.

Table 6.1 Individual and composite storm temporal hydrograph characteristics.

	STORMS					MEAN TIME
Inflection points	1	2	3	4	5	
Initial base flow (m^3/d)	1654	1924	1946	654	2135	0.0
Time to Peak-1 (stage)	150	138	172	294	21	155.0
Time to Trough-1	302	314	279	442	287	324.8
Time to Peak-2 (stage)	449	478	310	472	316	405.0
Time to Trough-2	746	669	315	757	501	507.6
Time to Peak-3 (stage)	773	936	327	799	660	699.0
Time to Trough-3	900	1407	443	953	796	899.8
Time to recession point 1	1082	1885	468	1082	943	1092.0
Time to recession point 2	1275	2734	596	1238	1105	1389.6
Time to recession point 3	1723	3688	767	1398	1294	1774.0
Time to recession point 4	2500	4640	936	1710	1740	2305.2
Time to recession point 5	3129	5590	1252	2197	2377	2909.0

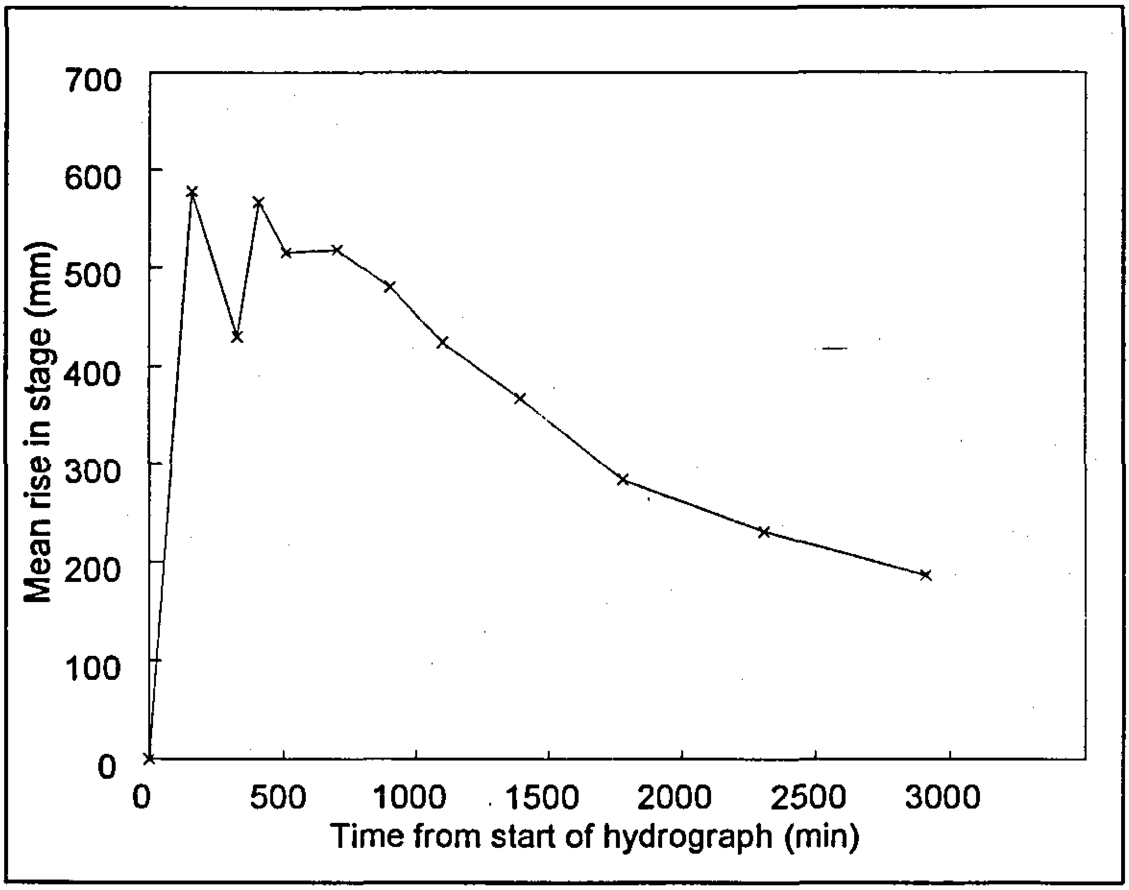


Figure 6.3 Characteristic storm hydrograph from W1H016 for short duration high intensity storm.

Each peak in the discharge hydrograph from W1H016 is only identifiable under very specific rainfall conditions that are assumed to produce a rapid runoff response in each sub-catchment. It is suggested that the three peaks in the discharge hydrograph emanating from short duration high intensity storms are due to the specific morphology of the catchment which transports the surface runoff component in series so that the rapid surface runoff from each sub-area arrives as a sequence of unit hydrographs. The two main restrictions in the drainage pattern are believed to induce the separations in the contributing hydrograph peaks.

The frequency distribution of hydraulic path lengths and the associated travel times derived by Kelbe *et al* (1998) also show these three distinct peaks (Figure 6.4) which have linked to the triple peaks in the discharge hydrograph. If these geomorphic features induce the triple peaks then they may be treated as three separate unit hydrographs that can be superimposed to produce the final discharge hydrograph at the outlet (Figure 6.5). Consequently, changes in physical and chemical properties at specific points during a hydrograph from short duration high intensity storms may be linked to specific sub-catchments. This is examined numerically in more detail by Kelbe *et al* (1998) who present specific case studies for several short duration high intensity storm events.

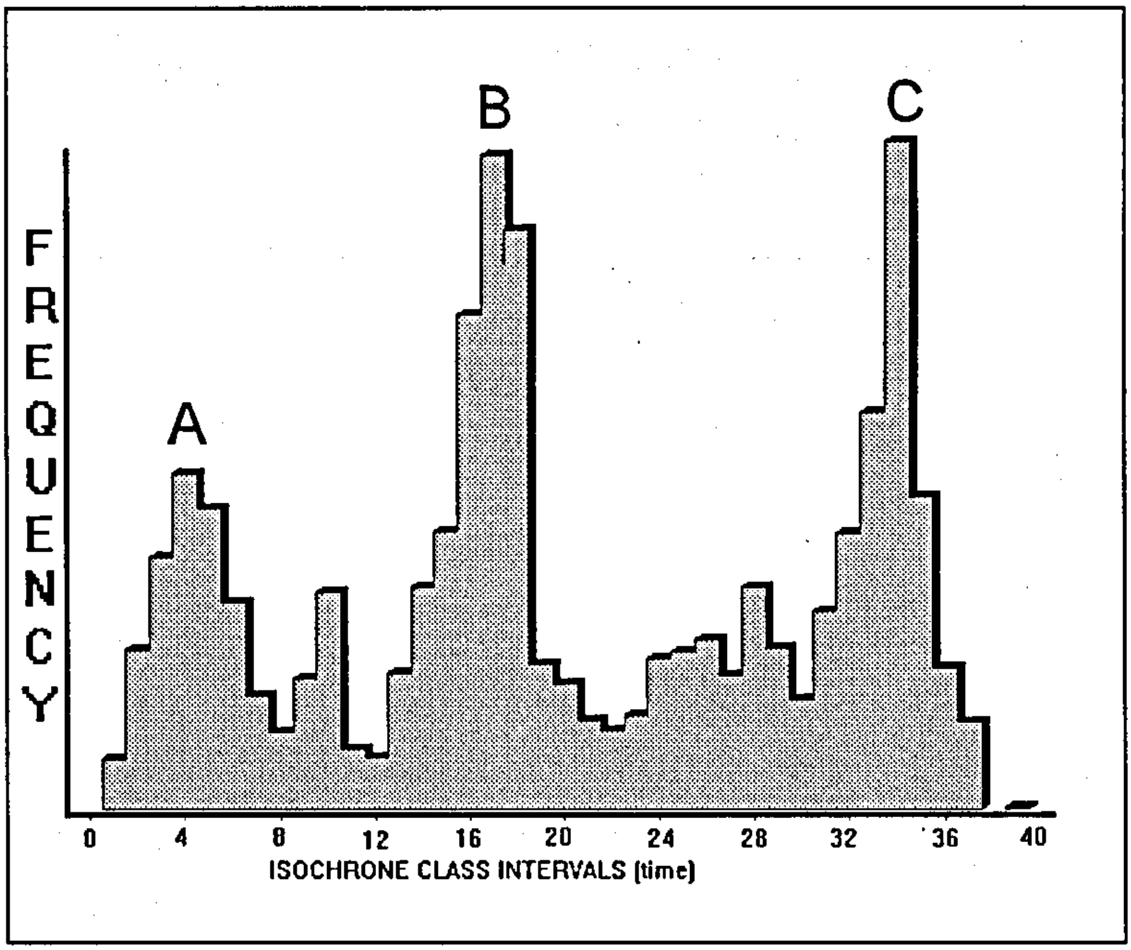


Figure 6.4 Frequency distribution of travel times from the outlet at weir W1H016 (from Kelbe et al, 1996).

For W1H016, the first unit hydrograph (labelled A in Figure 6.5) is assumed to be associated with the discharge from the sub-catchment immediately adjacent to the outlet at W1H016 weir. The third unit hydrograph (C = shaded area in Figure 6.5) is linked to the discharge from sub-catchment W1H017 after it has been routed along the stream for about 3.5 km. The second and third unit hydrograph (B &C) undergo some attenuation during the translation and consequently the second and third peaks would normally be smaller if they contributed the same volume of runoff. However, the second peak is generally larger than the other two peaks for the same rainfall events and therefore it can be assumed that the contributing area is generally greater. It is assumed the whole of the second and part of the third sub-catchments in Figure 6.2 are responsible for the runoff associated with the second peak.

Using standard hydrograph separation techniques (Chow et al, 1988), the base flow was removed and the remaining storm flow was modelled as three separate triangular unit hydrographs routed along a stream channel (Figure 6.5). The actual hydrograph recession curve shown in Figure 6.5 is a composite of digitization points at specific time steps.

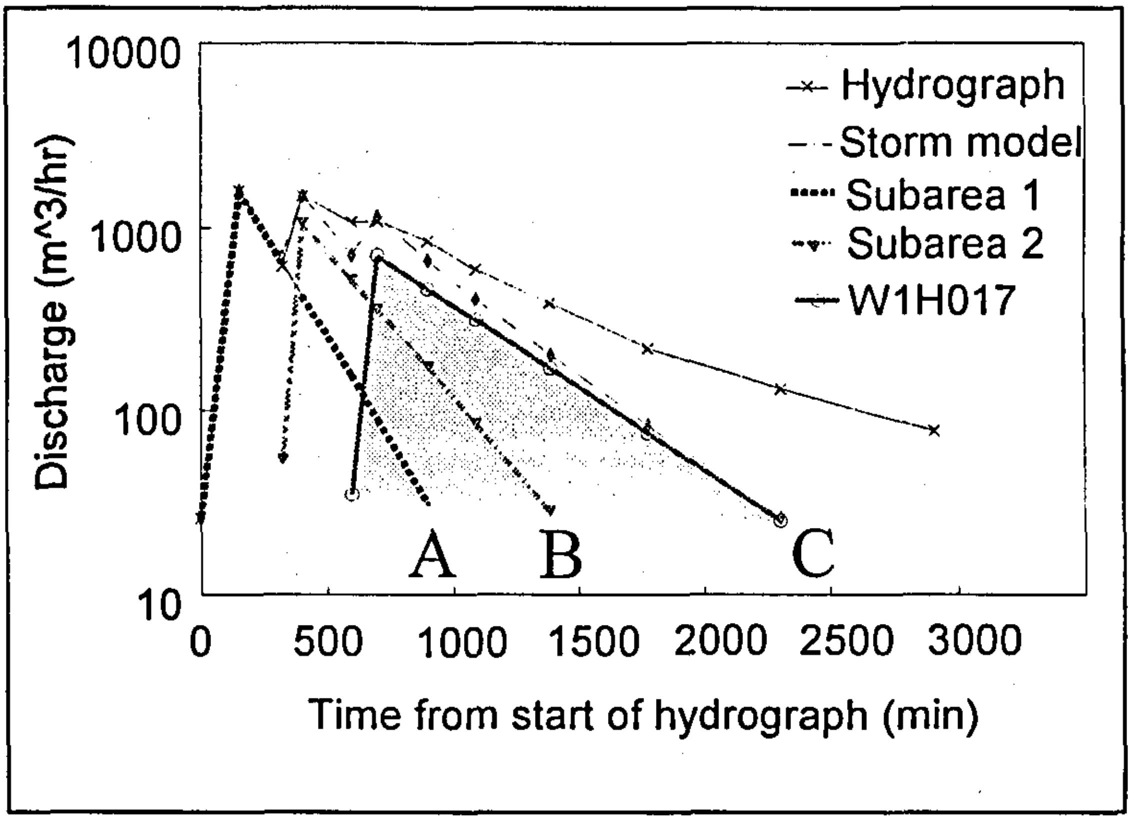


Figure 6.5 Composite model of hydrograph for W1H016 for short duration high intensity storm. A,B & C refer to the triangular unit hydrographs for the three peaks shown in Figure 6.4

– RAINFALL RUNOFF RELATIONSHIP

The integrated volume of actual **storm** discharge for W1H016 for the storm on DOY 317, 1992 was estimated to be 4 175 m^3. The integrated volume of **total** discharge (storm + interflow + baseflow) for the initial 4 230 minutes from the start of the storm hydrograph was estimated at 8 933 m^3. By extending the flow for seven days to include all base flow the total volume was estimated to be about 10 462 m^3.

The rainfall for this storm was integrated over the whole catchment to give a total rainfall volume of 113 900 m^3. This implies a runoff to rainfall ratio of 4, 8 & 9% respectively for the "storm", "4230 minute total" and the "7 day extended total" runoff periods described above. This indicates that less than 10% of all the rainfall leaves the catchment as runoff during these storm periods. This particular example for a storm in 1992, occurred during one of the driest periods on record when the stream at W1H016 ceased to flow on many occasions. Consequently, it is possible that groundwater storage was an important factor. However, other estimates for 1992 indicate that the runoff only exceed 10% of the rainfall in the late summer. One individual storm that was found to exceed 10% of the rainfall occurred in November 1989 and produced 218 mm of rainfall that resulted in approximately 180515 m^3 of runoff for a runoff-rainfall ratio of 36%.

– RUNOFF ROUTING FROM W1H017 to W1H016

The weir at W1H017 was instrumented in 1994 to continuously monitor the runoff and selected water quality characteristics. This catchment has been identified as the probable third unit hydrograph (peak) in the discharge hydrograph for W1H016. The routing of flow between the two weirs is examined here.

The discharge from W1H017 was compared with the discharge from W1H016 (Figure 6.6) to determine any lag that could be attributed to translation and attenuation effects that may play a role in the investigation of the water quality response characteristics discussed in the next chapters. The lag correlation between the discharge from W1H017 and W1H016 for most storms showed a maximum r^2 at a lag that ranged from -1 to >10 hours for the various periods examined. However, the maximum was generally near zero lag (Figure 6.7). This implies that the discharge at W1H017 generally peaks at or near the peak in discharge from W1H016. Consequently, the discharge at W1H017 must then be associated with a peak after the main peak at W1H016 because the flood wave requires some time to travel along the >3000m of the stream channel to the weir at W1H016. Consequently, the third peak in the discharge hydrograph from W1H016 is again assumed to represent the conditions emanating from W1H017.

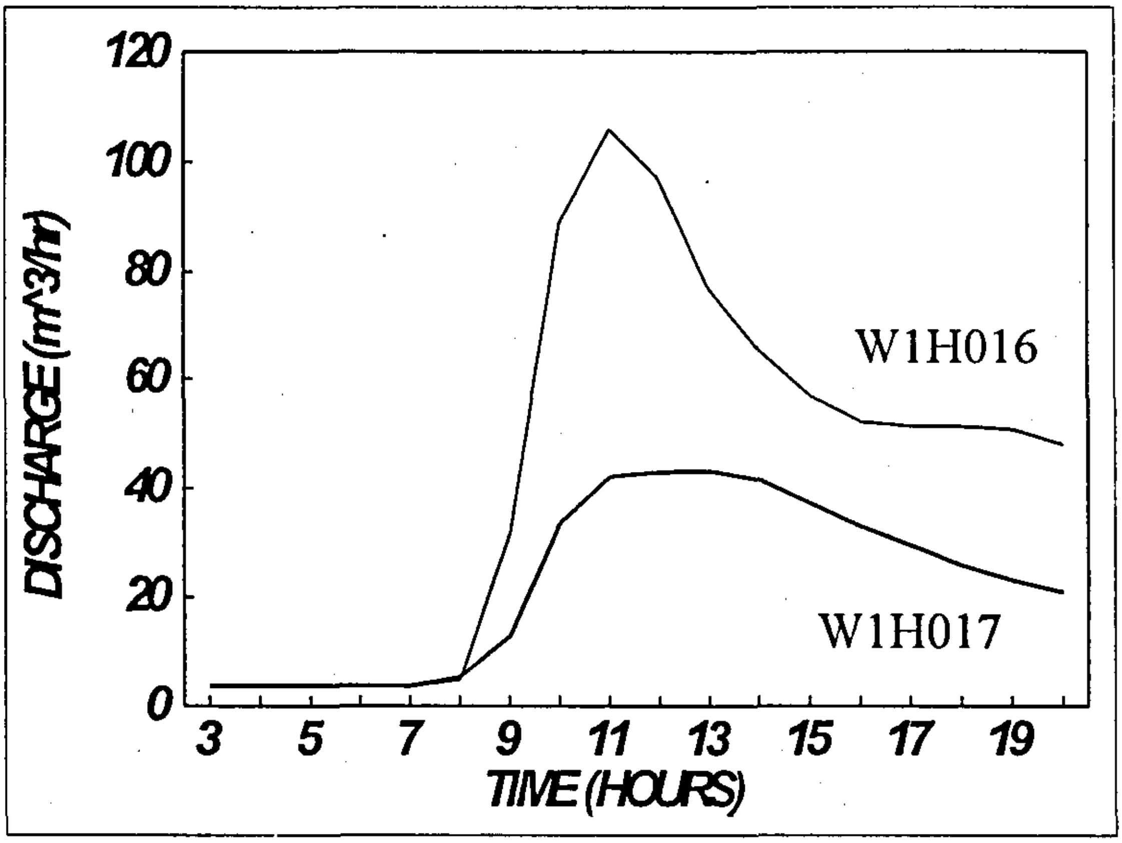


Figure 6.6 Example of simultaneous hydrographs from W1H016 and W1H031.

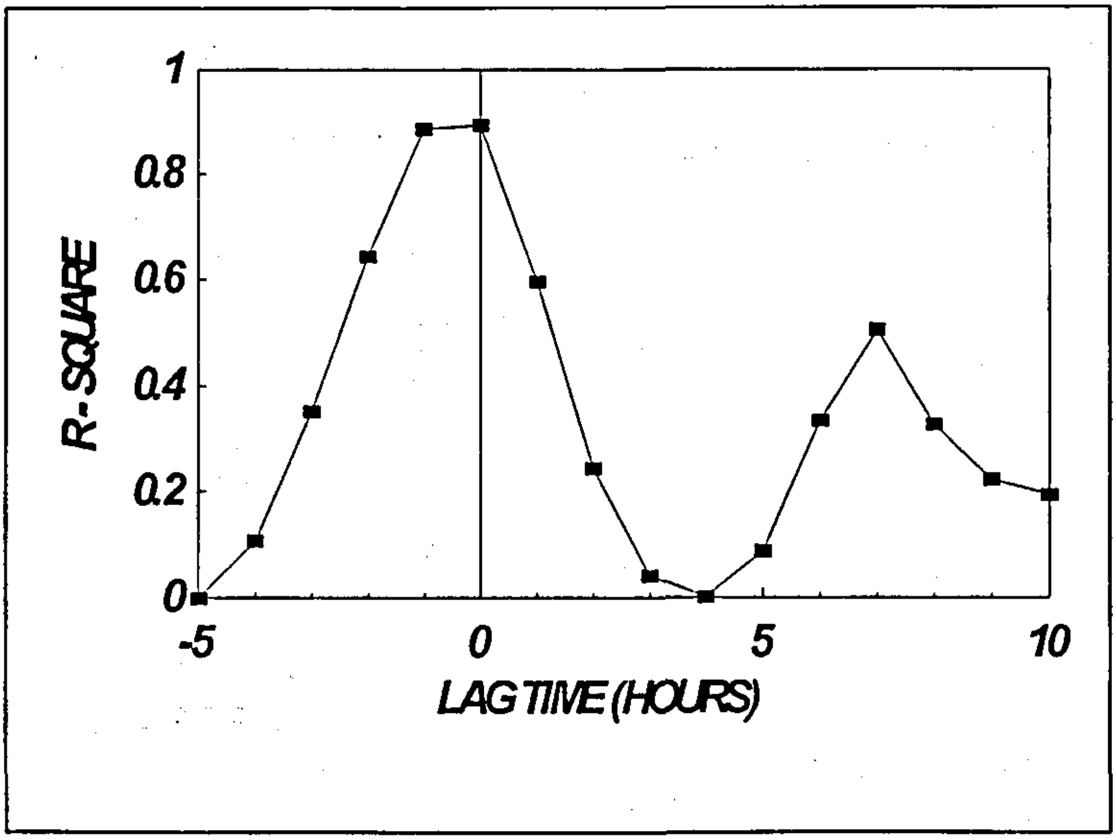


Figure 6.7 Correlelogram for the discharge from the storm in Figure 6.8

The third peak in the discharge hydrograph (Figure 6.3) was shown to lag the first peak by about five hours. If the lag time between the first and third peaks is five hours, then the estimated translation velocity from W1H017 to W1H016 is approximately 0.2m/s (10 m/min).

By separating the short duration, high intensity storms into distinct discrete components with their own hydrographs it may be possible to identify specific changes in the water quality characteristics of these storm discharge components (chemographs and sedimentographs) with specific areas of the catchment and hydrological processes. For instance, any rapid and systematic change in the conductivity or turbidity at a specific point in the hydrograph at W1H016 could be traced to a specific location in the catchment. Conversely, if specific land use practices produce a water quality response from short duration high intensity storms and the location of the contributing area can be linked to an associated point in the hydrograph then a response should be detectable at that point in the hydrograph. In order to detect where specific responses can be expected in the hydrograph of W1H016, Kelbe *et al* (1996) have used a Geographic Information System (GIS) and a Digital Elevation Model (DEM) to develop a numerical technique based on morphological characteristics of the catchment to examine the discharge hydrograph.

An example of the possible relationship between W1H017and W1H016 involving the translation effects is shown in Figure 6.8.

- The floodwave from W1H017 propagates along the channel to arrive at W1H016 as the third peak indicated in the upper right diagram of Figure 6.8.

- The floodwave from W1H017 arrives as the discharge from the other contributing catchments start to release sub-surface runoff with increased conductivity (upper middle Figure 6.8) which is diluted slightly with the arrival of the flood from W1H017.

- The pH drop after the initial peak is maintained and may decline slightly when the discharge from W1H017 arrives after which it starts to recover slowly.

- The turbidity at W1H017 is estimated to be low and this is reflected in the very rapid decline in turbidity at W1H016 (bottom right of Figure 6.8).

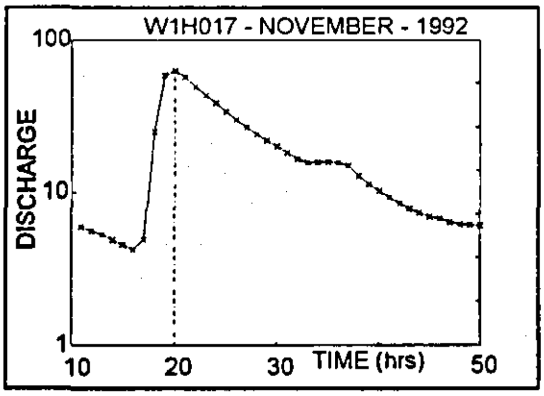
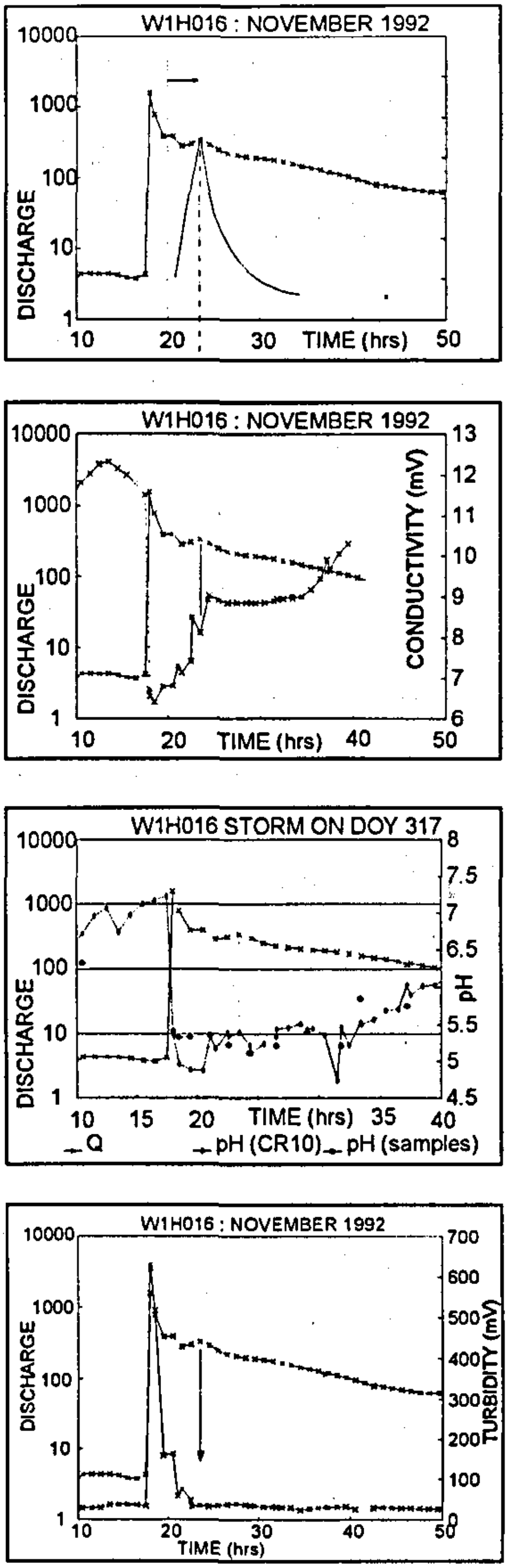


Figure 6.8 Example of the proposed response at W1H016 from the translation of a floodwave from W1H017. TOP graphs are the storm hydrograph at W1H017 and W1H016. Right hand graphs are the associated changes in conductivity, pH and turbidity. The vertical dotted line in these three graphs indicate the estimated temporal position of the routed discharge from W1H017 and the associated changes in the water quality characteristics due to the routed flow. This example shows some changes in conductivity but no discernable changes in pH or turbidity which could be due to the flow from W1H017.



7 STORM ANALYSES

The primary aim of the project was to examine the relationships between certain water quality components of the discharge and the corresponding hydrological processes identifiable in the discharge hydrograph from small rural catchments. The general features of the water quality have been examined in Chapter 5 while the main features of the discharge have been presented in Chapter 6. Differences between the two main catchment areas monitored in this project (W1H016 and W1H031) were identified in both the discharge hydrograph and certain water quality factors which have been related to physiographic features and land use management practices. The same two catchments are examined here for more specific and consistent relationships between the water quality variations within storm events.

In order to examine the relationship within a storm, the temporal resolution had to be sufficient to provide several observations that could identify the main characteristics of the individual hydrological processes. The main processes which are considered in this analyses are the surface runoff, the inter-flow and the base-flow. The continuous monitoring instrumentation system (Chapter 3) provided hourly averages of 10 second readings of measurements for analyses in this section. It also recorded the time of occurrence and the magnitude of all daily maxima and minima of the measurements.

Certain water quality properties of the runoff from catchments have been related to hydrological processes by researchers in other studies and these relationships were examined for the two main catchments in this study. General relationships that were observed in many of the storm events are presented here with examples for each water quality factor. However, there were examples of storm characteristics that did not adhere to the general observed relationships and these "anomalies" or atypical events are examined in a subsequent chapter where possible explanations for their departure from the expected relationships are presented.

7.1 STORM EVENTS

While there were many isolated storms that were monitored during this project, there were occasions when there were instrument failures and other problems with accessibility and data collection that restricted the number of physical and chemical factors available for analysis for some of these storms. There was a drought for several years in the middle of the project that resulted in very few storms from 1991 to 1993. However, 29 storms were identified as isolated events during this project (Table 7.1). Not all of these storms were derived from short duration, high intensity rainfall conditions as the maximum rainfall rate and the time to peak indicate. There is a large range in the peak discharge rates that vary from 18 205 m^3/hr to some storm events with less than 50 m^3/hr. The time to peak discharge (TTP) is also very variable and ranges from one hour to more than half a day. The peak rainfall rates given in Table 7.1 show some large differences between sites for the same storm events. Consequently, not all storms are ideal for evaluating the relationship between selected water quality factors and specific hydrological processes. Analysis in this section has been restricted to short duration storms (generally TTP < 5 hrs) with peak discharge between 1000 and 10 000 m^3/hr.

There are some observed trends in water quality factors during storm events that indicate a general relationship between the selected water quality features and hydrological processes for certain storm conditions. These trends are identified as being associated with specific conditions in the discharge hydrograph. These typical characteristic relationships are examined for some of the selected storm events from the two research catchments (W1H016 and W1H031) in this section. However, the two catchments exhibit differences in their relationships that are ascribed to the differences in land-use practice. Some storms exhibit anomalies when compared with these typical conditions and these are examined separately in Chapter 8, where an attempt is made to explain the cause of their deviations from the general relationships presented in this chapter.

Table 7.1 Peak values of runoff (Qmax : m^3/hr), Time to Peak (TTP : hr) and Rain (mm/hr) for storms from catchments W1H016, W1H017 and W1H031.

Storm Date (DOY)	W1H016			W1H017			W1H031		
	Qmax m^3/day	TTP hrs	Rain mm	Qmax m^3/day	TTP hrs	Rain mm	Qmax m^3/day	TTP hrs	Rain mm
61-92	550	6	33	?	?	?	298	6	15
305-92	41	6	15	?	?	?	?	?	?
317-92	879	2	21	62	3	20	272	3	29
328-92	66	16	3	12	1	?	?	?	?
347-92	44	4	11	15	6	9	104	13	13
74-93	4	6	13	98	4	27	985	3	22
267-93	724	1	24	?	?	12	68	4	?
272-93	164	8	2				287	12	?
274-93	158	4	26				312	7	?
278-93	3053	8	?	693	7	?	11800	19	?
317-93	1563	1	36	?	?	?	150	18	5
337-93	1054	8	12	155	9	7	1660	8	14
343-93	763	15	22	193	?	20	1136	15	15
356-93	165	12	10	13	10	?	352	7	11
363-93	2107	7	32	1105	3	23	4118	3	30
10-94	948	7	22	369	4	4	3682	3	52
21-94	811	7	22	502	3	40	1355	4	36
35-94	4294	3	31	1512	3	?	?	?	?
69-94	134	12	4	123	3	15	195	6	12
86-94	?	?	7	24	8	7	117	8	11
89-94	223	3	?	188	4	16	618	5	16
60-95	738	9	30	1036	3	36	4115	4	39
100-95	13223	5	62	3904	3	36	18205	6	28
168-95	2500	35	10	408	6	?	2745	30	?
10-96	1198	4	26	265	8	16	?	?	?
13-96	3921	4	7	2431	6	31	5541	6	20
17-96	7020	4	18	2856	2	33	7310	4	31
20-96	?	?	?	305	4	6	1481	8	6
27-96	?	?	?	1717	7	12	6999	10	17

7.2 CONDUCTIVITY (TDS)

Electrical conductivity (mS cm^{-1}) of the discharge during storm events have been examined for consistent trends that can be linked to features of the hydrograph. Particular emphasis was made to identify an association with surface or sub-surface hydrological processes. Matsubayashi *et al* (1993) suggest that conductivity could be used as a natural existing tracer to separate flowpaths in spite of its inherent instability. The main advantages over other foreign tracers (*eg* isotopes of oxygen) is that it is relatively cheap and easy to monitor on a continuous basis. It is used here to examine those storm events that indicate some evidence of surface- and subsurface-flow. However, antecedent storm conditions and the flowpath of the water (*ie* contact time with soil) as it moves through the system have a strong bearing on the conductivity response to a rainfall/runoff event (Matsubayashi *et al* (1993) and need to be considered in the analyses.

In nearly all storm events with surface-flow (Q), there was a definite drop in the electrical conductivity of the runoff **immediately** the discharge rate started to increase (see the examples in Figure 7.1 for both catchments). The conductivity reached a minimum value at almost the same time as the peak flow. The conductivity then started a recovery that often occurs at two different rates (see Figure 7.1). The initial recovery rate immediately after the peak discharge is very rapid in some cases, particularly for W1H031 (Figure 7.1b). It is generally slower than the initial decline rate, particularly for W1H016 (Figure 7.1a). From visual observations of the recession limb of the storm hydrograph, it appears that the discontinuities in the slope (rate of change) of the conductivity recovery curve coincide with discontinuities in the storm recession hydrograph. These discontinuities in the runoff hydrograph can be associated with cessation of surface- and through-flow conditions when base-flow becomes the dominant mechanism of discharge (see Figure 2.1).

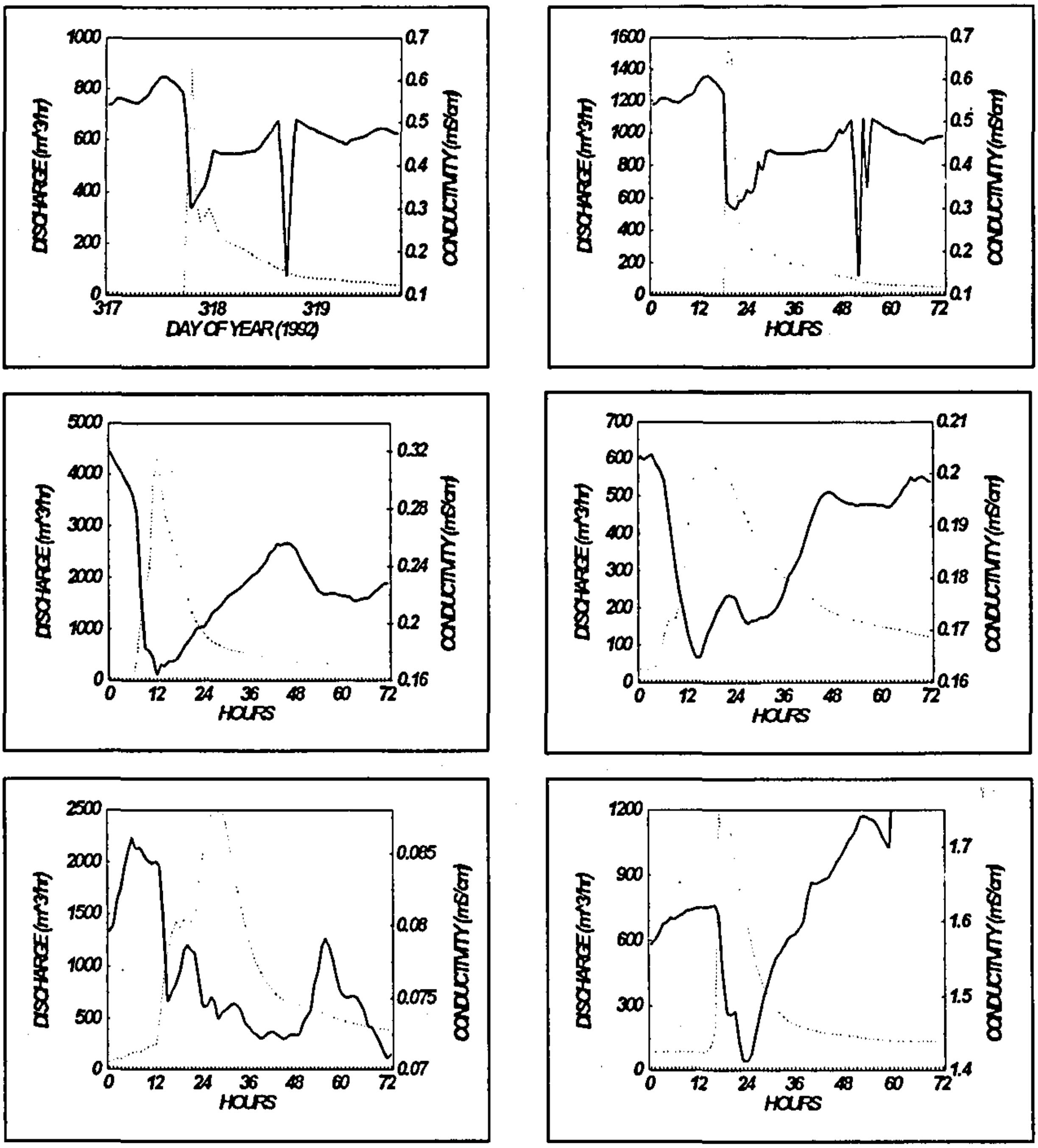


Figure 7.1a Examples of selected storm events for **W1H016** showing the discharge hydrograph (...) and the associated changes in **conductivity** (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 12 Nov 1992 (2) 13 Nov 1993

(3) 4 Feb 1994 (4) 23 Oct 1994

(5) 17 Jun 1995 (6) 10 Jan 1996.

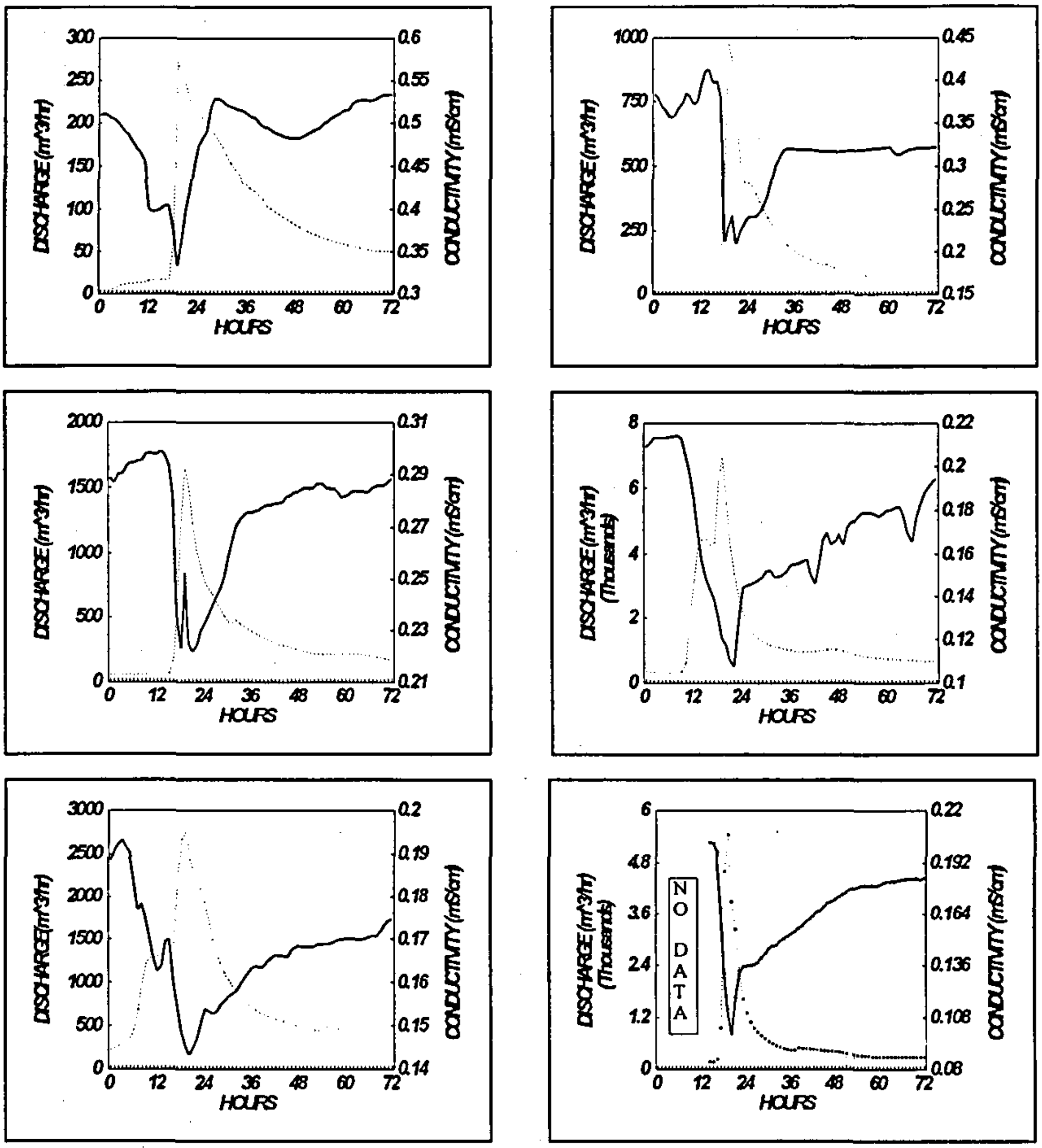


Figure 7.1b Examples of selected storm events for **W1H031** showing the discharge hydrograph (...) and the associated changes in **conductivity** (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 12 Nov 1992 (2) 15 Mar 1993

(3) 21 Jan 1994 (4) 27 Jan 1996

(5) 13 Feb 1996 (6) 15 Jun 1995.

The recovery rate of conductivity is often composed of two components. The initial recovery is usually associated with the surface-flow. The subsequent recovery rate is associated with sub-surface flow. This rate of recovery to pre-storm conditions varies considerably between storm events. For the larger storms (*ie* where the Qmax > 5000 m^3/hr.) the recovery is much slower than other storms (see large storm in Figure 7.1a [#3] where the discharge < 4000 m^3/hr). This is probably due to the large volume of rainfall that is forced through the system causing continual dilution of the Total Dissolved Solids after surface flow ceases.

Selected storm events for the two research catchments (W1H016 and W1H031) have been presented in Figure 7.1a & 7.1b. A typical relationship for changing conductivity during a storm event with surface runoff is proposed in Figure 7.2. Because the rainfall has a very low conductivity (see Table 5.1 & 5.2) there is an immediate dilution with the increase in channel flow that is associated with

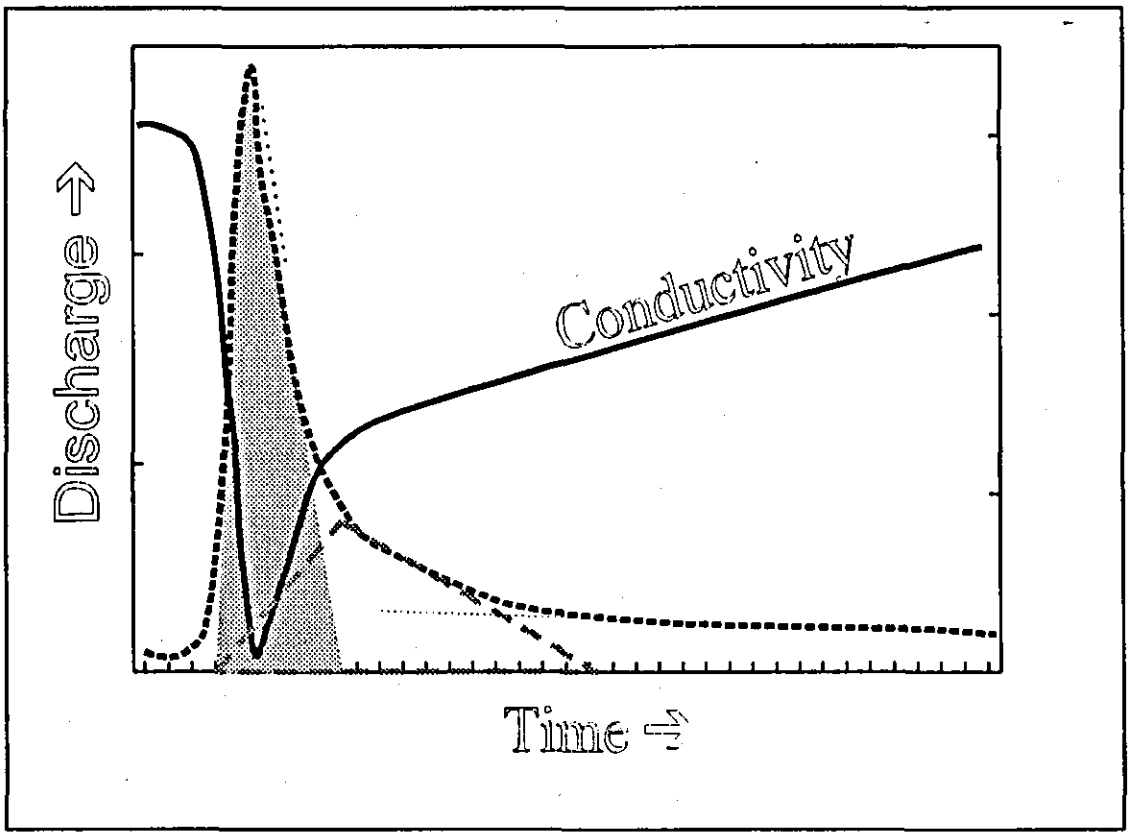


Figure 7.2 Typical Conductivity changes during short duration, high intensity storm.

the surface runoff of rainfall. The peak in runoff coincides with the minimum in conductivity and is due to "new water" derived directly from rainfall. Following the peak discharge, the recession in the surface runoff coincides with increasing sub-surface flow which has a higher concentration of dissolved solids. This produces a corresponding increase in conductivity associated with the mixing of the "new (rainfall)" and "old (subsurface)" water. The recovery in conductivity to pre-storm conditions becomes slower at the point where surface runoff is replaced by subsurface flow conditions (either inter-flow or base-flow conditions). Comparison between individual storm events suggests that the rate of recovery to pre-storm conditions is also dependent on the size of the storm event.

7.3 VARIATION IN STORM pH

The changes observed in the pH during the passage of a short duration high intensity storm, in some cases, appear to be very similar to the typical changes observed in conductivity described above. However, the variability in the continuous pH measurements is considerably higher than the variability observed in conductivity measurements. Generally, the continuous pH measurements show a drop immediately or very soon after the rise in discharge (Figure 7.3). The pH reaches a minimum value somewhere during the rising limb of the discharge hydrograph or near the peak flow rate. The recovery of the pH values is often very rapid and in some case reaches the pre-storm conditions almost immediately (see Figure 7.3a [#3 & #5]). In a few cases in W1H031, the initial drop in pH appears to be slightly delayed relative to the discharge and conductivity responses (see Figure 7.3b [#1 & #3]). The minimum pH also varies considerably, exhibiting extreme values prior to the peak discharge (see Figure 7.3a[#3]), at the peak discharge (see Figure 7.3a[#6]) and after the peak discharge (see Figure 7.3b[#1]). However, the variability in pH during and between storms is usually very large and this makes it difficult to characterize the response with any certainty.

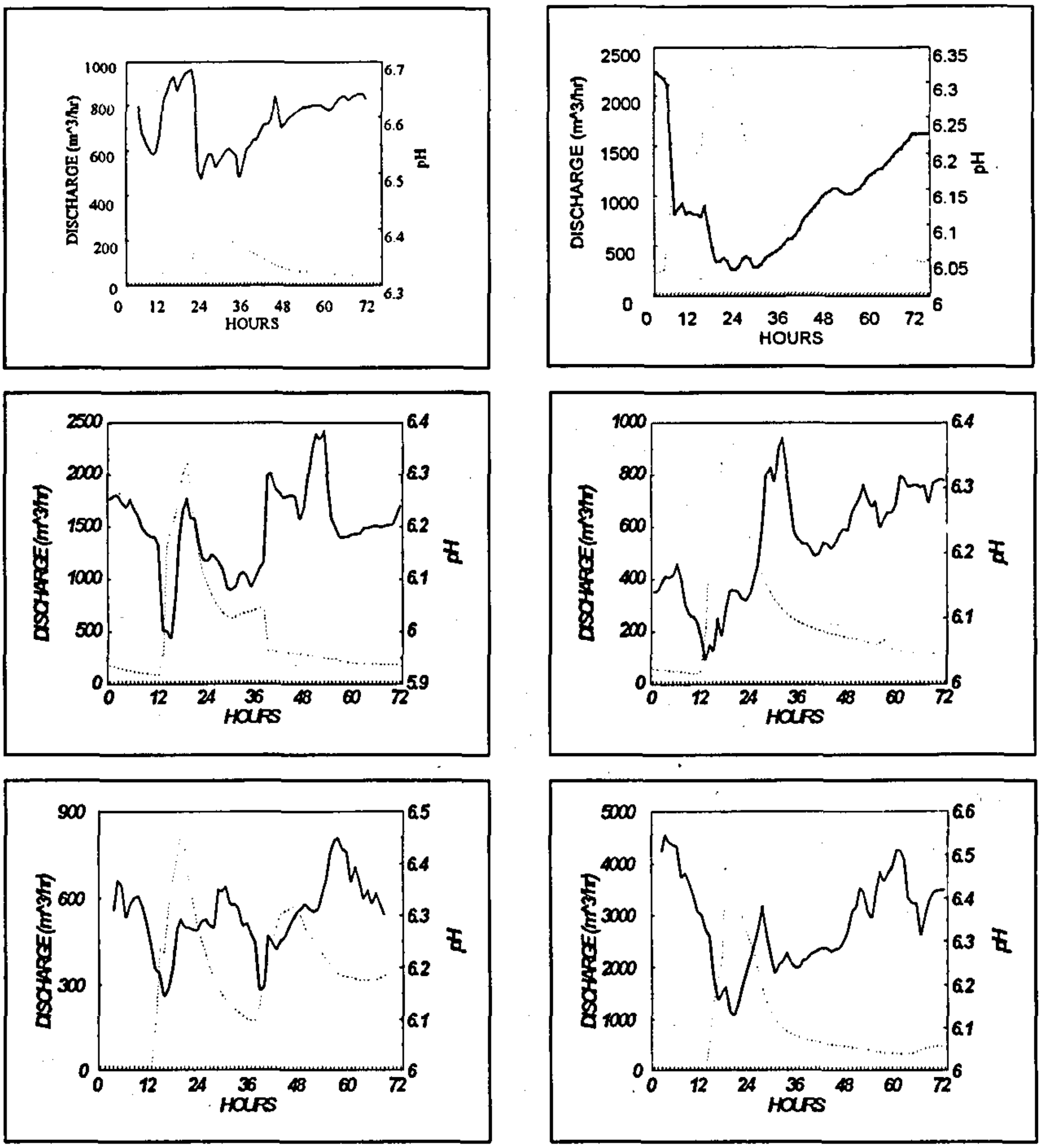


Figure 7.3a Examples of selected storm events for **W1H016** showing the discharge hydrograph (...) and the associated changes in pH (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 12 Nov 1992 (2) 17 Jun 1995
(3) 29 Dec 1993 (4) 10 Jan 1994
(5) 21 Jan 1994 (6) 4 Feb 1994.

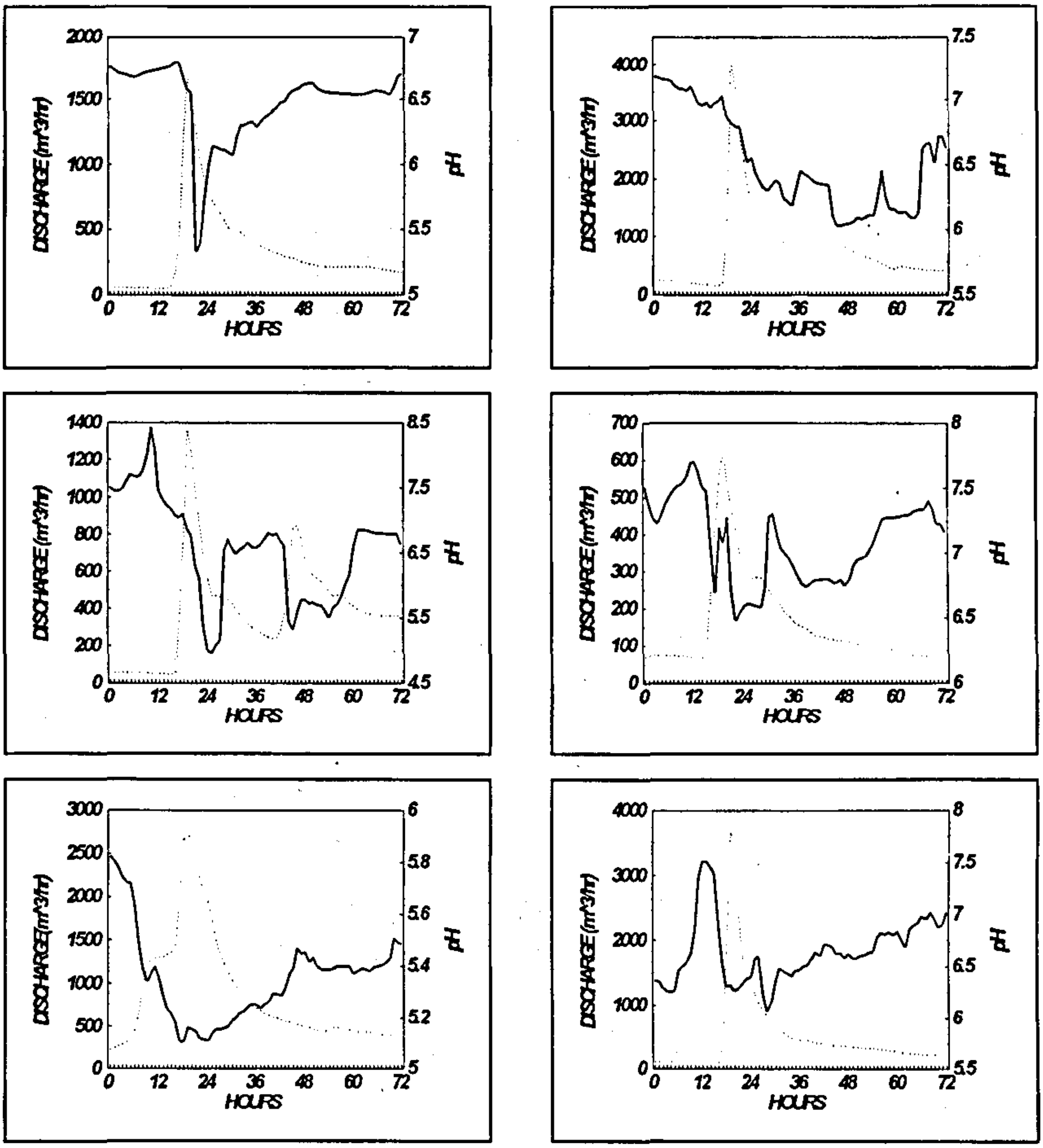


Figure 7.3b Examples of selected storm events for **W1H031** showing the discharge hydrograph (...) and the associated changes in pH (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 3 Dec 1993 (2) 29 Dec 1993

(3) 21 Jan 1994 (4) 27 Jan 1996

(5) 30 Mar 1995 (6) 10 Jan 1994.

7.4 TURBIDITY

There is a well defined relationship between the changes in turbidity and the short duration, high intensity storm events which exhibit surface-flow conditions. The continuous measurement system (infrared attenuation system) shows turbidity values in W1H031 (undisturbed catchment) which are generally a factor of two or more lower than those in W1H016 (rural subsistence settlements). The less turbid discharge from W1H031 shows greater variability in observations because of the lower values. However, both catchments exhibit a well defined relationship. The turbidity for short duration, high intensity storms, shows a short, sharp peak that coincides exactly with the FIRST indication of surface runoff of "new" water (Figure 7.4). There are small deviations that are caused by differences in the intensity or duration of the storm events. In some cases :-

- for storm events with a peak discharge (Qmax) exceeding about 500 m^3/hr there is usually an indication of surface-flow and the turbidity shows the short, sharp peak that returns to pre-storm conditions almost immediately surface-flow ceases.

- for storms with Qmax < 500 m^3/hr the turbidity peaks are erratic and sometimes show additional peaks with subsequent storms (discharge peaks). In these cases the subsequent peaks may be an indication that the initial storm event was insufficient to cause all the suspended sediment to be transported from the small catchments and the subsequent storm event, occurring on a saturated surface, provided an additional suspended solids transport mechanism.

- for single hydrographs with multiple peaks (from extended or multiple rainfall events/cells) there were seldom any indications of a turbidity peak associated with any of the second or subsequent peaks in spite of the probability that there was surface flow with these subsequent events.

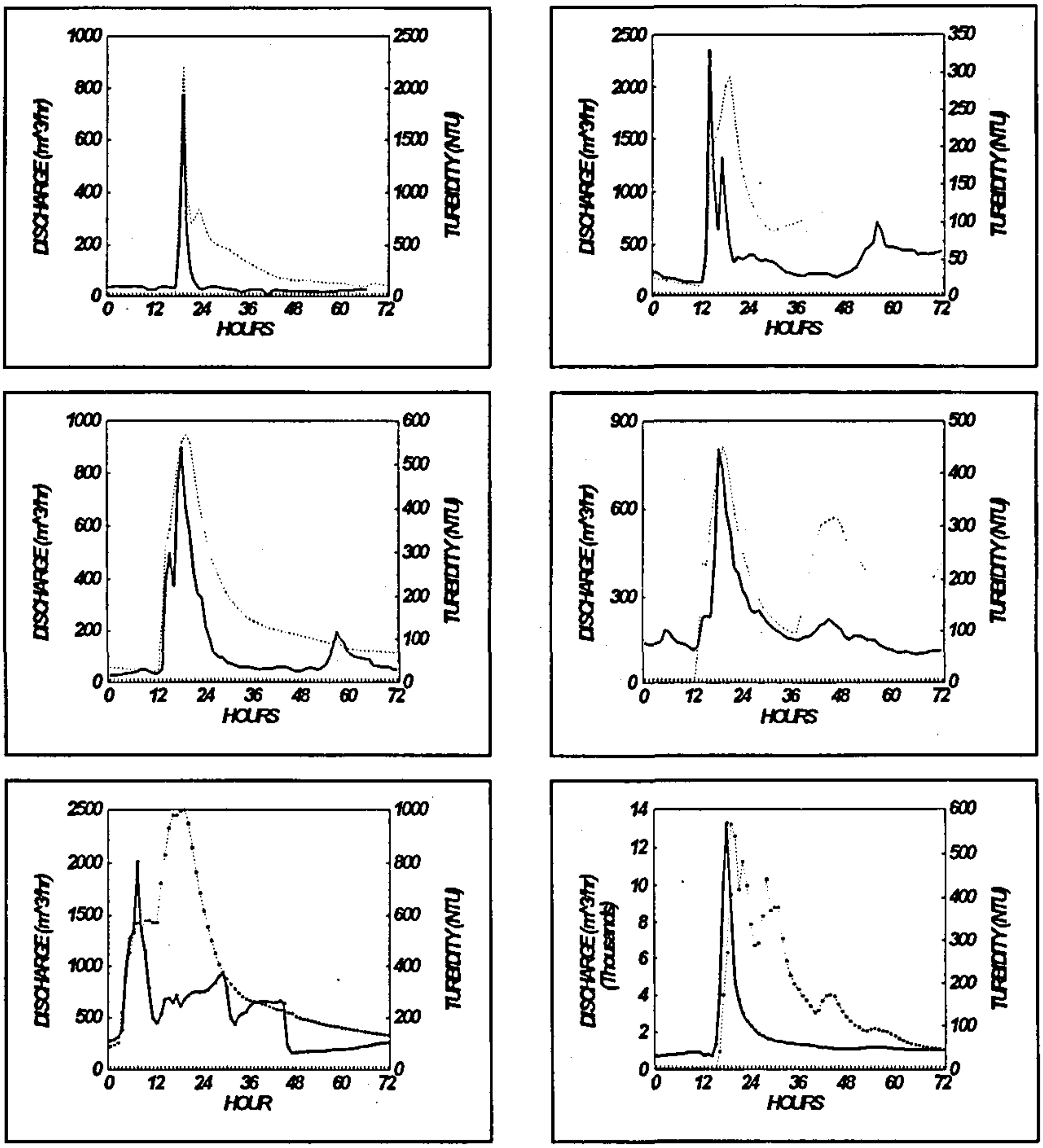


Figure 7.4a Examples of selected storm events for **W1H016** showing the discharge hydrograph (...) and the associated changes in **turbidity** (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 12 Nov 1992 (2) 15 Mar 1993

(3) 21 Jan 1994 (4) 27 Jan 1996

(5) 13 Feb 1996 (6) 15 Jun 1995.

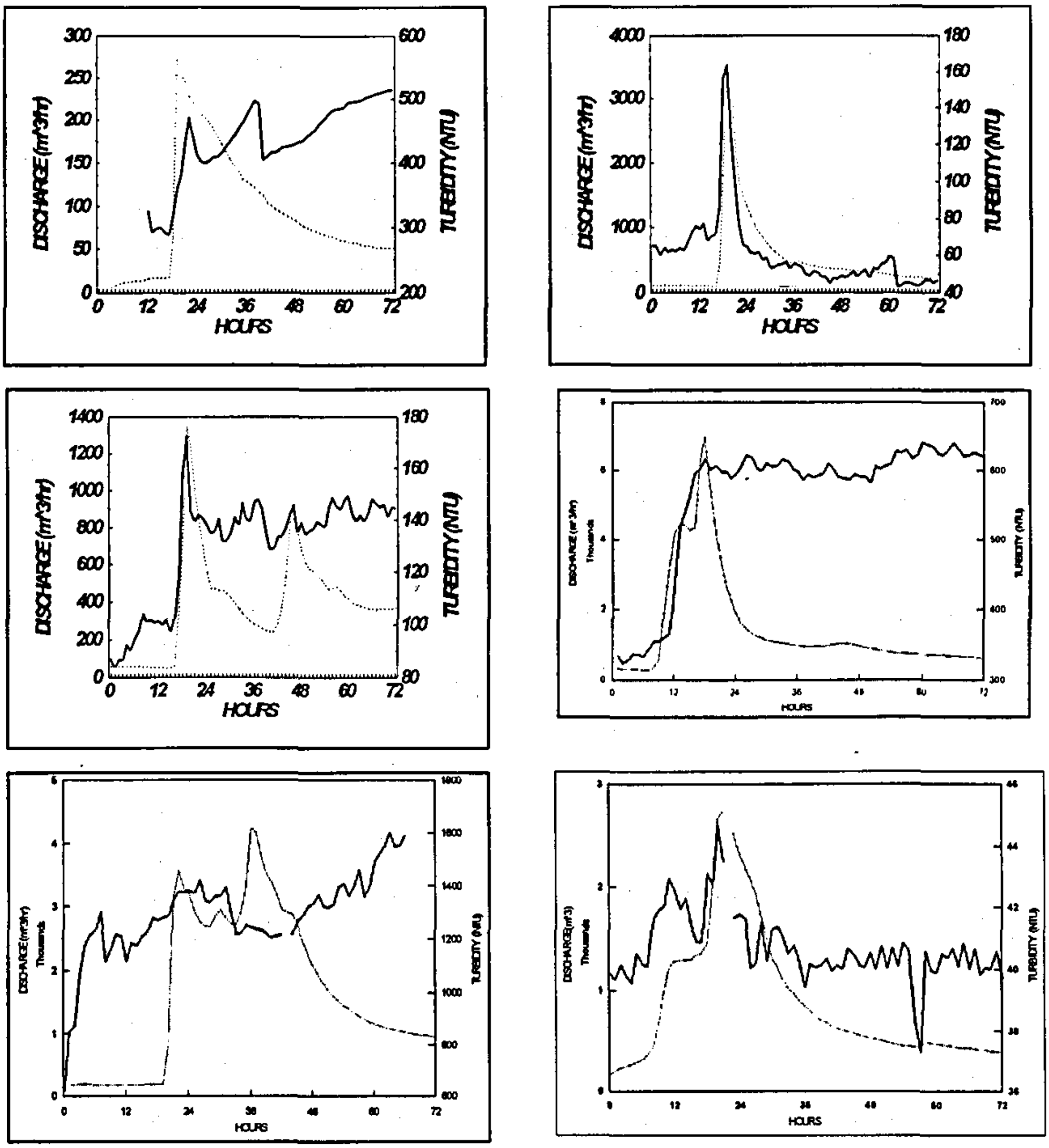


Figure 7.4b Examples of selected storm events for **W1H031** showing the discharge hydrograph (...) and the associated changes in **turbidity** (—) for storm events on the following dates (left to right, top to bottom) :-

(1) 12 Nov 1992 (2) 15 Mar 1993

(3) 21 Jan 1994 (4) 27 Jan 1996

(5) 13 Feb 1996 (6) 15 Jun 1995.

A typical relationship between the runoff hydrograph and turbidity for short duration, high intensity storms is shown in Figure 7.5. This typical turbidity relationship generally occurs with the first part of multiple peak storms and is seldom present with subsequent storms that occur immediately after the first storm event. This carryover effect is often observed within the same storm event for W1H016 where the third peak is not associated with sediment export (see Figure 7.4a[#1 & #6]).

There were insufficient storm events that displayed the triple peak hydrograph discussed in Chapter 5 for W1H016. Consequently, the contribution of sediment from the three sub-catchment areas, particularly from W1H017, could not be examined in detail. Figure 7.4a [#1] suggests that no sediment was transported from W1H017 to W1H016. The other storms in Figure 7.4a show a reduced turbidity with the later part of the recession limb that may support this theory.

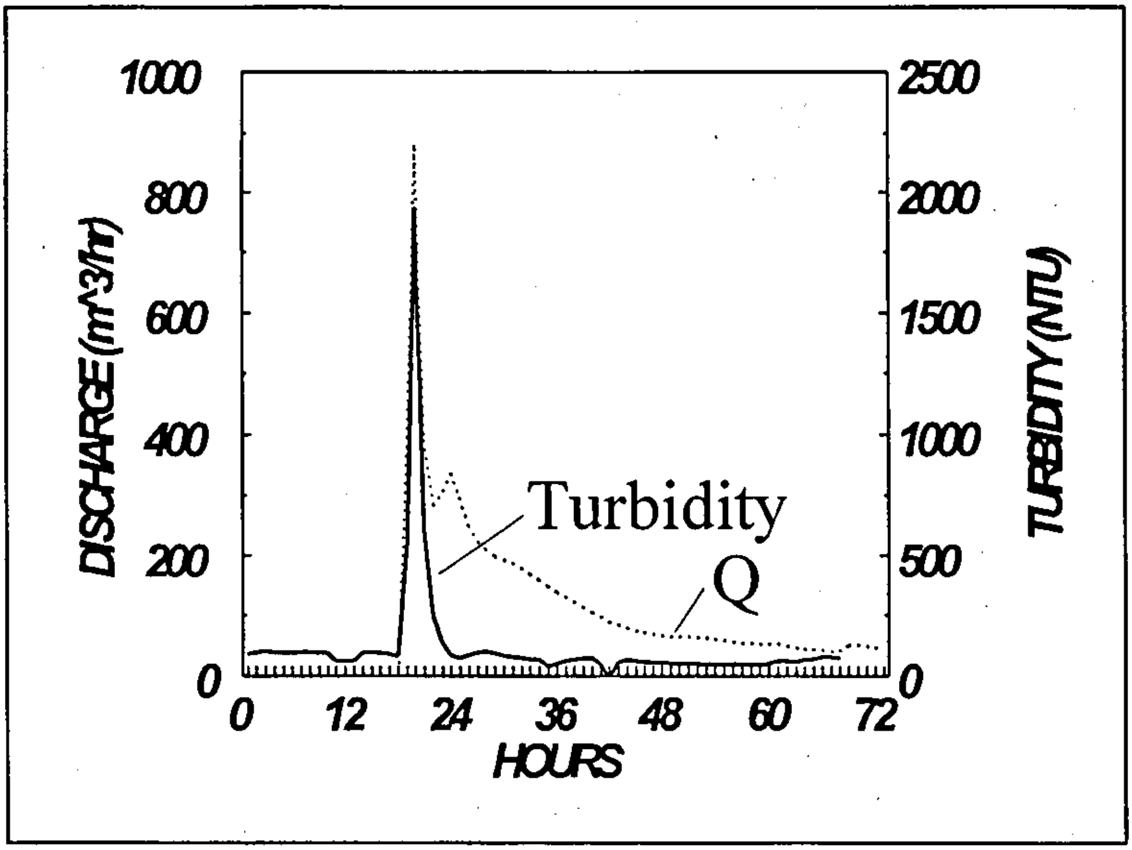


Figure 7.5 Example of variation in turbidity for short duration high intensity storm events.

7.5 NITRATES

Nitrogen in the natural environment exists in several forms and their interactions are generally described by the nitrogen cycle. The nitrogen cycle is complex and involves compounds that have various sources and sinks that are affected by interactions causing fixation, (de)nitrification and leaching (Figure 7.6). These processes are generally dominated by the organic matter component and the application of fertilizers (Fitter and Hay, 1981). In the natural catchment (W1H031) there is no application of fertilizers but there is some application in the sugarcane sector in W1H016.

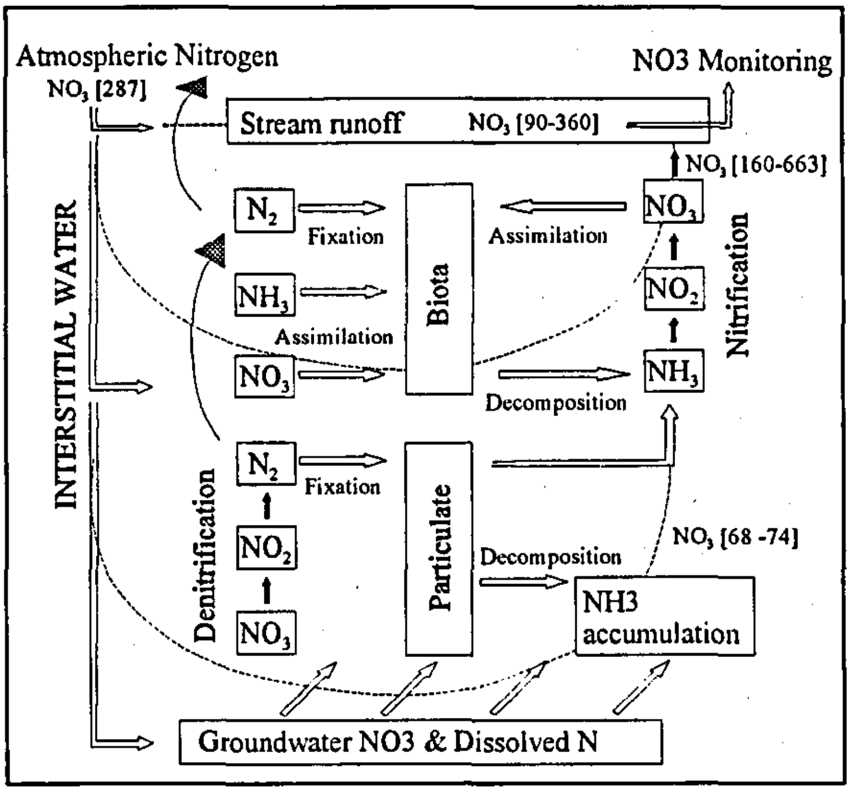


Figure 7.6 Diagrammatic representation of the nitrogen cycle.

Nitrogen in the form of N_2 and NH_4 is volatile. Previous studies (Simpson, 1992 and Kelbe *et al*, 1992) have indicated very low concentration of NH_4 in these research catchments (Table 1.1). Consequently, this project has only concentrated on the changes in nitrates (NO_3) which have shown relatively large changes during storm events.

The nitrate analysis presented here is based entirely on flow related grab samples of rainfall and runoff that seldom have the required temporal resolution to identify the changes sought in this study. The sampling frequency was set to initiate a grab sample every 2000 m^3 of discharge from the weir. This caused insufficient samples for small storm events where the **peak** discharge was less than 1000 m^3/hr, and too many samples covering only a portion of the hydrograph for the larger storms because it was not possible to change the sample bottles during the event when roads were inaccessible. Nevertheless, an attempt is made to link changes in nitrate concentration with hydrological processes.

7.5.1 PREVIOUS STUDIES

The nitrate concentrations are very low in comparison to other catchment studies (Simpson 1992). This makes it difficult to quantify the general trends because many samples have values close to the detection limit of the instrumentation used for the study (see chapter 3). However, the variations in the nitrate concentrations do give an indication where there are significant changes in concentration and where the peak may occur in relation to the changes in the discharge hydrograph.

Kelbe *et al* (1992), using flow related grab samples, compared the hydrological response of the two research catchments by separating the flow regime for several storms into the rising limb, peak flow and recession stages of the hydrograph. The <u>mean</u> water quality characteristics for each flow regime for several storm events are reproduced in Table 7.2. The separation of the flow into the four stages of the hydrograph were based on subjective assessments of the flow regime. However, the results indicate that the nitrate concentration generally increases from base flow values of 70 µg/l to values exceeding 600 µg/l during the storm event, particularly for the disturbed catchment.

Table 7.2 Mean sample characteristics for different flow regimes from Kelbe *et al* (1992).

Water quality factor for research catchments	Rain	Rising Limb		Peak flow		Recession		Base flow	
		W31	W16	W31	W16	W31	W16	W31	W16
pH	5.8	6.4	6.7			6.2	6.5	6.7	6.8
Conductivity (mS/m)	5.6	15.5	15.4	15.1	12.1	12.2	12.9	16.3	16.3
Turbidity (NTU)		9.5	21.4	14.0	36.0	11.7	33.0	5.1	11.6
Susp Solid (mg/l)		112	144	137	325	70	156	51	98
Phosphate (µg/l)		9.5	17.3	11.5	16.5	8.5	13.2	9.9	25.2
Nitrate (µg/l)	122	92	360	179	166	162	663	74	68
# samples/set		34	34	6	6	9	9	17	17

NB *peak flow was for samples subjectively linked (within several hours) to the peak*

Rainfall is a potential source of nitrates which could have an influence on the changes in concentration associated with discharge hydrograph. The nitrate concentration of the rainfall varies from 122 µg/l in previous studies to 287µg/l for the 15 samples per site collected during this study. These mean values are more than double the base flow concentrations for both catchments (Table 7.2). However, it is considerably less than the peak concentrations found in W1H016 for the recession limb components of discharge but it is generally close to the rising limb and peak values found for both the disturbed and undisturbed catchments.

7.5.2 TYPICAL STORM EVENTS

The variations in nitrate concentrations within selected storm events for both W1H016 and W1H031 are given in Figure 7.7. These events were chosen because they are considered to be associated with surface flow conditions and because they had a sufficient number of grab samples to give an indication of the changes in concentrations over the storm event.

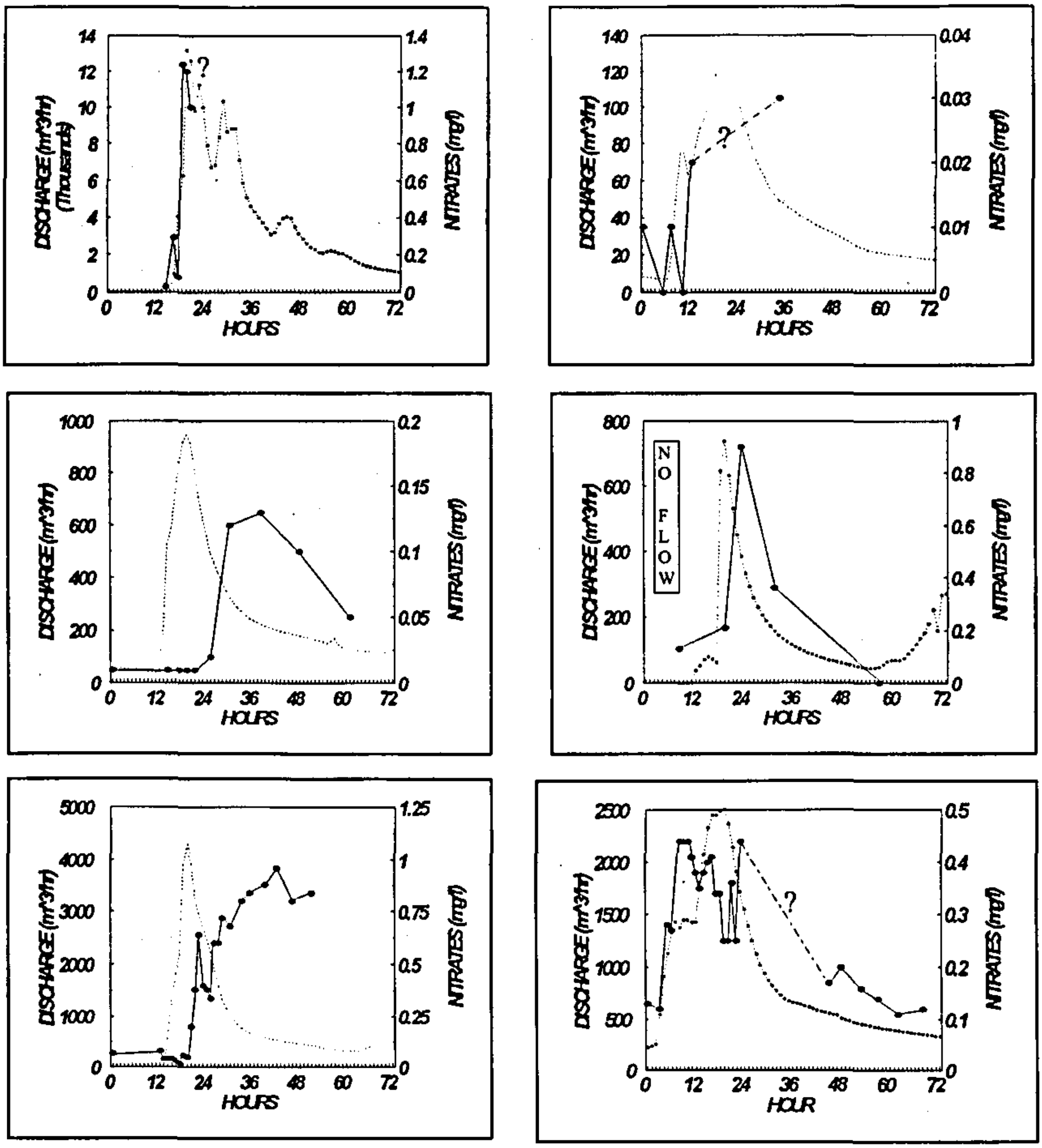


Figure 7.7a Examples of selected storm events for **W1H016** showing the discharge hydrograph (...) and the associated changes in **nitrate** concentration (—) for storm events on the following dates, (left to right, top to bottom):-

(1) 10 Apr 1995 (2) 10 Mar 1994

(3) 10 Jan 1994 (4) 1 Mar 1995

(5) 4 Feb 1994 (6) 17 Jun 1995

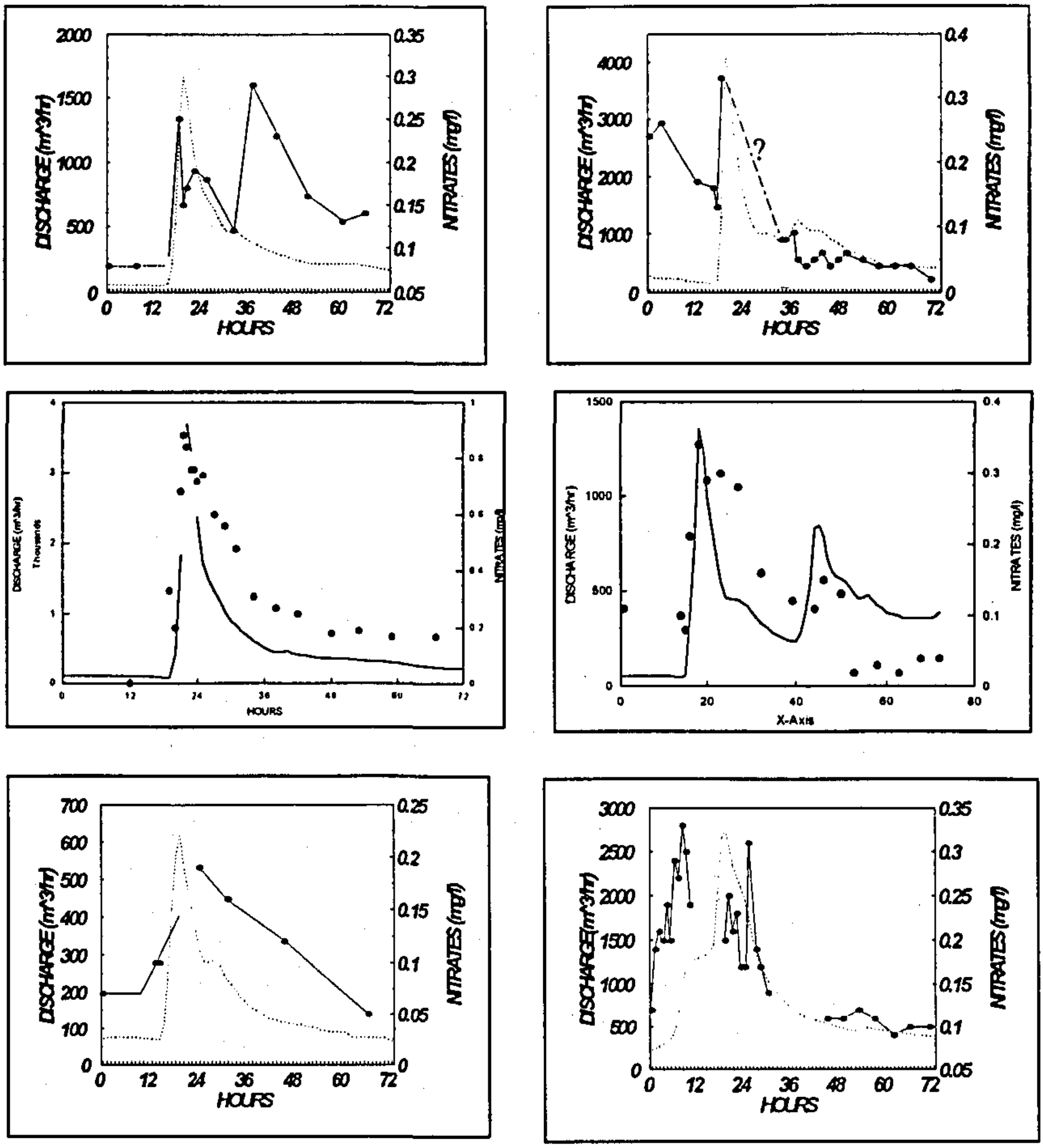


Figure 7.7b Examples of selected storm events for **W1H031** showing the discharge hydrograph (...) and the associated changes in **nitrate** concentration (—) for storm events on the following dates, (left to right, top to bottom):-

(1) 3 Dec 1993 (2) 29 Dec 1994

(3) 10 Jan 1994 (4) 21 Jan 1994

(5) 30 Mar 1994 (6) 17 Jun 1995

The changes in nitrate concentrations shown in Figure 7.7 indicate distinct differences between the two catchments during a storm event. The concentrations in W1H016 are generally higher than the corresponding values in W1H031. This difference in export loads varies with seasons (Figure 5.22 & Figure 5.23) and between storm events (Figure 7.7). However, there are several similarities in the temporal trends of both catchments for many storms.

In all the W1H031 storm events and in many of the storm events in W1H016, the concentration in nitrates increases with increasing discharge. Pre-storm (base flow) conditions have low concentrations which are generally much lower than the range of concentrations found in the rainfall. Most of the peak concentration values in the undisturbed catchment (W1H031) are comparable to the concentrations in the rainfall. They also appear to rise in conjunction with the rise in discharge. Since the rising limb of the hydrograph has been associated with surface runoff and "new" water (rainfall), the increase in nitrates are assumed to be derived directly from the rainfall and enhanced by some surface sources in the undisturbed catchment (W1H031).

There are cases of higher nitrate concentrations observed in several storm event for the disturbed catchment (W1H016) when compared to the undisturbed catchment. If the nitrate loads in the natural catchment (W1H031) are derived from the rainfall then the increased concentrations in the disturbed catchment (W1H016) must be derived from additional surface sources. The highest concentrations are associated with the largest storm events (see Figure 7.7a [#1]) or events with very dry pre-storm conditions (see Figure 7.7a [#4]). The large storm events are assumed to have the greatest proportion of overland flow contributions to the runoff and therefore the largest proportion of contamination by surface accumulations of nutrients. Since the nitrate concentration have decreased values for pre- and post storm conditions (base flow) in nearly all cases, the subsurface contributions to nitrates in these catchments is minimal for typical storm events.

The results of these analyses suggest that the largest export occurs in the disturbed catchment with subsistence agriculture from surface runoff processes. Unfortunately the flow related sampling method does not have sufficient temporal resolution to determine if there is any difference in export from the three sub-catchment areas associated with the three peak discharges in the discharge hydrograph. However, the flow path and land use contributions to the runoff hydrograph are discussed in more detail by Kelbe *et al* (1996).

7.5.3 DEVIATIONS FROM THE TYPICAL EVENT

There are three storm events in W1H016 (shown in Figure 7.7a [#3], [#4] and [#5]) where it is clear that the peak nitrate concentration occurred several hours AFTER the peak discharge. All three events show an initial flow impulse followed by the main storm event. The pre-storm conditions may have a direct effect on the delayed response. However, in these three events the nitrates do not appear to be associated with the quick flow conditions linked to the peak discharge rates and surface processes. They occur **after** the peak in discharge and must be associated more with subsurface conditions. Since, the pre-storm nitrate conditions are very low in nearly all events, the rise in concentrations after the peak must be associated with the inter-flow conditions rather than the base flow conditions. The electrical conductivity for the first two storms also shows a delayed response of about 20 hours before reaching a minimum value but the third example has a typically rapid decrease in the recession rate of conductivity.

7.5.4 SEDIMENT & NITRATE

The nitrate concentrations were also observed to be significantly higher after the peak in **turbidity** (discussed in section 4.3.2 (Table 4.3)) for a specific storm on DOY 100, 1995. Since the peak in turbidity generally corresponds with the peak in discharge, this difference in nitrates between the two limbs of the sediment graph also reflects the difference between rising limb and recession limb. This increase in nitrate concentrations in the recession limb is observed for both catchments (Table 7.2). However, because of the rapid changes in concentrations from onset to cessation of both the rising limb and the recession limb, the average values may include inherent errors caused by sample size. Nevertheless, the differences indicate that the increase in concentration after the peaks could be associated with the increased source of turbidity (assumed to be suspended sediments) or the increased dissolved solids (conductivity). The increased nutrient loads in the recession limb could be associated with a combined impact of nitrogen from surface sources. Unfortunately, improved sampling is required to distinguish between these surface and subsurface processes.

7.6 PHOSPHATES

The phosphate analysis suffers from the same restrictions as those discussed in the analyses of the nitrate concentrations. In addition, the phosphate concentrations for the research catchments are often lower than or very close to the level of detection (0.10 mg/l) for the instrumentation employed in this study (see chapter 3 for details). These problems with the concentration determinations and the temporal resolution of sampling have a profound impact on this analysis.

The previous study by Kelbe *et al* (1992) suggests that the dissolved phosphate concentration does not vary much throughout the hydrograph (Table 7.2) but does indicate a slightly lower concentration for the natural, undisturbed catchment (W1H031) in comparison to the catchment with subsistence agricultural settlements (W1H016). The mean concentrations for all components of the hydrograph given in Table 7.2 indicate very little change during storm events for W1H031. However, there is a rise in the base flow concentrations for W1H016. The individual storm events however, show much greater variability (Figure 7.8).

In many of the storm events (Figure 7.8) for both catchments there is an apparent decline from relatively higher values prior to or during the storm to almost negligible concentrations after the storm has receded. In section 4.3.2, where the hysteresis in turbidity fluctuations during a storm event where used to partition samples associated with a recession and a rising sediment component, the dissolved phosphates concentrations also showed a significant difference between these two periods. The rising sediment graph had a mean phosphate concentration of 1.4µg/l but the falling sediment graph had almost no detectable dissolved phosphate (mean = 0.07µg/l). Unfortunately, it is not possible to determine any reproducible trends in the dissolved phosphate loads during a storm event because of the lack of sufficient temporal resolution in the sampling and because the concentrations were so close to the level of detection for the instruments used in this study. Any trend is very speculative.

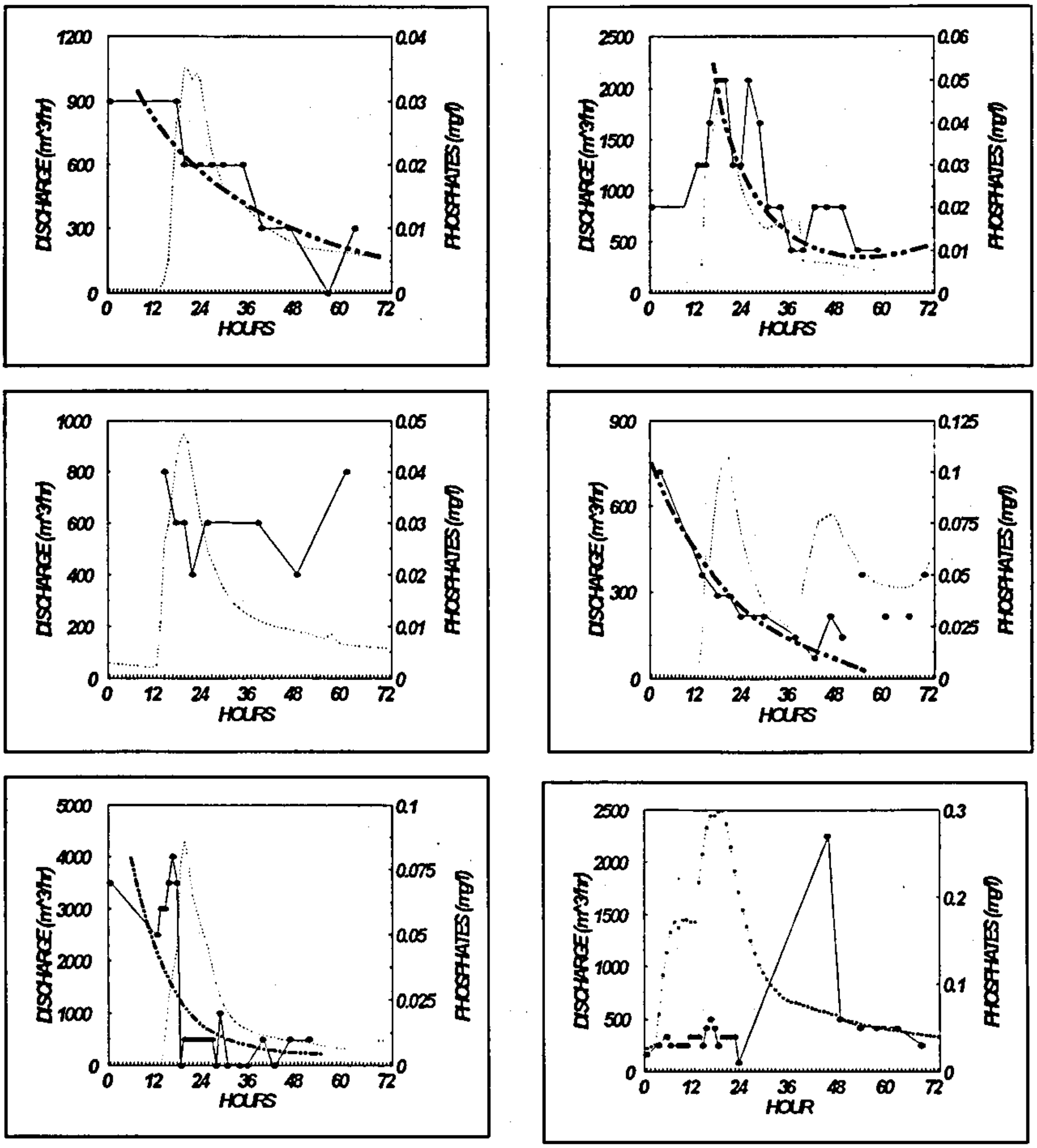


Figure 7.8a Examples of selected storm events for **W1H016** showing the discharge hydrograph (...) and the associated changes in **phosphate** concentration (—) for storm events on the following dates, (left to right, top to bottom):-

(1) 3 Dec 1993 (2) 29 Dec 1994

(3) 10 Jan 1994 (4) 21 Jan 1994

(5) 30 Mar 1994 (6) 17 Jun 1995

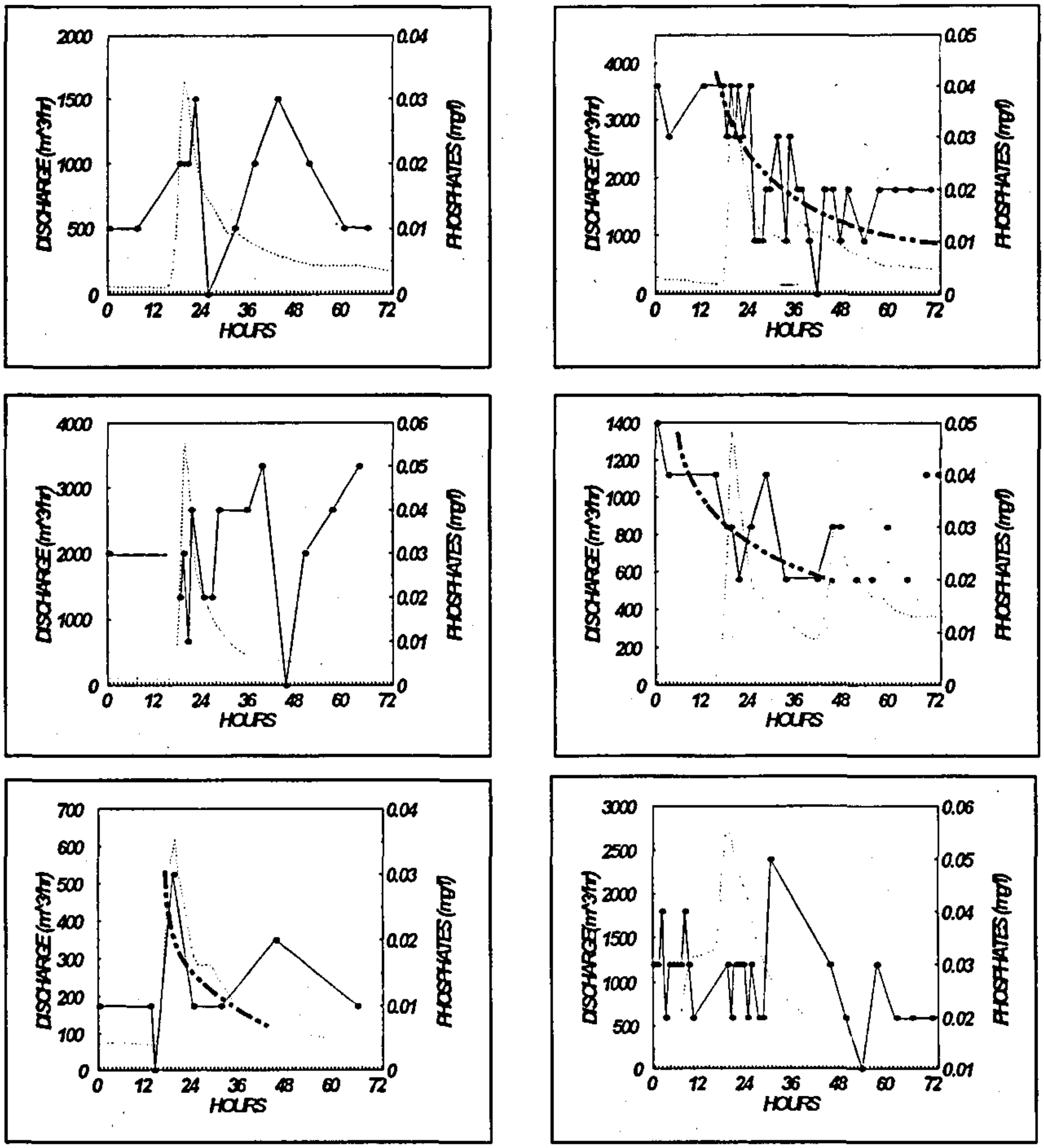


Figure 7.8b Examples of selected storm events for **W1H031** showing the discharge hydrograph (...) and the associated changes in **phosphate** concentration (—) for storm events on the following dates, (left to right, top to bottom):-

(1) 3 Dec 1993 (2) 29 Dec 1994
(3) 10 Jan 1994 (4) 21 Jan 1994
(5) 30 Mar 1994 (6) 17 Jun 1995

7.7 GENERAL WATER QUALITY PROCESSES MODEL

The general water quality changes during a typical, isolated, short duration, high intensity storm for the Zululand research catchments have been proposed in the preceding sections. Individual cases were presented which had some resemblance to the indicated conditions. In this section a composite model is derived for selected storms to gauge the extent and magnitude of the proposed typical characteristics.

The composite storm was constructed by aligning the storms so that all the peak discharges for the selected storms coincided (at time = zero). The composite model was then derived by averaging each hour over all storm values to obtain an "average" storm. For those factors determined from grab samples, the hourly values between samples were interpolated from the observations before the composite average was derived.

The storms chosen covered a large range of peak discharges to a maximum of almost 5000 m^3/hr. This resulted in a large range in the magnitude of the other water quality factors. The composite model is presented in relative values (*ie* as a percentage value between the maximum and minimum) in Figure 7.9 and Figure 7.10. This gives the changes as normalized values that indicate the RELATIVE CHANGES in magnitude and time within the storm.

The composite model conforms to some of the features described for individual storms but shows large deviations for some variables between the catchments.

7.7.1 DISCHARGE

There is a very distinct difference between the shape of the discharge hydrographs at both catchments. The hydrograph from W1H031 has a single sharp peak while the one from W1H016 has a discontinuity before the peak. This initial discontinuity is attributed to the first of the triple peaks shown in Figure 6.1 for this catchment. The third peak is not observable because of the averaging technique for different size storms with slightly different times between peaks (see Table 6.1).

7.7.2 CONDUCTIVITY

The conductivity for both catchments shows the expected rapid drop with the onset of storm flow that is followed by a rapid recovery within 5 hours of the peak discharge. The differential recovery rates are not observable in W1H016.

7.7.3 TURBIDITY

Both catchments show sharp peaks in field turbidity that coincide with the peak discharge rate. However, W1H016 shows two peaks that is due to the separate peak discharge rates. However, there are no indication of double peaks in any of the single storm events and it is proposed that the double peaks in the composite model are a result of changes that occur with one or the other peak but not both. The double peak could be due to either sampling error or to release of sediment within only portions of the catchment.

7.7.4 SUSPENDED SOLIDS

The suspended solids composite model shows almost an identical response to turbidity in W1H031. However, there is very little correlation between the suspended solids of W1H016 and the corresponding turbidity. The suspended solids showed very large range of values in the sample measurements (Figure 7.10 [#4])

7.7.5 pH

The pH composite model (not shown) shows little agreement with the proposed changes for W1H031. This could be due to measurement error of pH in low ionic solutions.

7.7.6 NITRATE

Both catchments show an increase in nitrate concentrations during a storm event but at very different time within the storm hydrograph. The response for W1H031 is almost immediately the rainfall starts - even before the storm hydrograph has responded. However, the nitrates in W1H016 remain very low until the start of the second (or main) peak discharge. Both show some indication of a recession as base-flow predominates, about 15-20 hours after the peak discharge.

7.7.7 PHOSPHATE

The phosphate concentration for the composite model shows an increase in concentration during the storm events for W1H016 which is seldom evident in the individual storms. However, there is still very little consistency in the trends of changing phosphate for either catchment.

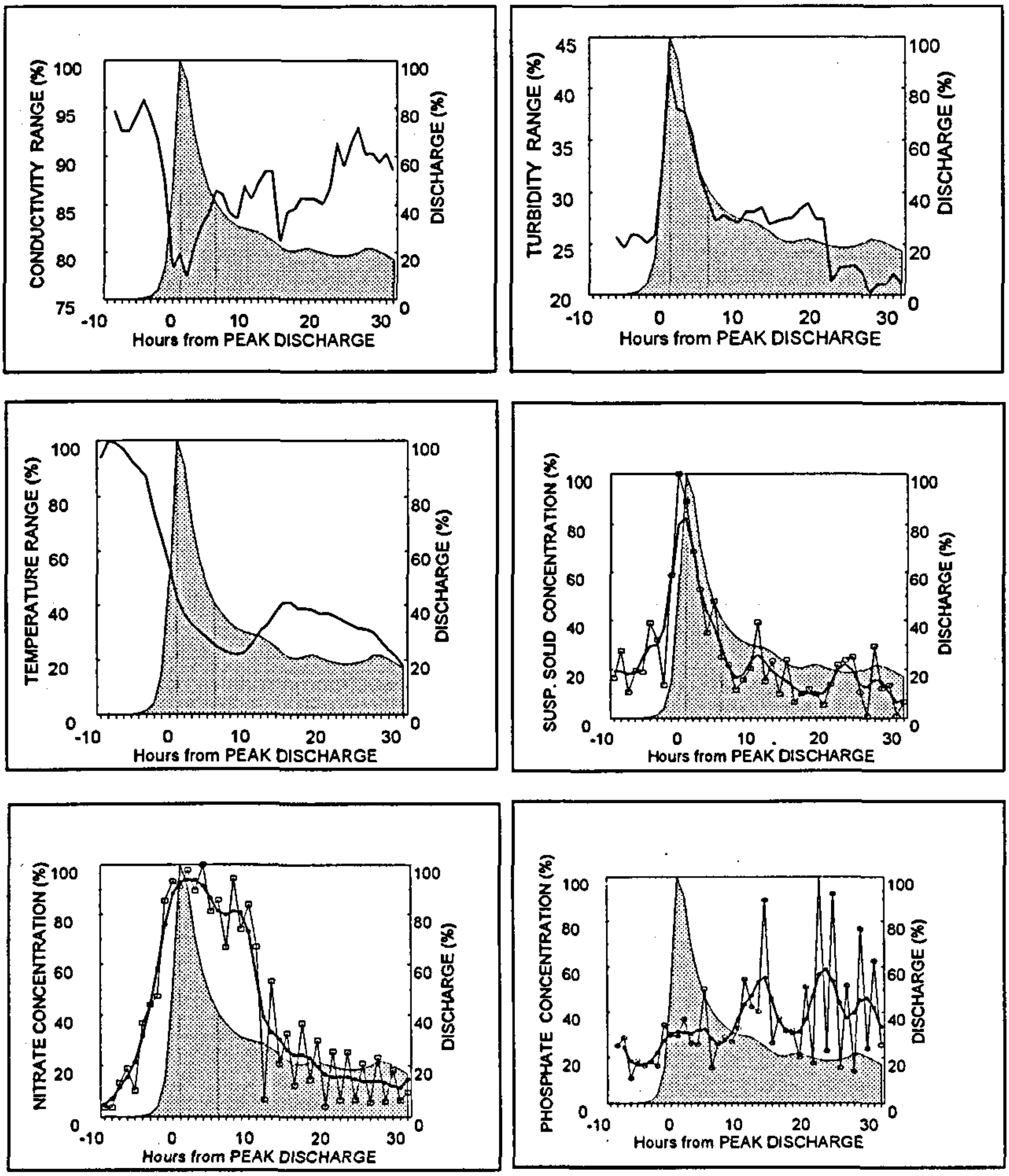


Figure 7.9a Composite model of storm discharge hydrograph (shaded) and selective water quality factors for W1H031. Model derived from average about a common peak. Intermediate sample value derived from interpolation. The dark line for nitrate, phosphate and suspended solids figures are smoothed series using a 5 term binomial filter.

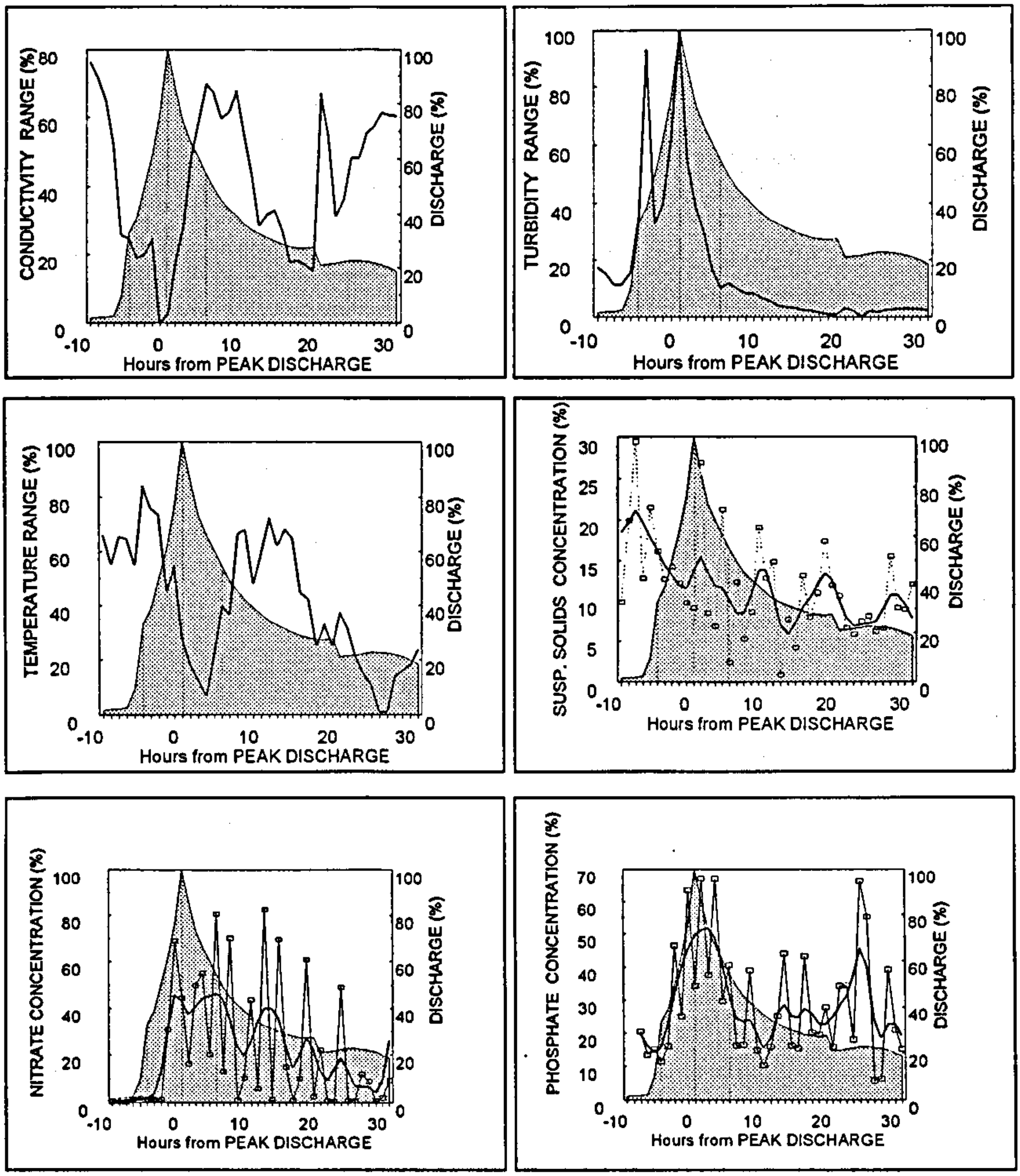


Figure 7.9b Composite model of storm discharge hydrograph (shaded) and selective water quality factors for W1H016. Model derived from average about a common peak. Intermediate sample value derived from interpolation. The dark line for nitrate, phosphate and suspended solids figures are smoothed series using a 5 term binomial filter.

8 CASE STUDIES

The general relationships between selected water quality conditions and the hydrological processes for selected storms were presented in Chapter 7. Some of the storms given in Table 7.1 were not the result of short duration, high intensity rainfall and would not have been expected to show the characteristic conditions because the surface flow processes may not have occurred. However, some storms did result from these rainfall conditions but their water quality response deviated from expectations. This chapter presents case studies that are suggestive of typical conditions and also a study of atypical storms. It is important to emphasize that there are always many sources of error in field measurements in this sort of project that could lead to "atypical" conditions. Before presenting the case studies of the expected and unexpected situation, an example of a system error that was only detected after a year of sampling had been completed is presented in section 8.1.

8.1 SYSTEM ERRORS

One of the earlier storms examined for W1H017 was observed to have very distinct features that are shown in Figure 8.1. It was eventually deduced that the inlet sample pipe for the automatic monitoring system (see Figure 4.6) was probably exposed underneath the sharp crested weir when the flow rose above a certain stage (~100 m^3/hr). This restricted the flow of water through the monitoring system and affected the sensors. It is assumed that the very distinct drop in both conductivity and turbidity are a direct result of system design which caused the sensors to be exposed to atmospheric conditions when the flow through the system was restricted. These types of problems are not always apparent. However, all efforts have been made to identify and eliminate any such errors in the data presented in this report.

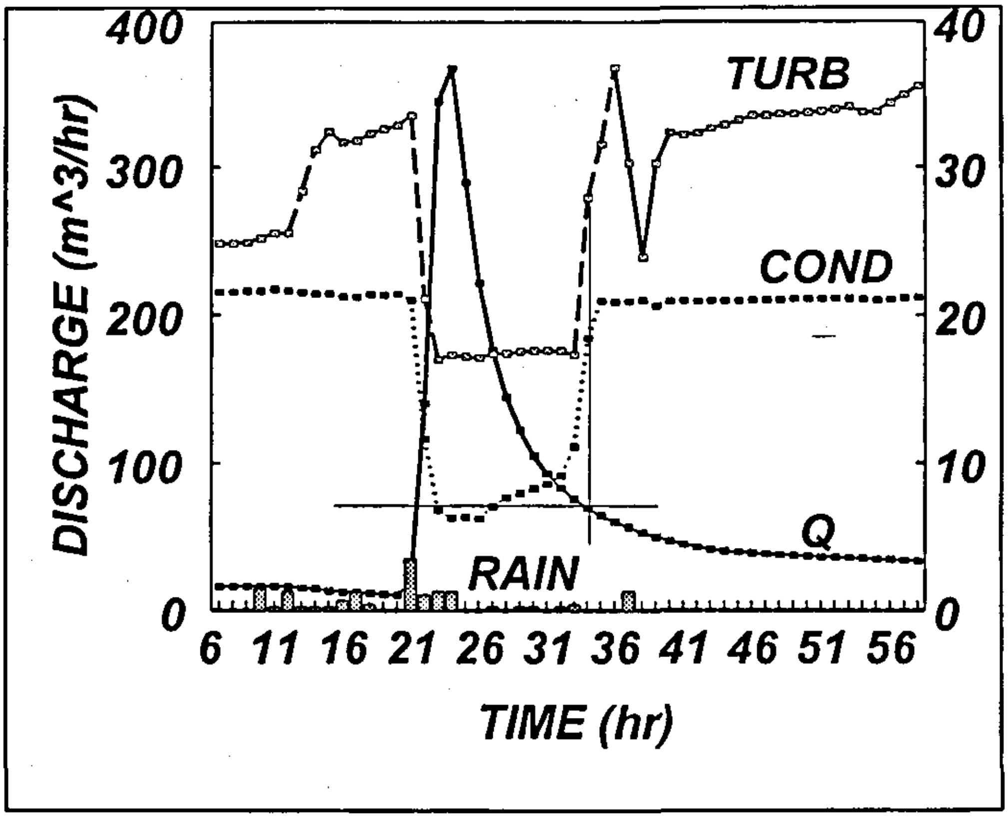


Figure 8.1 Example of system errors caused by the flow by-passing instrument housing at W1H017.

8.2 CASE STUDY OF A TYPICAL STORM [10/1/94]

A storm that displayed the suggested typical response in water quality for short duration high intensity rainfall occurred on 10 January 1994 and is presented as a case study for W1H031 in this section. The water quality factors in relation to the discharge hydrograph are presented in Figure 8.2 to Figure 8.5. The discharge hydrograph is shown as the shaded area in these figures. It shows the expected short sharp discharge peak for this type of storm.

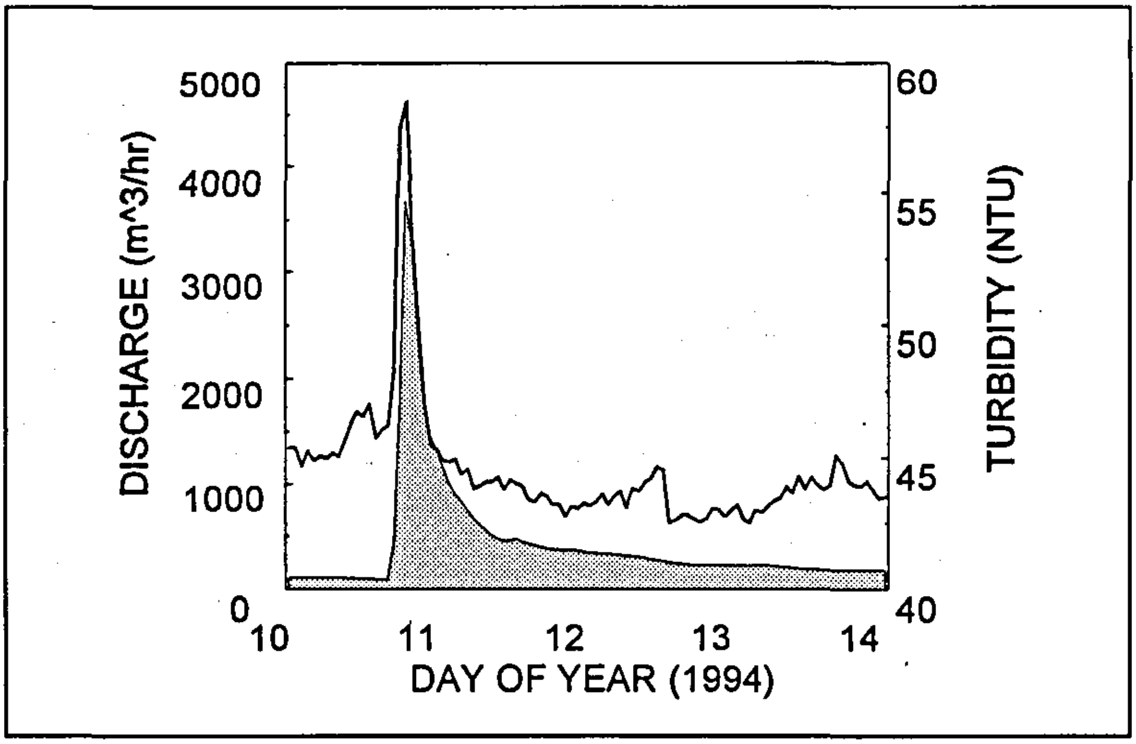


Figure 8.2 Example of a typical turbidity and suspended solids response.

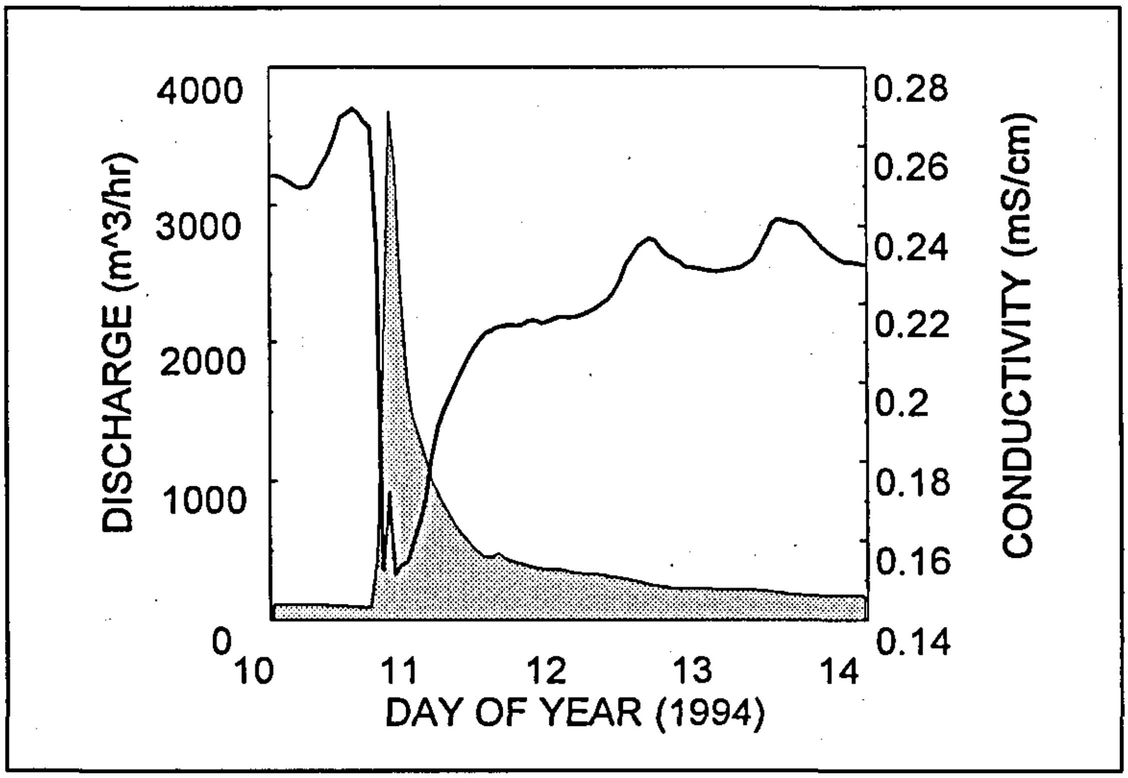


Figure 8.3 Example of a typical conductivity response for storm runoff.

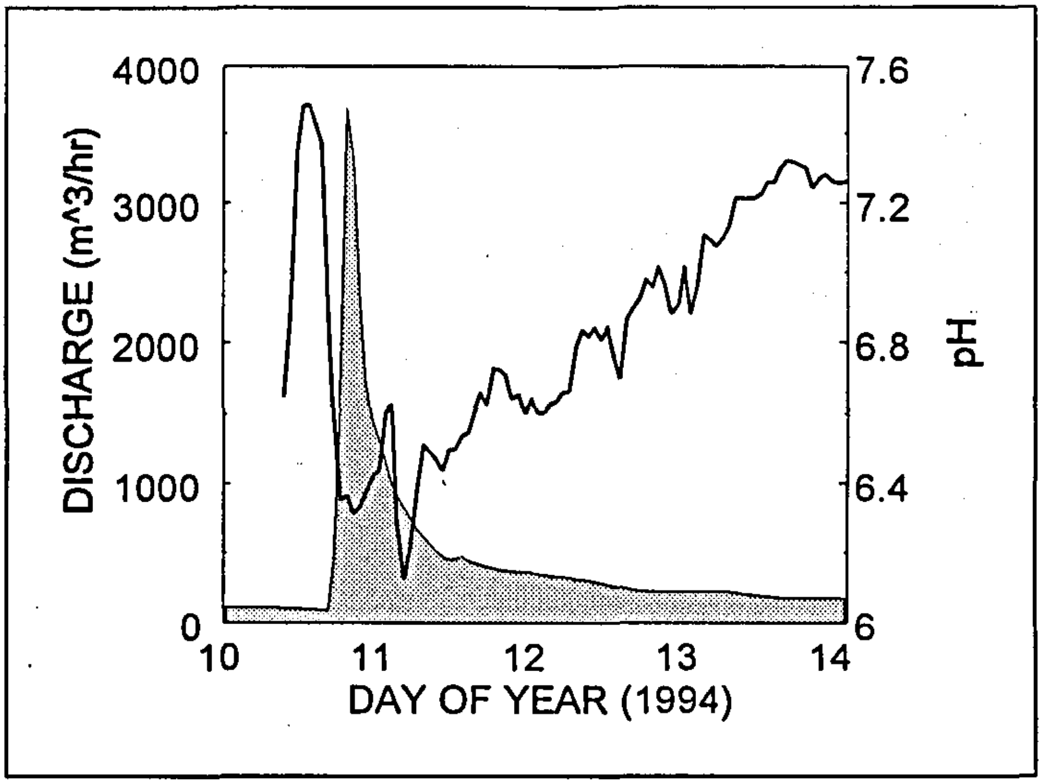


Figure 8.4 Example of the pH response in a typical storm event.

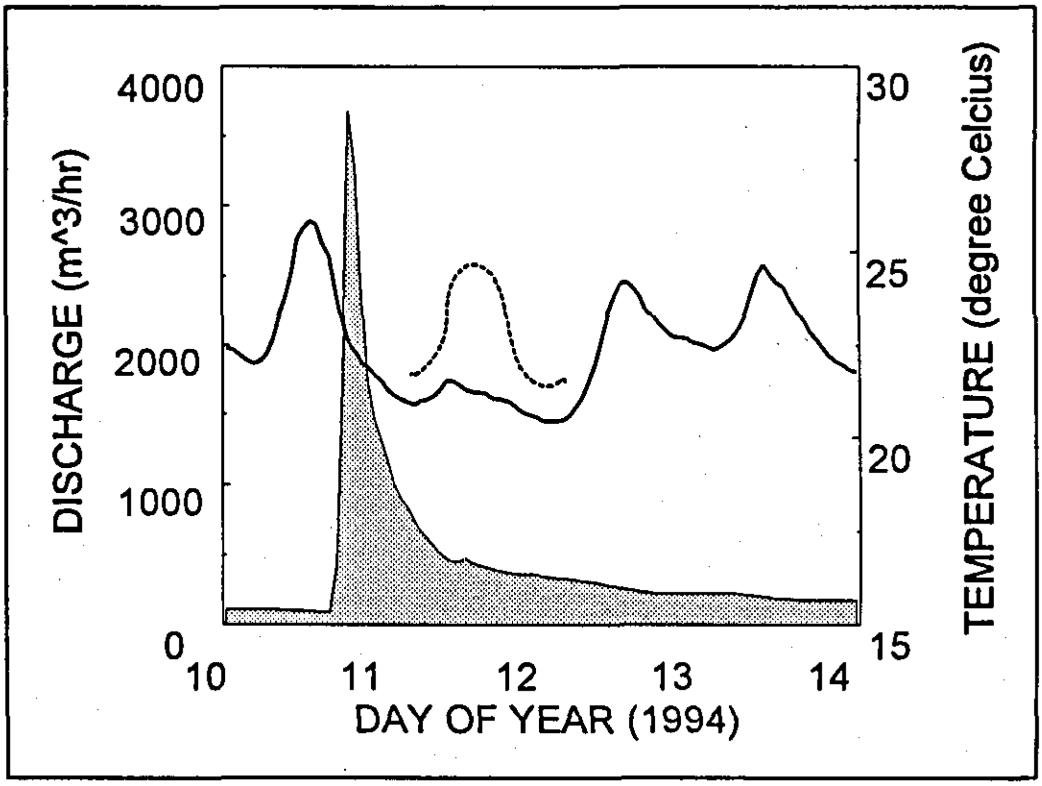


Figure 8.5 Example of a typical temperature response for storm runoff.

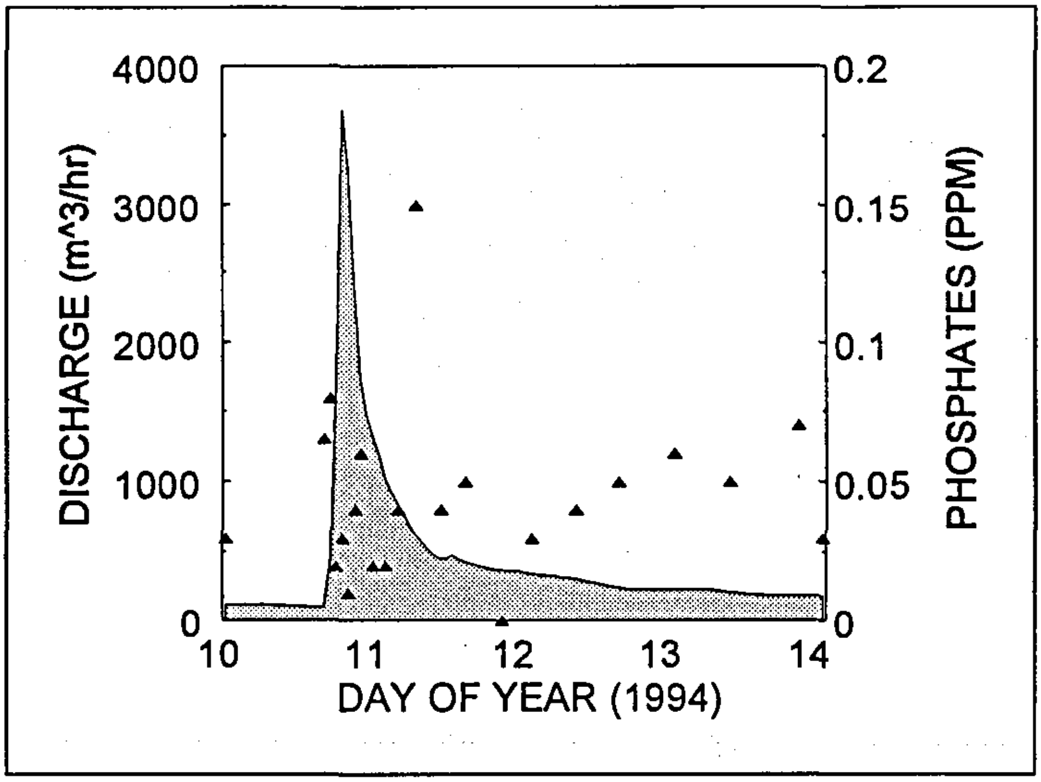


Figure 8.6 Example of the phosphate response for typical storm event.

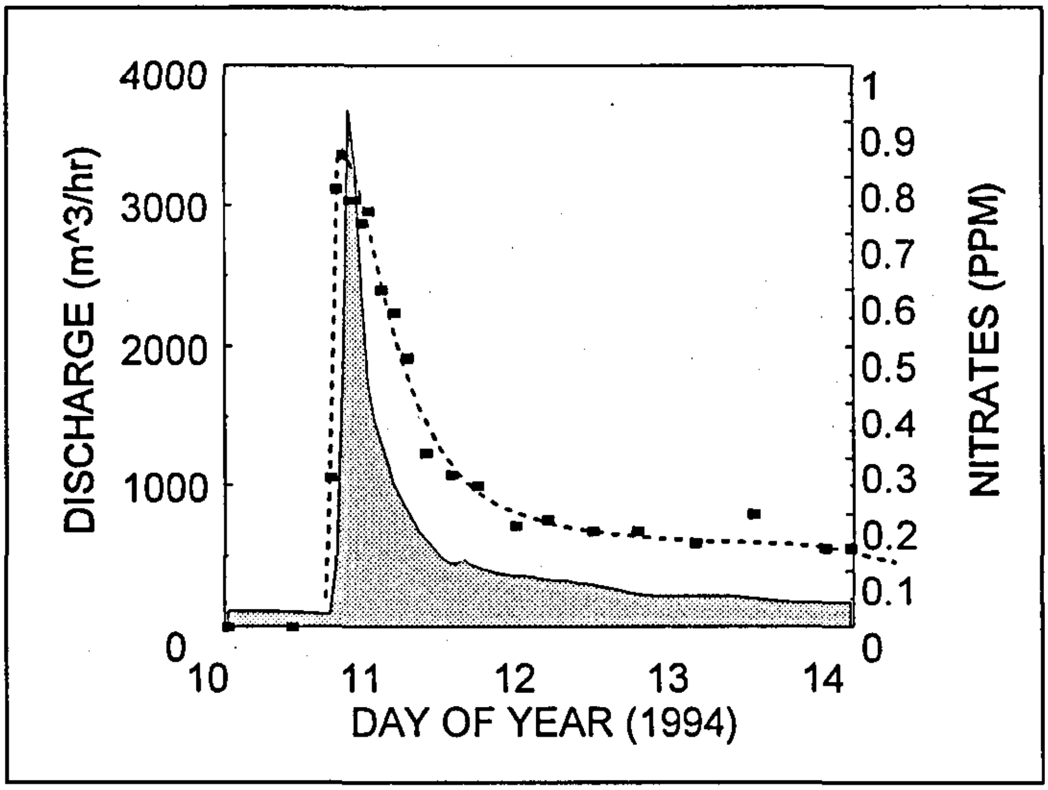


Figure 8.7 Example of the nitrate response for a typical storm event.

The peak in discharge coincides with the short sharp peak in turbidity (Figure 8.2). The turbidity recovers to pre-storm conditions very rapidly showing that the effect is associated only with the surface flow processes and not the inter-flow or base-flow. The turbidity response does not occur in subsequent storms immediately after the initial event (see section 8.3). This suggests that the turbid water is due to a build up of material between events that is flushed with the first storm event.

The conductivity drops immediately there is an increased response in the discharge to a short duration high intensity storm event (Figure 8.3) due to the dilution effects of incident rainfall. The conductivity then partially recovers almost in unison with the flow rate before slowing in the recovery rate when subsurface conditions predominate. There appears to be a distinct separation in the conductivity recover rate between inter flow and base flow conditions.

The pH sensor showed large fluctuation (±0.5 pH units) before the storm during the time of almost stagnant conditions with very low flow. The pH then drops very rapidly during surface flow conditions before a systematic recovery to pre-storm conditions that can take up to several days (Figure 8.4). The temperature during the storm event drops by several degrees Celsius below the expected diurnal cycle (shown as a dotted line in Figure 8.5).

The dissolved phosphates do not show any discernable trends during the passage of a short duration high intensity storm event in these catchments (Figure 8.6). However, there are discernable changes in the nitrate concentration during these events. There is an immediate increase in the nitrate concentrations that coincides with the increased storm discharge (Figure 8.7). The recovery to pre-storm conditions is almost a mirror image of the changes in conductivity.

8.3 ANTECEDENT EFFECT : 16/11/92.

There were several situations when two storms occurred within a short period of time of each other (typically one to two days apart). For most of these situations, there was a distinctly different response in turbidity between the two events. An example of these situations is presented in Figure 8.8 for the disturbed catchment (W1H016). This case is for a storm that occurred on November 15, 1992 and it shows a clear turbidity peak with the first storm (DOY 320) which was followed by a full recovery in the turbidity to pre-storm conditions long before the storm hydrograph had receded to base flow conditions. The second storm, however, had no significant turbidity response even though its peak discharge reached nearly 600 m^3/hr. This effect can be attributed to either the lack of surface-flow in the second event or the difference in production and removal rate of turbid materials (sediment, debris or colourants).

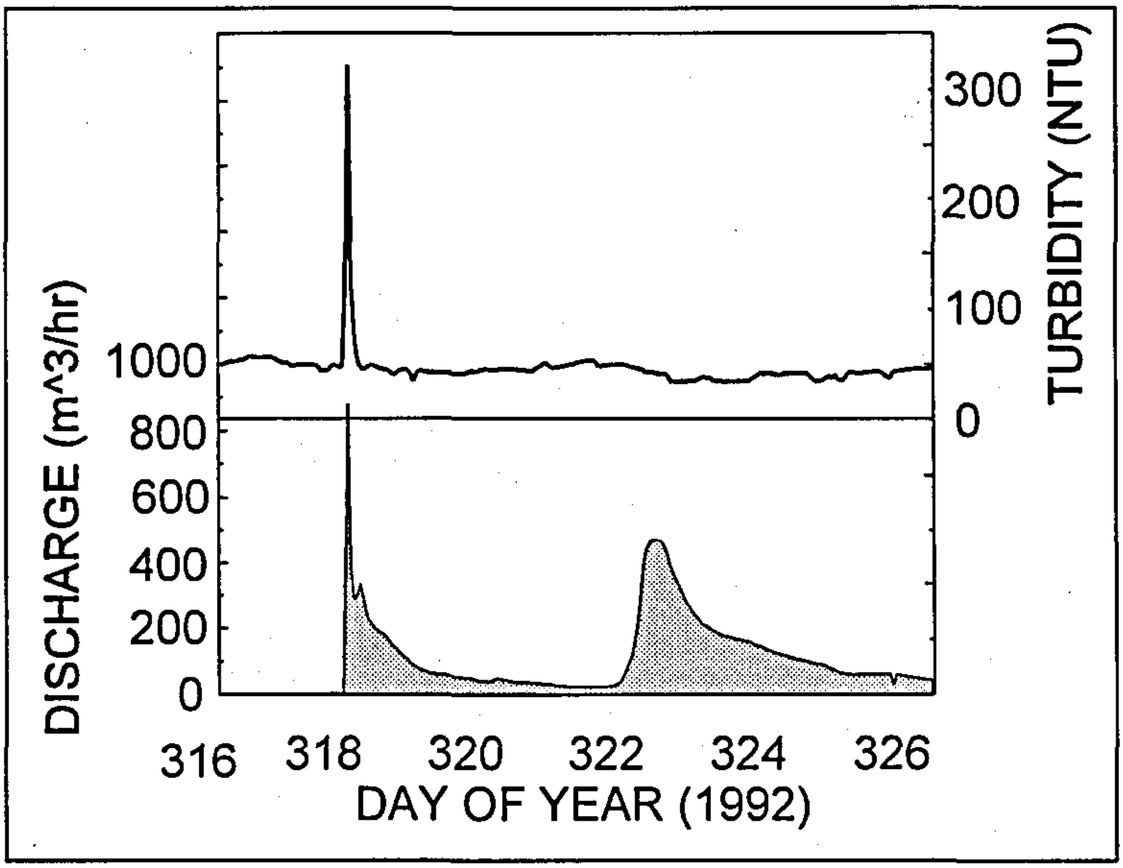


Figure 8.8 Different turbidity response to two short duration storm events for W1H016 (November 1992).

8.4 DROUGHT EFFECTS [1/3/95]

During the study period there were very severe drought conditions that resulted in the streams drying up for extended periods in some of the catchments. A storm that broke a period of no flow in W1H016 occurred on 1/3/1995 (Figure 8.9). W1H031 had almost stopped flowing before this storm occurred (pre-storm discharge dropped to 4 m^3/hr). The water quality response to this storm exhibited unusual behaviour that is ascribed to the antecedent conditions in this case study.

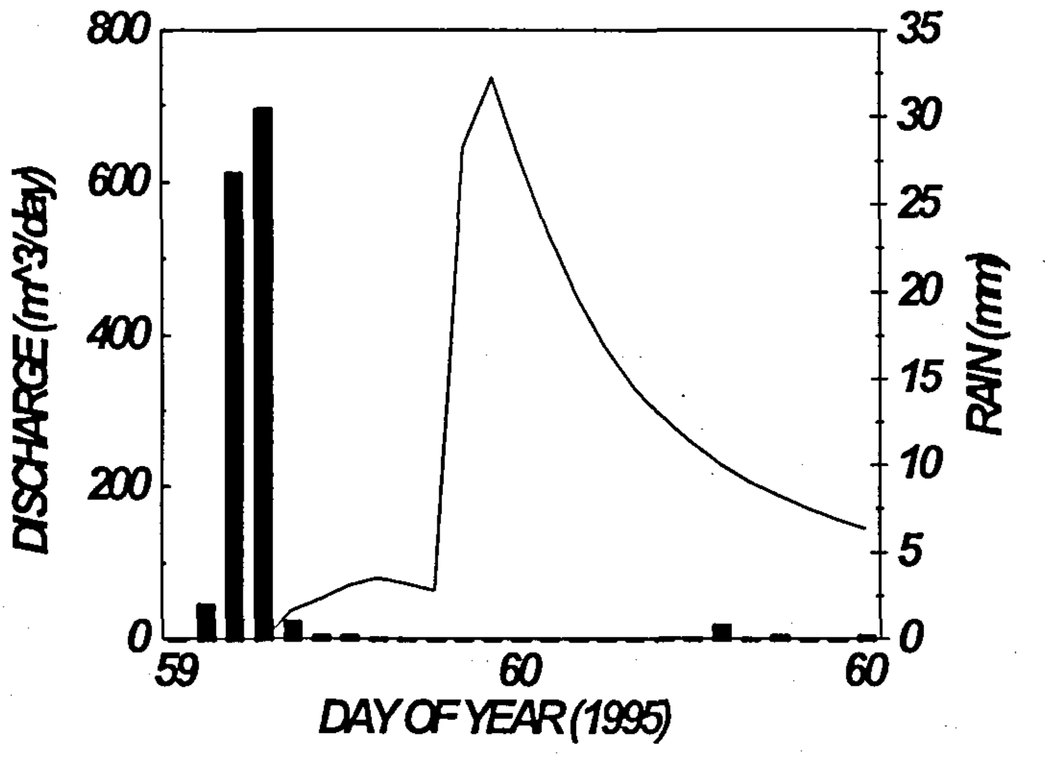


Figure 8.9 Storm rainfall and discharge on 1/3/95@ W1H016.

Before the storm there had been no discharge from W1H016 for several months while W1H017 and W1H031 continued to flow. Consequently, all the continuous sampling values for the pre-storm conditions at W1H016 were **not** representative of flow conditions and all these values were deleted from the data record as they represented stagnant water in the monitoring system. The continuous monitoring records from the first hour that the water commenced flowing at W1H016 were used as the first sample point in this study.

8.4.1 CONDUCTIVITY

In the previous section it was shown that the typical storm electrical conductivity observations are expected to decrease with increasing flow due to dilution effects. However, the storm conditions at W1H016 (Figure 8.10) showed an initial rise with increasing flow that was followed by the expected decrease in conductivity but only **after** the peak discharge had occurred. The minimum conductivity occurred about 20 hours after the peak discharge. These conductivities are very much lower (~10%) than the normal range during similar storm events (see Figure 7.1a). *Consequently, the oscillations in conductivity due to thermal effects (see* Figure 8.13) are more pronounced and should be compensated for in the analyses.

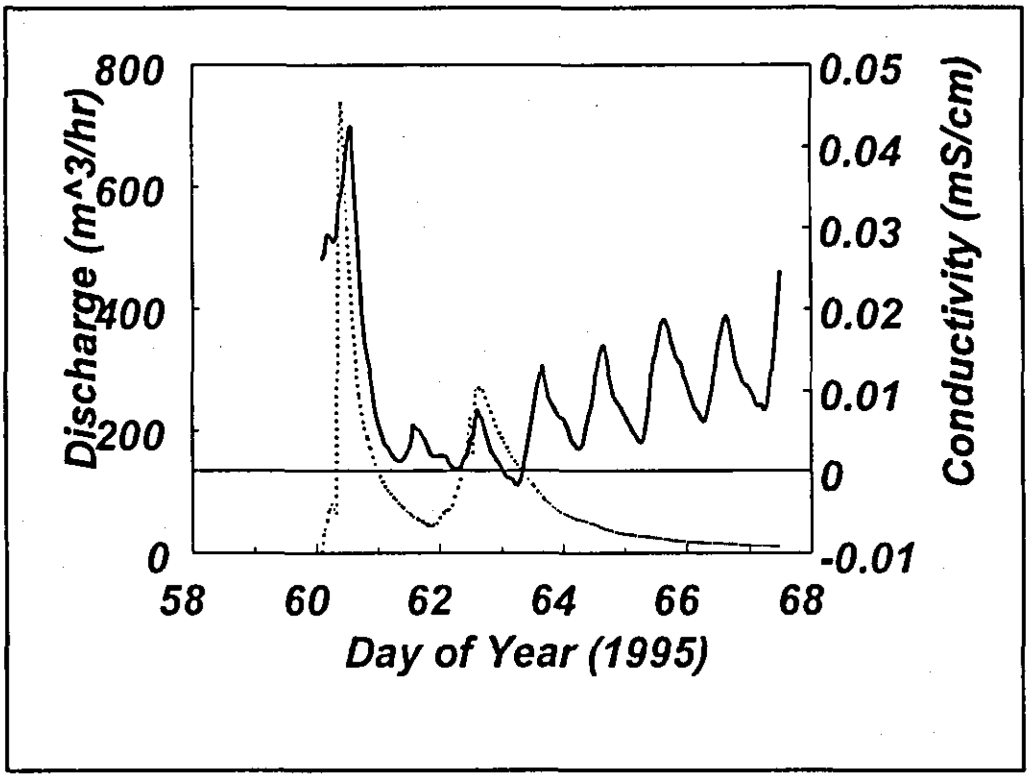


Figure 8.10 Changes in conductivity following drought conditions a W1H016

8.4.2 pH

No pre-storm observations of pH were available because there was no flow. However, the pH at W1H016 immediately after flow resumed was close to 7.0 (Figure 8.11). This initial pH steadily declined from the start of discharge to a value below pH 6.0 after the storm hydrograph had receded to nearly base flow conditions. There was no apparent recover in the pH associated with stages in the recession limb of the discharge hydrograph.

The subsequent storm two days later also showed a very small increase in pH which is atypical of storm response. These changes are attributed to the antecedent drought conditions

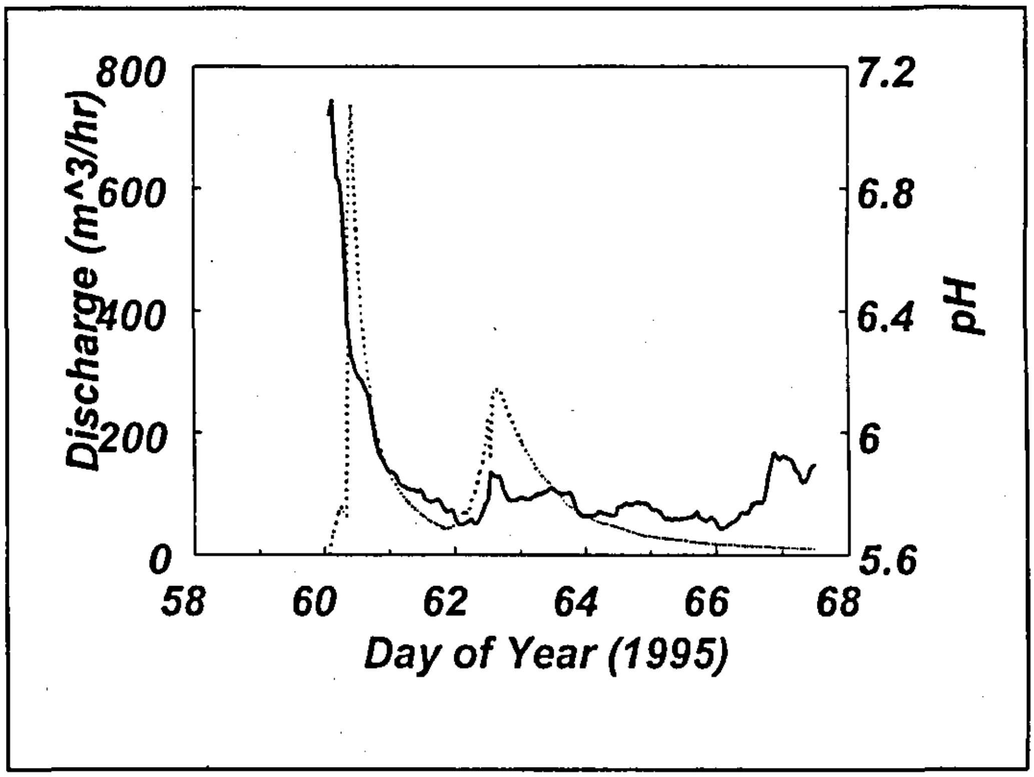


Figure 8.11 Changes in pH following drought conditions at W1H016.

8.4.3 TURBIDITY

The turbidity changes during the storm for W1H016 show the expected sharp rise with increasing discharge but there is a sharp drop which coincides with the peak discharge. However, the turbidity values are relatively low and subject to considerable noise. A similar situation occurs with the second smaller storm three days later (Figure 8.12).

The increases in turbidity with the onset of the storm discharge do conform to the general expectation for typical storm profiles but the rapid drop at peak discharges is atypical and is presumed to be due to antecedent conditions. The general rise in turbidity after the storm has receded was observed in several situations and needs to be investigated further. The rise in turbidity in the second storm suggests that the turbid material was not removed by the first storm or the material was regenerated quicker between storms in the drought conditions.

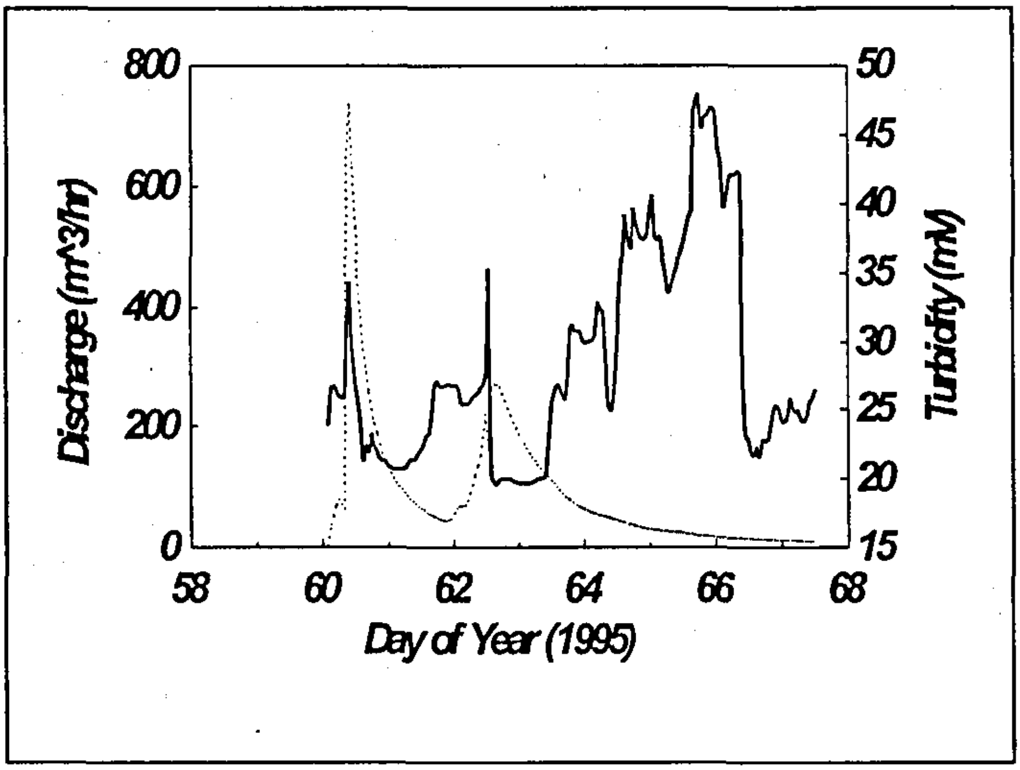


Figure 8.12 Changes in turbidity following drought conditions at W1H016.

8.4.4 TEMPERATURE

The temperature changes during the storm hydrograph is shown in Figure 8.13. This figure shows a sharp peak in temperature that is several hours **after** the peak discharge. Normally, the temperature is expected to decrease with the peak discharge due to the influx of cold rainfall (see examples in Figure 4.16). It is not clear why there is an increase in temperature for the first events. However, the second smaller storm is probably too small to influence the diurnal temperature regime greatly although it does retard the general increasing temperature cycle slightly.

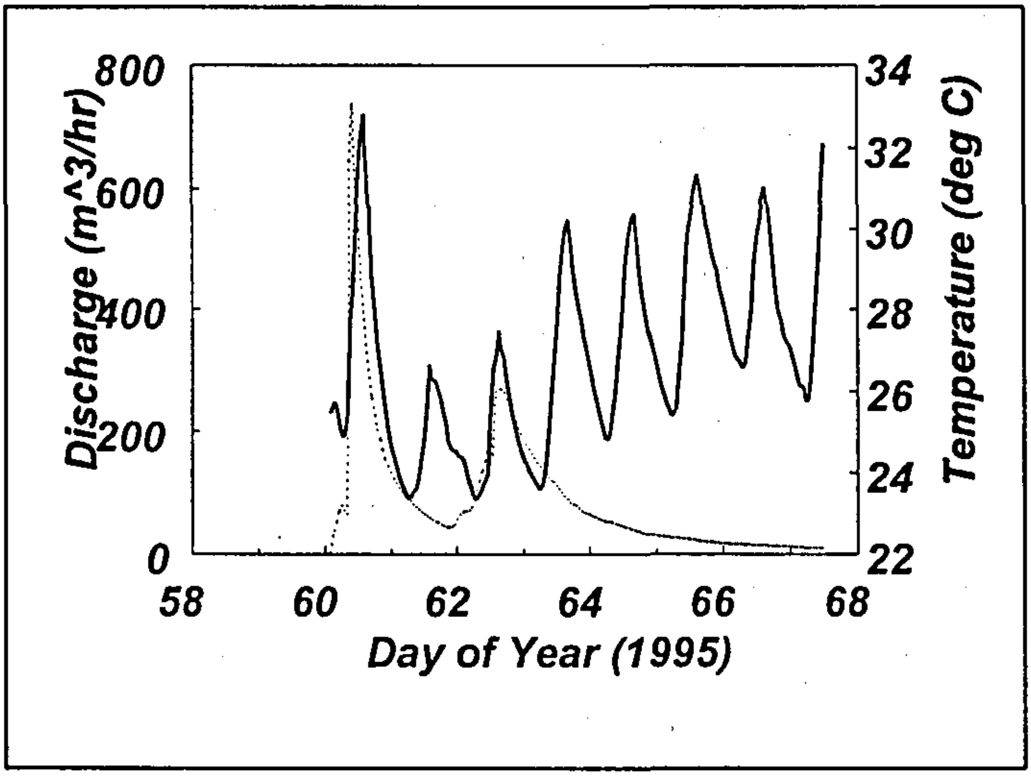


Figure 8.13 Changes in temperature following drought conditions at W1H016.

8.4.5 NITRATES AND PHOSPHATES

There were no grab samples prior to the commencement of flow following the rainfall event. However, when flow did start, the nitrate concentrations for W1H016 catchment increased to peak values near or just after the peak hydrograph. The phosphate concentrations on the other hand had very high initial values when flow first started which dropped very rapidly to values close to the level of detection.

The three main points of departure from the expected norm for this storm concern the delayed discharge hydrograph after the main rainfall event, the delay in peak conductivity and temperature changes and the unexpected drop in turbidity during peak flow for this catchment (W1H016). The delayed discharge is probably a result of high initial infiltration rates which is supported by the delayed conductivity response that implies very little initial surface flow. These anomalies are not evident during the runoff at W1H031 where the river never stopped flowing. If this hydrograph at W1H016 emanates directly from the routed discharge from W1H017, then the rest of the catchment must have infiltrated all the rainfall. All these factors still need further investigation and conformation from more events.

8.5 GENERAL

The changes in selective water quality factors within the storm hydrograph show considerable variations. Some consistent features were observed in Chapter 7 for many storm conditions and presented as an example in the second case study. However, there are many situations that do not conform to these "typical" conditions. Some of the variations from these typical features were presented in the case studies above with an attempt to explain their cause in relation to the hydrological processes. Unfortunately, these anomalies were derived from situations which could not be readily repeated within the study period. However, these conditions may be important if they are representative of more arid situations where ephemeral streams are more common.

9 SUMMARY

The main objective of the study was to determine the relationship between selected water quality characteristics and specific hydrological processes. The water quality characteristics were chosen for their suitability for monitoring on a continuous process, their response to land use changes in the Zululand region, and their tracer characteristics. The hydrological processes selected for examination in the project were those associated with surface (overland) and sub-surface flow paths. Only runoff events derived from short duration high intensity storms which produced a short sharp discharge response were considered for the main scope of this report.

9.1 MONITORING SYSTEM

Technological advances now provide instrumentation, storage and retrieval systems with sufficient resolution for monitoring some of the physical and chemical characteristics in catchment hydrology. This study developed a continuous monitoring system for field applications to evaluate the relationship between the hydrological processes operating in the Zululand Coastal region and some of the measurable water quality characteristics which are responding to land use changes in the region. The monitoring system was based on a reliable datalogger connected to several industrial sensors. It had inherent problems with siting of the sensors under field conditions. The system required maintenance at regular intervals to overcome fouling of the sensors. The sensors obtained from the various sources were designed for laboratory purposes and had to be adapted for field conditions where they generally had a much shorter lifetime. The system was programmable and required an understanding of electronic circuitry. Consequently, it needed a technical assistant with a basic knowledge of physics and computer programming to develop. However, it only needed a field assistant with secondary education to maintain in the field.

The general water quality characteristics and some initial investigations of the land use response have been undertaken in previous studies. These were used to identify suitable parameters for investigation in this study. The physical and chemical characteristics of the catchment which were measurable using the continuous field monitoring systems were the stream discharge rate, rainfall rate, electrical conductivity, pH, turbidity and temperature. The system was also developed to activate an automatic water sampler and to record the physical and chemical conditions of the system at the time of sampling. The water samples were generally collected on a weekly basis unless there was a chance that the sampler would be full before the normal collection time. The samples were analysed for nitrate [as N], phosphate [as P] and suspended solids concentrations in the laboratory using standard methods and equipment.

The electrical conductivity is assumed to be representative of the total dissolved solids concentrations although no effort was made to identify constituents. However, the conductivity was calibrated against known standards in the laboratory and with *ad hoc* field calibrations. The turbidity was derived using a sensor which determines the attenuation in transmitted infrared radiation. The laboratory calibrations provided a characteristic "S" shape calibration curve. Unfortunately the comparisons of these measurements with laboratory samples using an instrument that measured the scattered radiation in the visible spectrum and accounted for transmission losses (colour) did not provide an acceptable correlation. The probable reasons for this discrepancy include the sampling technique, the standing time of the samples, the measuring technique and possible contamination sources. While there are some problems with the sampling and monitoring system developed for this study which still need to be overcome, they are not unique to this project. However, the project results presented in this report are dependant on the **relative** changes in flow and quality, rather than the absolute values, which can be linked to associated hydrological processes. This system is adequate for representing relative changes in both flow and quality on a continuous basis.

9.2 GENERAL HYDROLOGICAL CONDITIONS

The study sites chosen were in the Ngoye hills near the Empangeni and Richards Bay metropolitan area. This area has a projected annual population growth rate of 2.8% and estimated growth in water demand of over 800% from 1986 to the turn of the century (Water Affairs, 1986). There is a large influx of migrant workers to the area which is placing increasing burden on the catchment resources and leading to increased environmental degradation. The two main paired research catchments chosen for this study represent an indigenous *undisturbed natural system (the Ngoye Nature Reserve) and an almost identical* catchment with rural subsistence settlements. The disturbed catchment is representative of developments in the Zululand region and has geomorphological features which are also representative of large areas of the Zululand region. The second catchment allows for comparative studies with the natural undisturbed system.

The general hydrological processes experienced in this project, which influence the water quality behaviour of the catchments, were responsive to a large range of climatic conditions during the study period. During the previous 15 years of monitoring, the flow through the research catchment seldom ceased completely. However, there was a very severe drought during the four years of this study which resulted in very few of the required storms. In two of the hydrological years the flow through the monitoring weir on the disturbed (subsistence farming) catchment stopped intermittently for several months. These two years started with virtually no flow in any of the rivers and they experienced different storm rainfall patterns. Consequently they were used to compare the seasonal transport processes because they started from the same hydrological state.

Turbidity has generally been used to represent suspended solids concentrations. Consequently estimates of suspended solids export loads were derived from grab sample measurements of suspended solids and turbidity as well as from continuous observations of turbidity. The turbidity measurements were based on different techniques (laboratory and field) which influenced their results. The effect of these estimation techniques were examined for export loads from the two main catchments (W1H016 and W1H031).

The two research catchments received very similar rainfall conditions but had significant differences in their discharge characteristics that had a large effect on the export loads. There were very big differences between the catchments in the export loads of suspended solids for the two years. However, the magnitude of the differences between catchments were dependant on the *estimation technique. For the natural catchment (W1H031) in the one year, the* export loads were almost identical for all three estimation techniques, but the loads deviated substantially in the next year between the different techniques. For W1H016, the estimation techniques gave very different export loads during both observation years for the disturbed catchment. The discrepancies between estimation techniques are difficult to resolve when the system has low concentrations of suspended solids because other factors (such as colour and particle size) become relatively important. For the few cases where storms had high suspended solids concentrations, the turbidity showed a good correlation with suspended solids but most samples had low concentrations where the relationship was poor (Figure 9.1). For catchments with a larger range and a higher concentration, the relationship may be stable and more suitable for estimating suspended solids using turbidity measurements.

Comparisons between the catchments using the daily estimates of suspended solids, derived through interpolated *flow related grab samples*, showed conflicting differences between the disturbed catchment and the natural catchment (Nature Reserve) for the two different years examined. It was concluded that the estimated export loads of suspended solids are critically dependent on the estimation and sampling technique used in the monitoring system. However, the main differences between catchments, irrespective of the estimation technique used, appears to be associated with the individual storm events which contribute the largest proportion of the sediment loads.

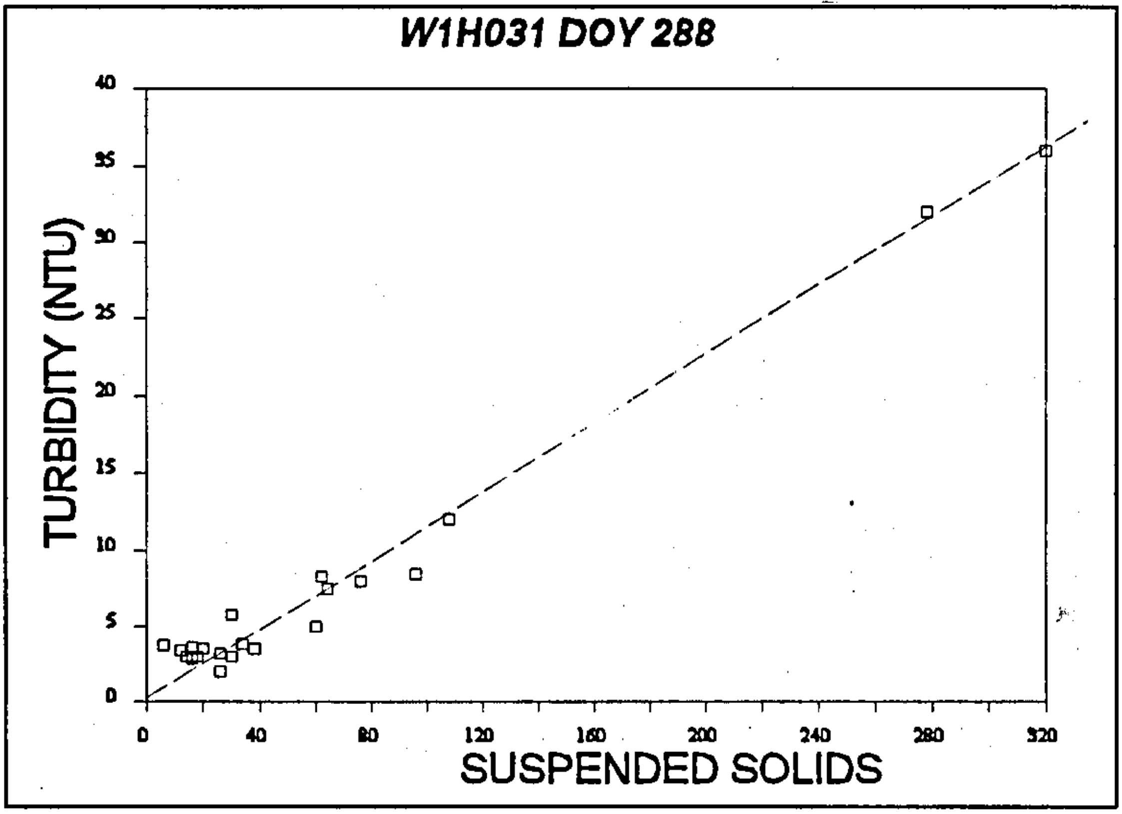


Figure 9.1 Example of relationship between suspended solids and Turbidity measurements.

The export of total dissolved solids, using electrical conductivity measurements, was similar for the two catchments during one of the years but showed big differences for the disturbed catchment in the other year. The main difference was associated with individual storm events but this difference may have been exaggerated by the drought which caused a lack of solute for long periods of time that effected the equilibrium state of the system.

The nitrate and phosphate export loads during the two years examined in this project exhibited very big differences between the two catchments which could also be associated with individual storm events.

9.3 STORM ANALYSES

The analyses of export loads have shown that the individual storms have the largest impact on the export loads of nutrients and sediment from the research catchments. Consequently, the response to individual storm events were examined in greater detail in this report. Selective storms were chosen which were sufficiently large to involve the main hydrological flow-paths that are likely to affect the selected water quality characteristics. The storms selected were those associated with short duration high intensity rainfall which are assumed to produce runoff that can be associated with both surface and sub-surface flow-paths. The characteristic hydrographs for both research catchments had distinct features that were linked to the stream network and different contributing areas. Specific points (peaks) in the discharge hydrograph from the disturbed catchment were linked to different contributing areas that may help in identifying the source, the sinks and the pathways of hydrological and chemical functions.

The severe drought during the study period limited the number of suitable storms for analysis. Instrument, monitoring and other failures also reduced the number of factors for analysis in some of these storms. However, sufficient storm events were analysed to identify certain trends in the water quality factors during suitable storms which were linked to hydrological flow paths. The storms identified for analyses varied considerably in their peak discharges and the time to peak. Those chosen for analyses had a time to peak of less than five hours and a peak discharge that was generally above 1000 m^3/hr.

The response to selected water quality factors during a storm is considered to be "typical" when the response can be observed in several storms which were judged to have surface flow conditions.

The most consistent water quality condition to be observed with short duration high intensity storm events was the immediate reduction in **conductivity** with the onset of storm flow. The conductivity response is almost instantaneous which indicates a very rapid response to the rainfall from the contributing areas. This conforms closely to other studies and is a direct response to dilution effects of the rainfall. The time and rate at which the response occurs, and the minimum conductivity value attained are very closely (inversely) related to the rate at which the discharge hydrograph responds to rainfall.

The recovery of the conductivity from the minima appears to be closely linked to the size and duration of the storm event. The recovery rate may differ between the two catchments but the intra-storm variability is too great to quantify this difference. However, there appears to be two rates of recovery following many storm events. The initial recovery rate is very rapid but decreases at some point to a slower rate which varies with events. The point of inflection between the recovery rates are considered to be associated with the changes in subsurface flow processes which introduce relative amounts of "new" and "old" water with differing conductivities. These discontinuities in the recovery rates of the conductivity coincide quite closely with the change in dominance of the different hydrological flow processes.

The **pH** variation within and between storms is highly variable. This large variability has been observed in another field study by Hoenicke *et al* (1991) which highlighted the tenuous nature of field measurements in pH. There are many sources of error which involve both the sensor (particularly in the reference junction construction and interaction with moving solutions), the sample collection methods and measurements of low ionic solution with poor buffering capabilities.

The **turbidity** variations during a storm event show some very distinct traits in the disturbed catchment which were not so clear in the natural system. This may be due to observational errors in runoff with low sediment concentrations. However, in both catchments there is nearly always a very short, sharp peak in turbidity that coincides almost exactly with the rising limb of the storm hydrograph. This peak in turbidity seldom last for as long as the discharge hydrograph. This difference in turbidity response between rising and recession flow rates produced a clear hysteresis effect. This was used to examine the difference in the early storm and later storm sediment composition. The difference in sediment composition before and during a storm were clearly evident in the laboratory analysis as differences in the colour of the sediment residue (observed during sample analyses).

The turbidity trends show several discontinuities for the disturbed catchment (W1H016) that coincide with identifiable discontinuities in the discharge hydrograph. These traits in turbidity are not as clear in the undisturbed catchment because the water generally has much lower turbidity and some discolouration. However, there are nearly always short sharp peaks that correspond with the peak discharge but these events do not always show the same recovery trends to pre-storm conditions. These traits in turbidity are sufficiently consistent to propose a "typical" storm condition.

Many attempts were made to derive a suitable relationship between the turbidity and suspended solids. A random subset of the soil samples taken at 100 m intervals along the river channel and the adjacent banks were washed in a sieve analysis and the residual solution was used in an investigation of the turbidity and suspended solids relationship. The particle size analyses of the samples were used to investigate scattering theory in deriving a relationship between turbidity and suspended solids concentration. Unfortunately there was no clear relationship between the CR10 turbidity and a model based on particle size (Figure 9.2). This figure indicates two possible relationships and suggests that this concept needs further investigation.

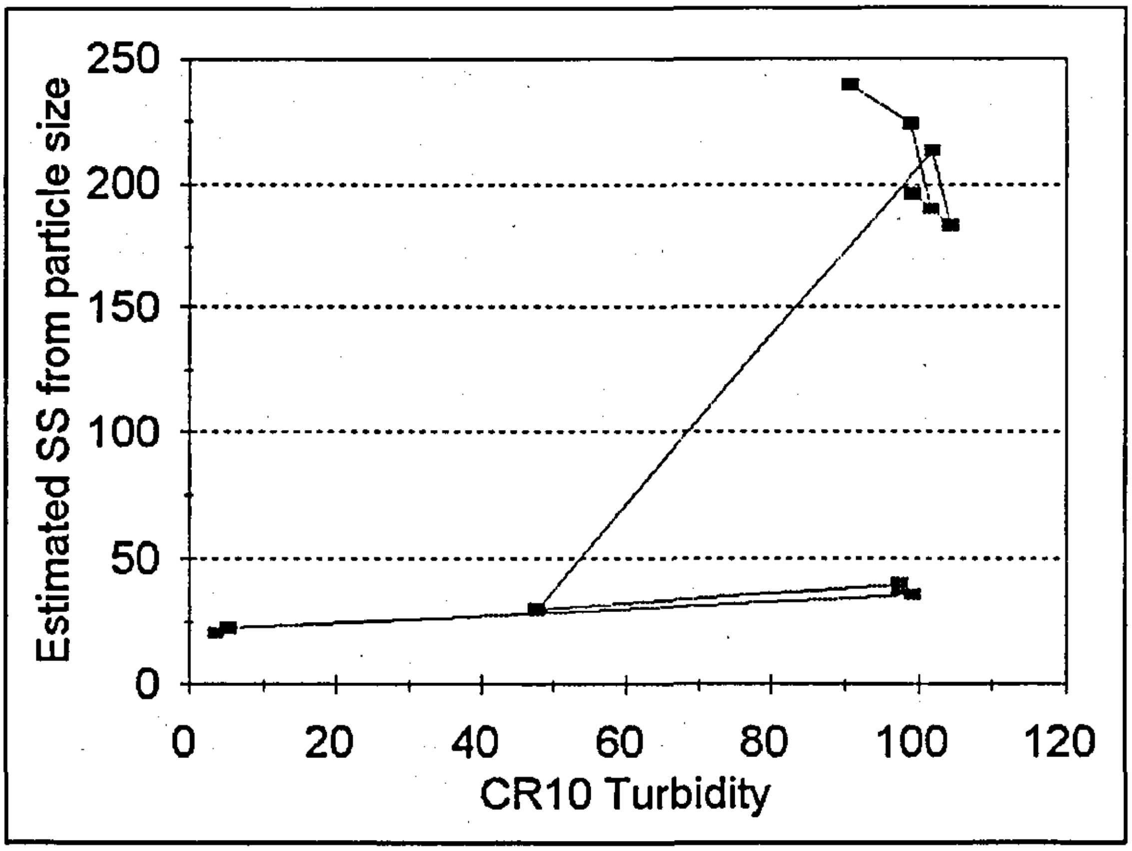


Figure 9.2 Scatter plot of CR10 turbidity against the Model of SS using particle size.

A common approach for determining export loads is to use flow-related sampling (Simpson, 1992). The suspended solids, nitrates and phosphates trends were determined from flow-related grab samples which were collected from the field at weekly intervals. These were found to be inadequate for the analyses required in many instances. The sampling rate was generally too high for small storms and too low for large storms. The main problem with the flow-related grab sampling strategy in this project was changing the bottles when there was a suitable storm event. The access roads to the weir had to cross the river and this was often inaccessible during large storm events because of flooding.

Continuous observations and flow related samples were derived for conductivity and turbidity using the same laboratory instrument. These were used to investigate the difference in export loads between continuous hourly measurements and flow-related samples.

Several sets of storm measurements were partitioning using the observed hysteresis in turbidity observations. The mean water quality values for both partitions indicated a significant (<99.9%) difference between the suspended solids, nitrates and phosphates in the rising storm turbidity-graph (sediment-graph) and the receding turbidity-graph. However, the analyses of each specific storm shows a very large variability within the storm event and between events.

9.4 TYPICAL STORM RESPONSE

A composite model of selected storm events was developed by synchronizing all the peak discharges and then superimposing (averaging) the hourly values in the periods before and after the peak. The composite storm model shows the same basic features as those describe above but obviously lacks some of the temporal resolution due to the composite technique employed with different size storms. The composite storm is intended to portray typical conditions for specific rainfall events. However, the inclusion of atypical events in the composition can distort the model. The composite model of nitrate response is probably composed of two separate models.

There are several storms that do not conform to the composite model and these are discussed as individual case studies. There is an antecedent effect in turbidity for storms that occur fairly soon after a major storm event. Generally the initial storm removes the bulk of the turbid material that is then not available for the subsequent storm event. There are also cases where the conductivity response does not occur immediately with the increased discharge but is delayed several hours. This appears to occur after drought conditions when the catchment is too dry to support surface flow and there is time for the sub-surface "old" water to contribute initially to the discharge runoff. "Un"fortunately there were not enough opportunities to verify this assumption.

10 CONCLUSIONS & RECOMMENDATION

The project has identified some of the water quality responses that can be linked to hydrological pathways. However, the relationships between many of the water quality constituents and the hydrological processes are complex and not easily identifiable, particularly through the application of grab sampling. The difference in estimated discharge loads of an intensive flow related grab sampling system and a continuous monitoring system can be gauged from the cumulative Suspended Solids load from W1H016, for 1993-94 season, shown in Figure 10.1. The difference in the cumulative loads is almost entirely due to difference in the estimates derived from individual storm events (the vertical impulses in Figure 10.1). The short duration high intensity storms cause large changes in some selective water quality factors. These changes are generally associated with the peak flow rates and in some cases they last for a very short period (hours). Because they are associated with peak flows they contribute a significant amount to the overall discharge loads from these catchments. Consequently, any sampling strategy which does not capture these events will have a large error component. Any monitoring system which does not capture these events would grossly underestimate the loads for these conditions.

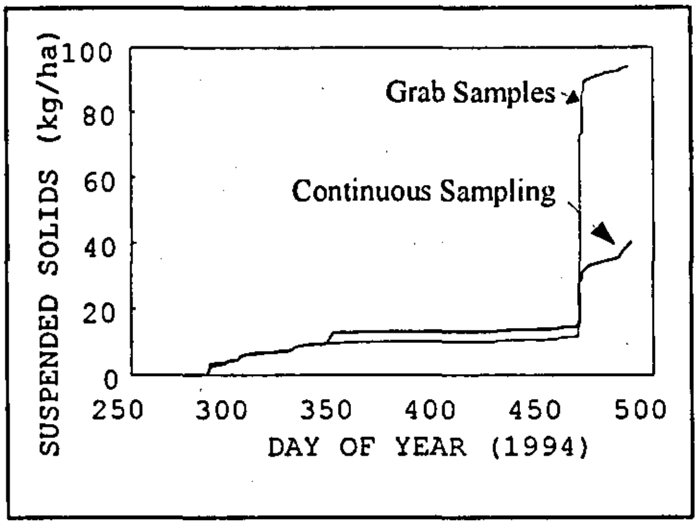


Figure 10.1 Difference in cumulative export coefficients derived from different sampling methods.

The flow related grab sampling methods used in this study used the most practical rate of monitoring possible. The study used a much higher rate (every 2000 m^3) than the usual weekly or monthly sampling rate adopted by many agencies. Consequently, regular weekly or monthly sampling of discharge from small catchments with frequent short duration high intensity storms may be inadequate for monitoring the discharge loads of the system.

Flow related grab sampling may be adequate for estimating export loads from a catchment but they are inadequate for determining the relationship between water quality characteristics and hydrological processes. The continuous monitoring system developed in this study is capable of achieving any required temporal resolution, but it requires constant maintenance and is susceptible to numerous errors. Since the weekly and monthly monitoring systems require site visits, the maintenance of the system is no more expensive. The difference in cost between running the laboratory analysis and purchasing the continuous system instrumentation is probably similar. However, the continuous system does provide many additional advantages for water quality monitoring. It can provide realtime monitoring and the information is in digital format. However, the ease with which the system can be altered (upgraded or program changes) or left to deteriorate, could reduce the uniformity of the present regular sampling strategy. Further studies on the suitability, reliability and sustainability of the continuous monitoring systems are required.

The monitoring system identified many changes in the water quality response to significant storm events. A typical relationship for short duration high intensity storms was suggested (Figure 10.2). However, there were many atypical events which need further investigations. The only relationship which was sufficiently regular to use as a tracer was the

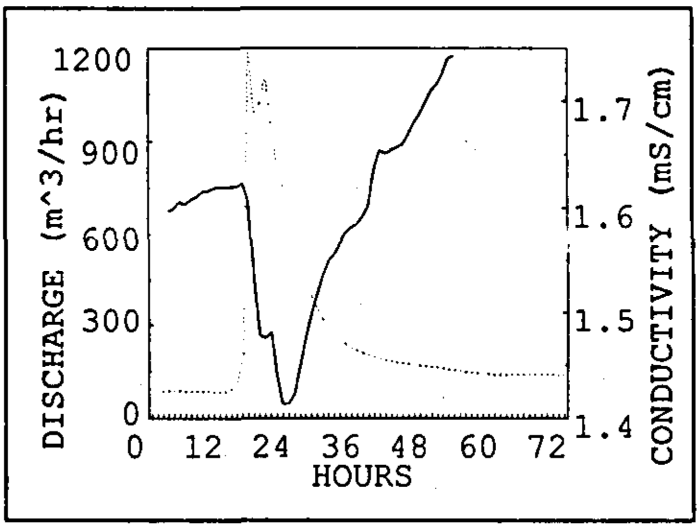


Figure 10.2 Example of a typical relationship between conductivity and hydrological conditions.

change in conductivity. However, the use of this in other catchments needs to be investigated.

Additional research with more intensive monitoring system using higher resolution sensors is needed to delineate the hydrological pathways if natural tracers are to be used. Numerical spatial analysis methods presented in an accompanying report (Kelbe, Snyman and Mulder, 1996) are being developed to link the pathways in a catchment with source and sink areas. The method is designed to predict the theoretical hydrograph and chemograph response to various land uses (pollutant sources) which can be used to target specific section of the hydrograph in order to establish a more intensive monitoring system.

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