UNIVERSITY OF SOUTHAMPTON

INTERACTIONS BETWEEN BANANA PLANTATION AGRICULTURE AND THE LAND-OCEAN SUSPENDED SEDIMENT FLUX: BELIZE, CENTRAL AMERICA

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Abstract

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Land-Ocean Interactions in the Coastal Zone (LOICZ) are receiving high profile international attention. A core focus of this research has been to understand how anthropogenic forcing functions interact with fluvial suspended sediment delivery to the coastal zone over time and space. Recent concern about sedimentation stress on the Belizean barrier reef has emphasised the importance of monitoring this process relative to key anthropogenic drivers of fluvial suspended sediment delivery from the land to the ocean.

Interactions between banana plantation agriculture and the sediment delivery process are poorly understood, despite the location of numerous plantations throughout the coastal plain river network in southern Belize. The high profile of the banana industry as a major employer and as the country's largest export earner, necessitates the focus of immediate attention on this issue to prevent any future conflict between environment and development.

This research has offered a characterised conceptual model based on the LOICZ framework to promote the understanding of interactions between the plantation, fluvial and coastal systems of the Stann Creek District in Belize. The driver, transfer and delivery mechanisms comprising the continuum of sediment movement from the plantation to the peripheral environment were investigated during four months field research between April and August 1998.

Driver research focused on interactions between climate, hydrology and agricultural practice within a 5.5km plantation unit on South Stann Creek. Agricultural drainage channels - essential for rapidly discharging excess storm water away from the plantation to the nearest creek, were identified as fundamental mechanisms for delivering suspended sediment to the fluvial system during local storm events. Within the transfer system a provisional fluvial sediment budget was calculated from suspended sediment concentration (SSC) and discharge dynamics upstream and downstream of the characterised banana plantation unit. Results suggested that sediment load increased by approximately 200 tonnes within the budgeted reach, constituting a net increase in basin sediment yield to the coastal zone of 16% during the monitoring period. The delivery system was investigated through a feasibility study of *in-situ* and remote methods for monitoring the flux of sediment discharged from South Stann Creek to the Belizean coastal zone. System characterisation took place through spatial estimates of secchi transparency for insertion into a framework integrating fluvial sediment yield. A conceptual model was developed for future monitoring of the sediment flux pending forthcoming advances in observation technologies.

Interactions between the driver, transfer and delivery components of the system were subsequently explored over time and space within an integrated framework to provide a platform for future model calibration and understanding within the continuum and within the wider Belizean coastal zone. Monitoring and management options for the banana industry were considered within a cost-benefit model promoting the integration of science and management and the development of system understanding within the wider scale of change.

To Grandad

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Chapter 1

Introduction to the research

§1.1 General Concepts

The world's coral reefs are changing. High-profile reports of degradation, recovery and cyclical change have firmly positioned "Rainforests of the Sea" in the global media over recent years (UNEP, IOC, WMO, WWF, ICUN, 1993). International monitoring initiatives have focused attention on the Pacific Rim, Indian Ocean and Caribbean reef systems where studies have been striving to identify patterns in the extent, nature and cause of change (Hatcher, *et al.,* 1989).

However, despite its recent topicality within environmental change research, global coral reef monitoring is still very much in its infancy. It has only been within the past twenty years that underwater technologies have advanced sufficiently for large scale monitoring initiatives to be practical. Indeed, the boundaries of marine research are still fundamentally defined by the breadth of logistical challenges that the ocean presents (Sapp, 1999).

Researchers are now beginning to understand the mechanisms by which localised environmental conditions affect coral physiology*. We know that if the penetration of sunlight through the water column is restricted then photosynthesis by microscopic algae found in coral tissues, known as *zooanthellae*, will slow down and subsequently stunt skeletal growth (Hughes, 1980). We know that if unusually large quantities of cohesive sediments and associated contaminants settle on coral polyps then the organisms will become smothered, accelerating reef deterioration and promoting coral death (Hunte & Wittenberg, 1992). We know that stress symptoms will

---

* Corals are small animals that tend to group together by the thousands creating colonies that attach to the hard surfaces of the sea floor. They take in calcium carbonate from the sea-water and convert it into hard skeletal structures, which may be found in a variety of forms. These species collectively form the limestone framework of tropical reefs.

They are, contrary to popular belief, members of the animal kingdom and are classified as *Phylum Cyndaria.* All reef systems are characterised by constant death and new growth, explaining their popular analogy with tropical rainforests.

Corals are usually divided into two groups, hard and soft corals. Soft corals have a protein-like skeleton, and are less vulnerable than hard corals to environmental modifications, due to their flexible form and fast rate of growth. Although they do not secrete calcium carbonate they are an integral part of the coral reef system and are good indicators of reef health. Hard corals are best known for their contribution to barrier reefs and are subsequently known as *reef forming corals.* They are extremely vulnerable to external environmental changes and require warm water (usually above 18°C) with low concentrations of suspended sediment and contaminants, sunlight and a firm growing foundation. These conditions are usually found within the tropics where the majority of today's coral reefs may be seen.

begin to develop in reef communities where localised environmental conditions are modified, affecting the basic physiological requirements for coral growth.

However, we know very little about the relative contribution of global, regional and local system drivers to changing conditions within the reef environment and how these operate within space and time. Indeed, distinguishing between "natural" cyclical events and anthropogenically driven change within the coastal zone has proved to be exceedingly difficult, especially where cause and effect are often separated by significant gaps in time and space (IGBP, 1993).

Despite the very real challenges presented by this issue, it can not be neglected until the wider system is understood. Whilst researchers are attempting to piece together the jigsaw of interactions between global change and human development, anthropogenic activities are continuing to change the nature of the systems that we are trying to understand.

It is now increasingly realised that to understand anthropogenic impacts on regional change, localised studies are required that use solid science to identify direct cause and effect mechanisms between human activity and change within the coastal zone (IGBP, 1999). Such studies may later be amalgamated to comprise the base level data for larger system studies.

However, when striving to understand links at the local scale between human activities and change within the marine environment, economic development issues arise. The majority of the world's coral reefs are located within the humid tropics where environmental resources are particularly rich (Hughes, 1980). Industries such as agriculture, aquaculture, fishing, mineral exploitation and tourism are subsequently of immense value and importance to regional economies. Indeed, activities dependent on environmental resources are the principal economic base for many post-colonial developing countries within the tropics (E.I.U, 1999).

Belize, is no exception. Formerly British Honduras, Belize is located on the east coast of the Yucatan Peninsula in Central America (Figure 1.1).

Belize hosts the largest barrier reef system in the Western Hemisphere, second only to Australia's and is unmatched within the Caribbean for its tremendous wealth of marine and coastal resources. However, it is well recognised that the coastal systems of Central America are changing (CCAD, 1997).

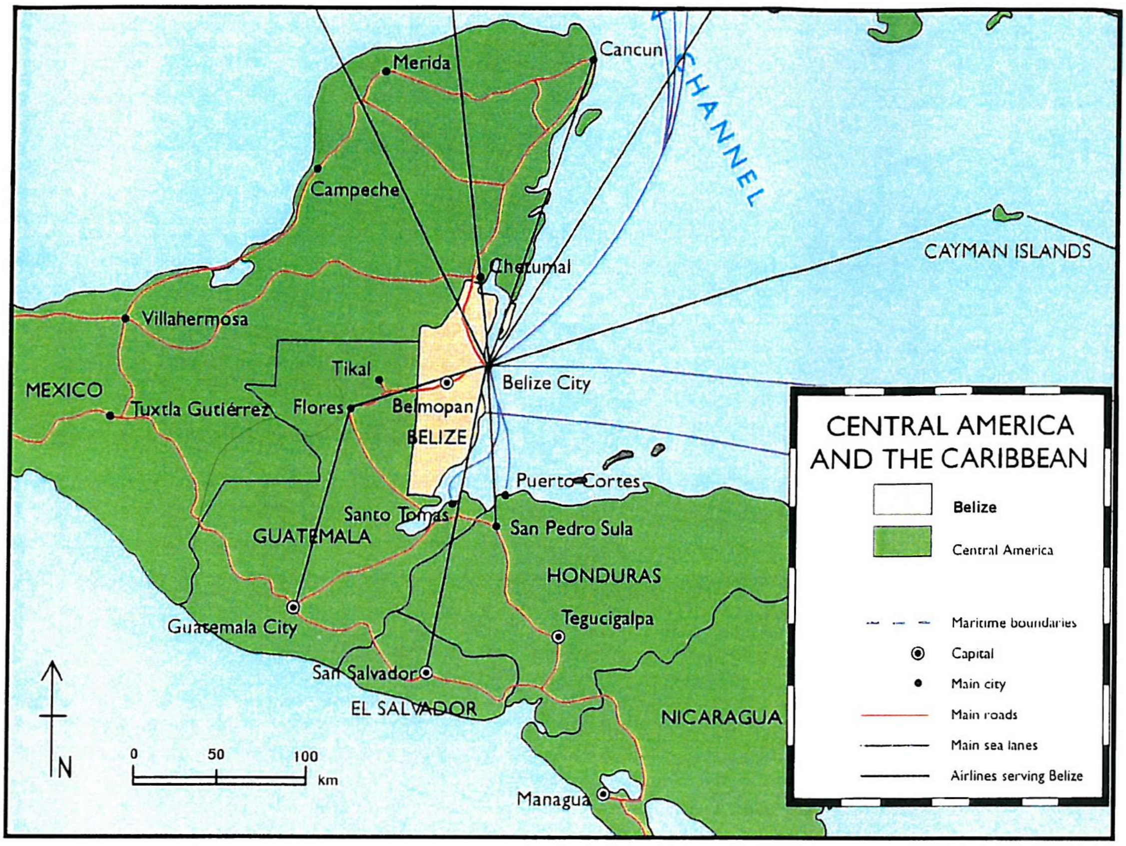


Figure 1.1: Belize, Central America (Adapted from Cubola Productions, 1996 (Atlas of Belize))

Despite reports in the early 1990's indicating that the Belizean barrier reef has suffered little disturbance from human activity (Smith & Ogden, 1993), it is now widely recognised that the system is threatened by a wide range of processes operating within the coastal zone (G.O.B., 1999). Indeed, a significant increase in development activity has occurred throughout this region over the last decade. Whilst commercial agriculture, fisheries and tourism development drive the Belizean economy, generating substantial revenue in foreign exchange, recent concern has been expressed with respect to the potential impact of these activities on the marine environment (Mumby, *et al.,* (1995), Stednick, *et al.,* (1998)). In particular, changing conditions such as elevated fluvial sediment and contaminant delivery to the coastal zone from agricultural activities within the drainage basin, have been identified as potentially serious threats to the health of the reef system (Hall, 1994). Such activities have been tentatively connected with processes such as elevated sedimentation and algal growth within the reef zone, although it is recognised that this is an important area for more research and that there are many potential drivers of such processes (GESAMP, 1994).

Changing conditions within the reef system will, therefore, be a complexed function of integrated anthropogenic and "natural" causal factors (Brown, 1987). It is subsequently of immeasurable importance that key anthropogenic drivers are identified and monitored, so that they may be distinguished and managed accordingly. At the present time there is a distinct lack of quantitative data relating to these drivers and their respective position within wider system interactions.

The research presented in this thesis provides an integrated approach to understanding interactions between banana plantation agriculture on the southern coastal plains of Belize and fluvial suspended sediment delivery to the Belizean coastal zone.

There has been little research relating to the role of banana plantation agriculture as a driver of suspended sediment to adjacent fluvial and coastal environments. Within Belize there is a distinct lack of data linking anthropogenic drivers of suspended sediment to processes operating within the coastal zone. Whilst, somewhat pre-empting an understanding of coastal suspended sediment dynamics in Belize, the philosophy of this research is that given such a dynamic system, anthropogenic drivers require immediate definition for the subsequent insertion of base level data into monitoring and management frameworks.

Therefore, whilst set within the broader context of barrier reef system change, this research is focused towards understanding integrated processes at the local to regional scale, between banana plantation agriculture, the fluvial system and the coastal zone. This has been used to promote the extrapolation of a conceptual framework to broader programmes of monitoring and management within the area. The high profile of the banana industry in Belize has underpinned the need to understand the immediate and future nature of interactions between agricultural development and environmental change within the Belizean coastal zone, hence preventing potential conflicts between environment and development.

§1.2 Research Objectives

The fundamental objective of this research is to identify the nature of interactions between banana plantation agriculture, the fluvial system and the coastal zone to assess whether the industry acts as a significant driver of suspended sediment to the Belizean barrier reef system. In achieving this objective, this thesis provides information on a number of aspects of the interrelationships between hydrology, agricultural practice, suspended sediment transfer and delivery for the catchment and associated coastal zone of South Stann Creek, in southern Belize:

- A characterised conceptual model of the relationship between hydrology, agricultural practice and suspended sediment delivery from banana plantation agriculture to the fluvial system.

- A fluvial suspended sediment budget for a banana plantation unit adjacent to South Stann Creek.

- A characterised spatial conceptual model of fluvial suspended sediment delivery from South Stann Creek to the associated coastal zone.

- An integrated framework for linking suspended sediment behaviour at the mouth of South Stann Creek to system drivers.

Within this conceptual framework, options are also assessed to formulate a cost-effective monitoring and management strategy for the banana industry.

§1.3 Research Hypotheses

To meet the objectives outlined above three key research hypotheses were developed for investigation:

1. Practices used in banana plantation agriculture interact with the hydrological and geomorphological systems of the drainage basin to increase suspended sediment delivery to the fluvial system during storm events.
2. Fluvial suspended sediment load in a reach adjacent to a banana plantation unit is likely to increase during episodic storm events.
3. Changes to suspended sediment load associated with banana plantation agriculture may be conveyed to the drainage basin outlet and the associated coastal zone.

Together with research objectives outlined in §1.2 these hypotheses identify the need for an integrated approach to understanding interactions between banana plantation agriculture and the land-ocean sediment delivery system to prevent potential conflicts between environment and development in the Belizean coastal zone. Field research was conducted during one extended field season period.

The research reported in this thesis was sponsored by Fyffes UK Ltd as part of their commitment to understanding the environmental implications of the banana production industry. Activities and preliminary findings were reported to the sponsor during the research, but at no stage did the sponsor suggest or impose any direction for, or constraint on the study.

§1.4 Outline of Thesis Structure

The following section provides an outline of thesis structure. To address the objectives defined above, the thesis has been divided into 8 chapters. This has facilitated the transgression throughout the thesis from a general overview of land-ocean interactions in the Belizean coastal zone to an integrated study of the continuum of sediment movement from banana plantation agriculture to the coastal zone, culminating in a monitoring and management framework for future research.

Chapter 2 divides into two parts. The first of which discusses global, regional and local perspectives on anthropogenic sediment delivery interactions within the Belizean coastal zone. Research has been introduced within the integrated framework of the International Geosphere Biosphere Project (IGBP) core initiative, Land – Ocean Interactions in the Coastal Zone (LOICZ). The second part of the chapter gives a background to the physical and climatic characteristics of the study area within southern Belize. *Chapter 3* introduces the banana industry within Belize within the context of sediment delivery interactions between the plantation and the river system. Relationships between hydrology, agricultural practice and fluvial suspended sediment delivery are examined within this chapter. *Chapter 4* divides into two parts, the first of which discussed the value of using a sediment budget for understanding anthropogenic drivers of suspended sediment to the coastal zone and outlines the methodology for monitoring the net input of suspended sediment to the river system from a banana plantation unit during a field monitoring programme. The second part of the chapter presented results obtained during the monitoring programme and discussed data quality. *Chapter 5* presents an overview of the value of remote sensing and coastal suspended sediment plume monitoring techniques for evaluating the spatial extension of a turbid sediment plume into the Belizean coastal zone. Methods were discussed and demonstrated for linking a budgeted fluvial sediment yield to a spatial framework for conceptualising the continuum of sediment movement from the land to the ocean. *Chapter 6* discusses in more detail the nature of linkages between the components of the sediment delivery continuum from the plantation to the coastal zone. Data quality has been given further consideration in this chapter. *Chapter 7* outlined the potential options for monitoring and management prior to discussing their insertion into future programmes of research and development within the water quality and agricultural land management communities of Belize. *Chapter 8* presents conclusions and offers a perspective on research findings.

The components of thesis structure may be seen in Figure 1.2:

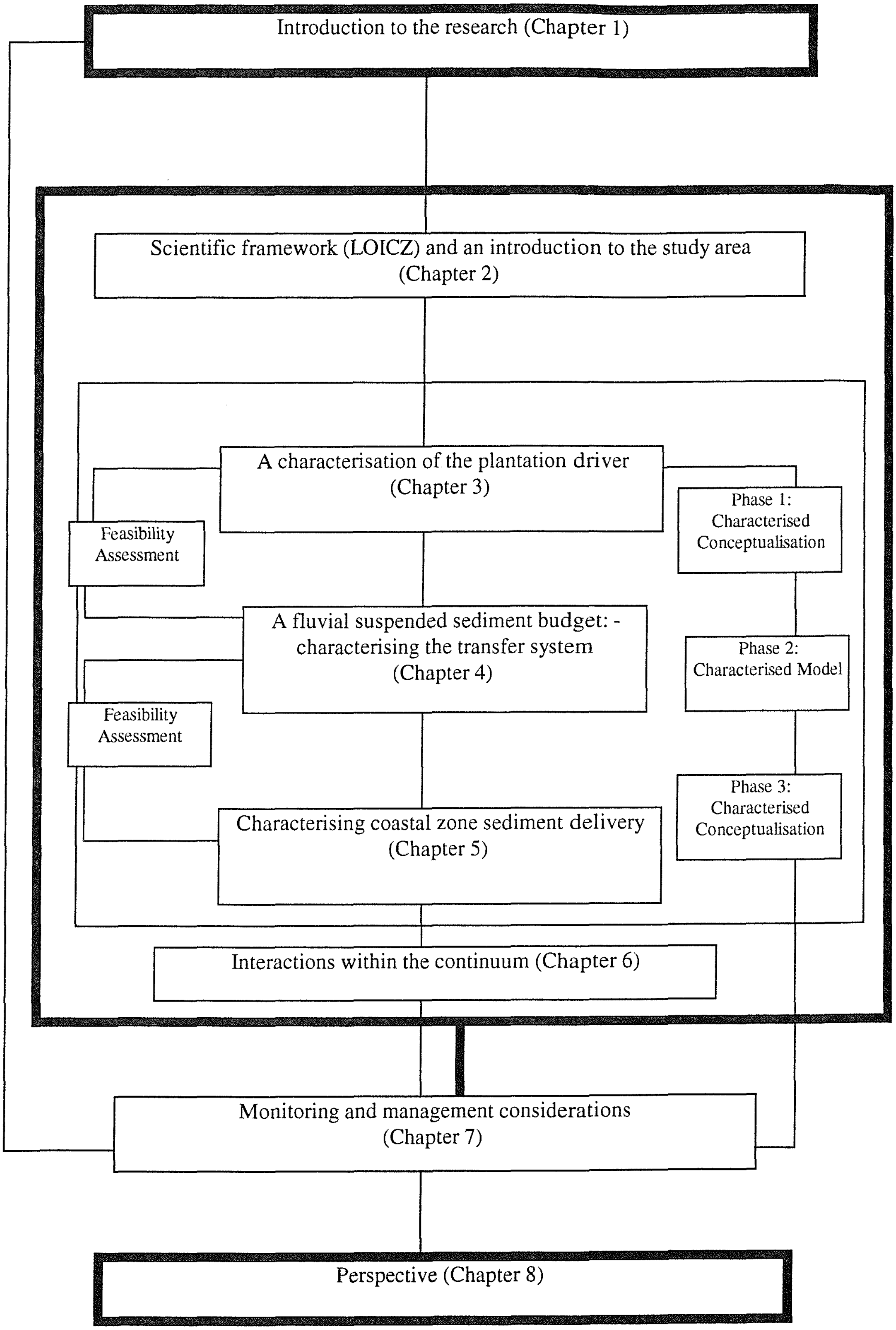


Figure 1.2: Thesis structure

Chapter 2

Global, regional and local perspectives on anthropogenic sediment delivery to the Belizean coastal zone and Introduction to the study area

§2.1 Introduction

> *"Human land and sea use are already causing changes in coastal environments at local, regional and continental scales and altering the fluxes of freshwater, sediment and nutrients from the land to the ocean. The effects are both direct, due to dense human populations along the coastline and indirect as a result of human activities within catchment systems. The extent to which changes are already altering the function of coastal ecosystems and hence change the role of these systems in global biogeomorphological cycles is uncertain. To evaluate this issue in relation to sediment dynamics, the fluxes and fates of terrestrial material derived from riverine inputs...must be better documented."*
>
> (IGBP, 1995)

Interactions between the drainage basin and the coastal system across the land – ocean interface are fundamental moderators of environmental change (IGBP, 1999). However, drainage basin and coastal system research have essentially developed along separate paths, resulting in the rather fragmentary history of scientific thought concerning land – ocean interactions in the coastal zone. In particular, research into the continuum of sediment movement from the drainage basin to the marine system has effectively disintegrated across inter-disciplinary margins, where drainage basin sediment delivery and near-shore coastal - ocean processes have seldom received holistic attention.

An integrated approach to understanding this continuum is now of significant importance as increased pressure has been placed on coastal resources across the globe. There is a need to understand the anthropogenic and natural forcing functions of change within regional and global systems. The International Geosphere - Biosphere Project's (IGBP) core initiative "Land – Ocean Interaction in the Coastal Zone" (LOICZ) provides a valuable international research base for studies within this area.

The scientific planning team for LOICZ was created in 1990 and by 1992 the "LOICZ science plan (IGBP, 1993)" was developed. The plan outlined:

> ***"the issues and uncertainties concerning the role of the coastal sub-system in the total Earth system and the possible nature of changes which might be expected under scenarios of future change"***
>
> (IGBP, 1995)

This plan resulted in the development of an "implementation plan (IGBP, 1995) that paved the way for scientific research tasks and activities concerned with collaborative coastal LOICZ research ultimately to:

> ***"contribute to the resolution of the issues and uncertainties originally outlined in the science plan"***
>
> (IGBP, 1995)

The present status of LOICZ implementation has just seen the 4th Open Science Meeting in Bahia Blanca, Argentina, where focus was given to Latin America, the human dimension of coastal change and the potential for global LOICZ synthesis (IGBP, 1999).

Interactions between banana plantation sediment delivery and coral reef sedimentation within the Belizean coastal zone may be investigated and understood within the IGBP-LOICZ framework (Delaney, *et al.,* 1999), (Appendix 2).

This chapter has been divided into two parts. The first discusses the value of an integrated land-ocean framework for understanding sediment delivery mechanisms within the Belizean coastal zone. The notion that the coastal zone is a dynamic interface between the physical *and* economic environments of the drainage basin and marine system has been introduced with respect to developing the application of the LOICZ typology to plantation / fluvial/ coastal lagoon and reef interactions in Belize. The second part of the chapter provides a background to the study area and introduces the climatic characteristics of Belize's southern coastal zone.

§2.2 Land – ocean interactions in the coastal zone – the forces of change

The coastal zone may be defined as:

> ***"That space in which terrestrial environments influence marine environments and vice versa"***
>
> (Carter, 1989)

Land – ocean interactions in the coastal zone are attracting considerable research attention at the present time (e.g. Zeldis & Smith, 1999). High profile international monitoring programmes have emphasised the importance of processes operating across the land – ocean interface within the framework of the coastal zone. Particular attention has been given to the anthropogenic component of this, as a force that drives and responds to cumulative and systemic change within the reef environment. This section discusses the development of international awareness surrounding this issue and highlights key areas where more research is urgently required.

§2.2.1 Anthropogenic activity within the coastal zone

Man's influence on the marine environment is certainly not a new concept. Studies dating back to the 1970's (e.g. Goldberg, 1976) have considered human impacts on coastal ocean processes. However, this attention was exclusively reserved for activities performed directly in the ocean (GESAMP, 1990). Over recent years it has become clear that there are wider spheres of influence, where human interaction with Earth system processes across land, ocean and atmospheric boundaries may have considerable repercussions throughout the marine environment (IGBP, 1990). In particular, it has increasingly been recognised that man's activities within the drainage basin are often inextricably linked to processes occurring within the coastal and open ocean (IGBP, 1993).

The need to understand the nature of land - ocean interactions has driven a wave of monitoring initiatives concerned with understanding anthropogenic impacts on the coastal zone. Particular attention has been given to the potential link between coral reef deterioration and human activity within the drainage basin (Brown, 1987).

In October 1994 the IGBP-LOICZ core project team, the Intergovernmental Oceanographic Commission (IOC) and the World Conservation Union (WCU) met at the "Expert Meeting on Coral Reef Monitoring, Research and Management" ((IOC-IUCN-LOICZ/WKSHP/94.4) IGBP, 1995) to discuss the formulation of a LOICZ scientific agenda for research in this area. Understanding the response of coastal biogeomorphological systems to anthropogenic activity from within catchment systems was highlighted as a key research area:

> ***... "the major goals (of this Subtask) will be to assess past and potential sediment, nutrient and toxic chemical loads of major rivers discharging into coral reef areas..."***
>
> (IGBP, 1993)

Recent conservation initiatives concerned with researching patterns of degradation across the coastal zone and their causes, such as the "International Year of the Reef" (1997) and "International Year of the Ocean" (1998) have also served to provide a global context for international and regional research efforts along this vein. The realisation that activities taking place hundreds to thousands of kilometres from a marine environment may be linked to pollution events within the coastal zone has promoted the need to monitor, understand and predict anthropogenic influences on the coastal zone at all levels.

§2.2.2 A drop in the ocean? Cumulative and systemic change within the coastal environment

Changes to coastal environments are associated with a multitude of factors ranging between human influence on physical processes, global change and natural cyclical events (Brink, 1987). The identification and evaluation of these interactions is of key importance both in terms of global system modelling and local environmental management. However, there have been significant difficulties with quantifying the extent of interaction between the coastal zone and its peripheral environment. The principal difficulty lies in reliably monitoring and predicting cause and effect relationships between parallel systems where for the most part they are separated by substantial gaps in time and space (IGBP, 1995). Relative to the identification of anthropogenic impacts on the atmospheric system where process interactions between cause and effect are often more rapid, the coastal zone is significantly more challenging.

This difficulty is particularly prevalent when attempting to understand the processes responsible for the global deterioration of coral reefs. The general trend towards a decline in worldwide reef productivity has received considerable coverage in the public media and physical sciences over recent years (e.g. The Times, (1997), Johannes, (1975)). Extensive research has demonstrated the potential for a link between systemic changes such as sea level rise, increased ocean temperatures, accelerated hurricane and tropical cyclone disturbance and widespread coral death (IOC, 1992). At the same time cumulative changes, such as anthropogenic modifications to sediment dynamics within the drainage basin and throughout the coastal zone, have been associated with a decline in reef productivity (Rogers, 1990)[†].

[†] Unusually large quantities of suspended sediment within the marine environment may result in extensive problems for coral communities. Sediment may affect corals directly, by swamping coral polyps (Johannes, 1975), or indirectly by raising water temperature and turbidity, preventing photosynthetic activity, stunting growth and promoting algal growth (Grigg & Dollar, 1990). Chemical contaminants, sorbed to fine sediments have also been found to accelerate algal growth and alter the physiology of coral species (Tomascik & Sander, 1987). Sedimentation stress on shallow reef communities has been given extensive attention throughout the literature. Hatcher, *et al.*, (1989), provides an excellent review of research relevant to this issue.

The principal challenge in attempting to understand cause and effect relationships between cumulative and systemic change and reef deterioration is that the effect i.e. modifications to sediment dynamics within the coastal zone, may respond in the same way despite many causal factors. The dual role of suspended sediment as a natural component of environmental systems and a pollutant of fragile habitats within the coastal zone, complicates source identification and system budgeting (IGBP, 1990). There are significant difficulties in differentiating between short-term anthropogenic cumulative change and long-term global systemic modifications to the marine environment. Although it may be assumed that changes in sediment delivery to marine habitats over the past couple of decades are largely attributable to anthropogenic influences within the coastal zone, the fact that the effects can not be quantified, gives rise to serious difficulties in understanding direct causal factors.

Controls over the flux of sediment to the coastal zone are, therefore, of significant importance and demand vigilant monitoring to facilitate understanding of the relationship between cumulative anthropogenic inputs of material to the marine environment and longer-term systemic change. There is a need to discriminate between natural and human forcing functions of change across the land – ocean interface both in terms of local coastal resource management and global process modelling.

§2.2.3 Drainage basin sediment delivery to the coastal system: The anthropogenic link?

The flooding of the continental shelves at the end of the last glacial resulted in the formation of a number of shallow seas (Brink, 1987). These seas work effectively as a "reaction vessel" for all the material delivered to the coastal zone from natural and anthropogenic sources (IGBP, 1993). This material would previously have been discharged to the open ocean directly. Subsequently, the coastal zone has a higher level of biological productivity than the open ocean, although at the same time it is more vulnerable to the effects of anthropogenic pollution.

The majority of anthropogenic pollution enters the coastal system through "point inputs" of suspended river material (IGBP, 1995). The "mobility" of suspended matter facilitates the transfer of change from catchment land – use processes through the fluvial system to the land – ocean interface. Although suspended matter may be composed of sediments, nutrients and contaminants, suspended sediment is by far the largest component of the total load and the transfer of nutrients and contaminants through the system will be strongly related to its movement. Monitoring the fluvial sediment flux will, therefore, be of significant benefit to studies aiming to understand anthropogenic pollution from nutrient and contaminant loading within the coastal zone.

Suspended sediment is maintained in the water column through turbulent mixing processes that counteract settling of the particles under gravity (Gurnell, 1987). Interaction frequently takes place between the components of a river sediment load and there may be times when bed load is suspended and *vice versa* or suspended sediments go into solution and become part of the dissolved load. Such dynamic characteristics serve to promote the mobility of suspended sediment after it has left the catchment system in its transfer across the land – ocean interface. It has been reported that fluvial inputs of suspended sediment to marine habitats may significantly impact biogeomorphological processes. This is particularly evident in shallow reef environments:

> ***"Since many coral reef communities exist in shallow and/ or enclosed water bodies or in close proximity to major land masses, river flow may transmit the effects of land and water use practices occurring hundreds to thousands of kilometres from the reef itself."***
>
> (IGBP, 1995)

Due to the transferable nature of suspended sediment, there is a *potential* for anthropogenically derived fluvial sediments to interact with coral communities within the coastal zone. However, it should be noted that numerous environmental and physical variables control the dimensions and extent of this interaction. Variations in river suspended sediment delivery occur across a range of temporal and spatial domains. Interactions between the physical properties of a drainage basin, anthropogenic activity and climate serve to drive catchment suspended sediment generation, transfer and delivery. The scale of transition ranges between long-term global sediment flux modifications to periodic changes in catchment sediment output.

The importance of these interactions, both in terms of global system processes and for local environmental management has driven a number of major research initiatives into attempting to quantify and ultimately qualify river suspended sediment delivery to the coastal system. The first comprehensive database of such data was created by Milliman, *et al.*, (1995), who developed the Global River Index (GLORI), following the earlier work of Milliman and Meade (1983) and Milliman and Syvitski (1992). This volume provided a central index of river discharge to the sea. At the same time, a number of studies attempted to understand general patterns in the land – ocean sediment flux associated with different fluvial environments. In particular, it has been reported that small drainage basins deliver a disproportionately large quantity of suspended sediment to the sea (Milliman & Syvitski, 1992) and it is thought that they account for much of the variability in the global sediment flux. Human disturbances to sediment dynamics appear to be conveyed more efficiently to the river mouth in smaller catchment systems that can not adjust to rainfall events in the same way as larger basins (Milliman, *et al.*, 1996). Activities such as agricultural development and urbanisation mobilise sediments for subsequent discharge from the system.

Within geomorphological research, river sediment delivery to the coastal system has been understood within the framework of "sediment yield" investigations. Sediment yield is seen as a "useful perspective" on erosional and depositional processes occurring within the catchment (Walling, 1988) whilst also providing a quantification of sediment eroded within the catchment. However, caution has been expressed for any studies striving to ascertain a *direct* link between anthropogenic activity upstream and basin sediment yield:

> ***"Only a fraction and perhaps a rather small fraction of the soil eroded within a drainage basin reaches the basin outlet and is represented in the sediment yield."***
>
> (Walling, 1988)

Episodic climatological events have been found to play a particularly important role in controlling sediment discharge from the drainage basin to the marine system across the land – ocean interface (Milliman & Meade, 1983). This may be seen particularly in tropical environments, where the frequency of episodic events tends to be greater than in other parts of the world and where the extent of anthropogenic disturbance throughout the catchment is often considerable (e.g., Douglas, 1996). It has also been found that in humid, tropical environments significant variation exists in the transport of suspended load compared to that of temperate fluvial environments. There appears to be a trend towards the episodic transfer of particularly large suspended loads through the system during the rainy season which contrast greatly with the low sediment concentrations characteristic of the dry season (Thomas, 1974).

At the same time, the humid continental shelves are also noted for their marine bio-diversity and most present day reef communities are found within humid tropical environments (Hughes, 1980). Episodic sediment delivery to the coastal zone associated with interactions between climate, natural change and human activity is therefore a particularly challenging issue within these regions. However, the environmental impacts of extreme episodic events on the coastal zone are usually only observed by chance and hence remain poorly understood with respect to interactions between the land and the ocean. This is widely recognised as an important area for further research (IGBP, 1993).

Anthropogenic interaction with river suspended sediment delivery to the coastal system is, therefore, a highly topical and pressing issue, especially where fragile marine habitats are located adjacent to the drainage basin. However, numerous environmental controls govern the nature of interaction between system components and any attempt to understand the "anthropogenic link" must give careful consideration to the multitude of factors at local, regional and global scales that interact to drive change within the coastal zone.

§2.3 The global change framework: a multidisciplinary intellectual context

Over recent years awareness that land – ocean interactions are of immense relevance to global system research within the context of ongoing change has increased. Until the early 1990's river catchment process interactions with the near-shore marine environment were conceptualised within frameworks striving to understand catchment dynamics, the carbon cycle, and human impacts on the coastal environment (IGBP, 1995). Little attention had been given to the role of these interactions within global system processes. This was recognised by the IGBP in a 1989 workshop (IGBP, 1990b), which by 1991 culminated in the appointment of an IGBP core project planning committee for the development of a LOICZ science plan. Within the IGBP framework, the coastal zone has been recognised as a system that *responds* and *contributes* to global change. The position of LOICZ within this framework may be seen in Figure 2.1.

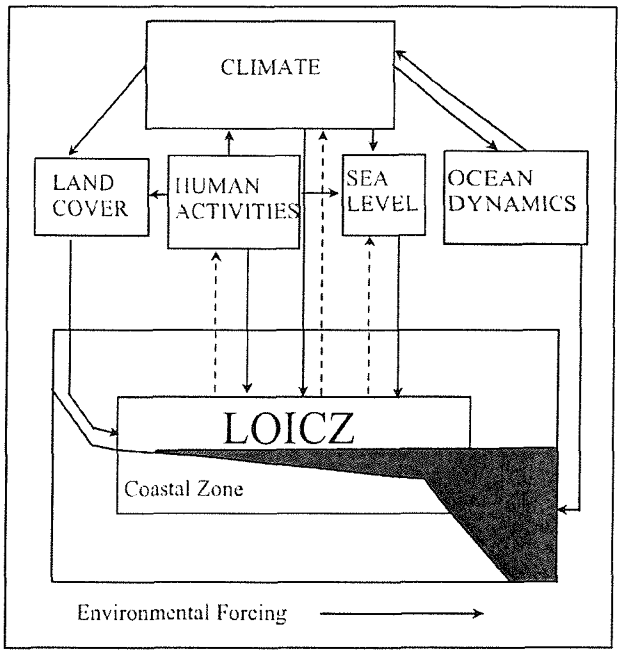


Figure 2.1: The position of LOICZ research within the IGBP framework (Adapted from IGBP, 1994)

§2.3.1 Understanding the fluvial sediment flux within global system change

The flux of fluvial sediment to the coastal zone is clearly of significant interest at the global scale. Sediment delivery to the marine system is a device through which many complexed feedback mechanisms operate where global alterations to the land – sea movement of material encompass a broad range of high profile research issues. IGBP – LOICZ science at a regional scale has been driven by the need to understand the global picture through an integrated research matrix. It is, therefore, essential for research conducted at the regional scale to consider the broader framework of change.

There are significant gaps in scientific knowledge surrounding the global pattern of fluvial sediment delivery to the coastal zone and its interaction with Earth system processes (e.g. Milliman & Syvitski, 1992). As a result it is most appropriate to consider the key areas where present knowledge is lacking and subsequently identify specific issues that demand greater research attention.

Primarily, there is a great need to understand feedback responses in the coastal system to climatic forcing conditions at the land – ocean boundary. Such mechanisms will have significant impact on global physical, chemical, and biological cycles and must be fully understood prior to system management. Notably accelerated anthropogenic sediment delivery to the coastal zone has been associated with changes to biogeomorphological interactions between the drainage basin and marine system (GESAMP, 1993). Widespread modifications to coastal zone sediment input are intrinsically linked to the carbon cycle, through physiological changes to biological productivity and nutrient transfer (Kempe & Pegler, 1991). Such modifications will have significant impact on the economic value of marine and coastal resources across the globe.

There is considerable uncertainty within Earth system science as to the specific nature of interaction between sediment delivery to the marine system and feedback mechanisms associated with the global carbon cycle, sediment, chemical and nutrient pathways, and climatological change. The role of extreme events in driving sudden change within the marine environment is still poorly understood, as too are the effects of seasonal storms, driven by changes in physical forcing functions.

It is generally accepted that a series of complex feedback mechanisms exist between the components of the land-ocean sediment system. However at the present time insufficient data prevents values from being accurately given to these fluxes, and hence only tentative conclusions can be drawn about the nature of interaction between regional processes within the coastal zone and global change.

Suspended sediment interactions across the land – ocean interface are an integral component of earth system processes and their transition over time. Information on the quality and timing of the river borne material flux from the land to the ocean is essential for the construction of mass balance and biogeomorphological process models. Such information will guide the construction of unified global system models, which will provide a framework for linking the components of change across the land – ocean interface. Earth system models are essential to the positioning of regional process studies within the coastal zone, however, they can not be constructed without quantitative information on processes operating at this scale.

§2.3.2 Cumulative anthropogenic changes in the coastal zone within a global LOICZ framework

The coastal zone is an area that has encountered considerable stress over recent years. Within the international community and the public media it is an area that most people want to preserve from environmental, economic and aesthetic perspectives. Human development within the drainage basin and coastal zone challenge this ideal and it has increasingly become the focus of immense conflict between parties of different interests. As approximately 90% of anthropogenic pollution, i.e., sediments, nutrients, toxic chemicals and waste remain mainly in the coastal ocean (GESAMP, 1990) there is a strong argument that because of potential impacts on coastal resources these activities must be handled in a sustainable manner. Hence, coastal zone assets need to be sustained relative to ongoing changes in environmental and anthropogenic systems.

Earlier this century the flux of anthropogenic sediment from the land to the ocean exceeded the natural rate of flux (Milliman & Meade, 1983). Anthropogenically driven change within the coastal zone may be attributed to a number of factors, including population growth and tourism to agriculture and marine developments. In terms of drainage basin sediment delivery, a particularly important factor is the predominance of fertile agricultural land within the coastal zone. This serves to promote accelerated levels of land use change and agricultural development. Such development has become increasingly sensitive over recent years due to the perception that environmental features within this region are of greater importance than elsewhere.

The nature of anthropogenic change within the coastal zone subsequently needs to be understood if the monitoring and ultimate management of drainage basin sediment delivery are to be set within a comprehensive framework. Within the context of global change there has been growing recognition that the physical and economic components of this process need to be integrated to achieve a greater understanding of the human dimensions of change (IGBP, 1999b). However, to achieve this effectively, anthropogenic sediment delivery drivers need to be assessed at a finer spatial resolution, where economic and physical process interactions are defined at local to regional scales. Such information may subsequently be inserted into broader system models to contextulise and add meaning to data within a global sediment delivery framework.

§2.3.3 The importance of system models

Anthropogenic sediment delivery to the coastal zone needs to be quantified and modelled as a *pre-requisite* to understanding process interactions with biogeomorphological systems as a response to varying degrees of change. Up to the present day system models concerned with the above, have tended to focus on the magnitude of sediment transport (IGBP, 1995). Such models provide a core basis for integrated system modelling. There are however, numerous problems with this approach to understanding the global and regional patterns of sediment delivery to the coastal zone. These problems are related to advancing understanding of the forcing functions of change within the system. Processes operating within the drainage basin such as hydrology, land-use, etc. have essentially been ignored within such models due to wider concerns in data collection and assimilation being of priority. Quantitative and predictive models of processes operating with the catchment need be built into the framework of interactions between the land and the ocean. Without this there will be no comprehensive "story" of interconnectivity between cause and effect, even though it is recognised that in reality this "story" will be a rather complicated one. This framework, however, presents considerable scope for the integration of local and regional research projects into the global framework for understanding land – ocean interactions in the coastal zone.

Suspended sediment interactions between catchment land-use and biogeomorphological processes in the coastal zone are subsequently of considerable importance within the global framework of Earth system change and within the economic and environmental frameworks of local and regional change. Interactions across the land – ocean interface may be understood through the IGBP-LOICZ framework and further developed at the local to regional scale in accordance with local development objectives.

§2.4 The LOICZ framework

The value of the LOICZ framework as a tool for understanding interactions between anthropogenic activity within the drainage basin and sediment delivery to the coastal zone has been established. It is however, important to identify the key scientific themes of LOICZ that are central to this issue. Whilst the IGBP-LOICZ initiative is concerned with the identification, quantification and projection of physical processes operating at the land-ocean interface, the framework may be used as a base for understanding the interaction of economic development with the coastal ocean system. It is therefore essential that the boundaries of the LOICZ framework are identified, so as not to lose its value between physical and economic systems.

Of the LOICZ objectives, Focus 1: ***"The effects of changes in external forcing or boundary conditions on coastal fluxes"*** Activity 1.1: ***"Catchment basin dynamics and delivery"*** may be integrated with Focus 2: ***"Coastal biogeomorphology and global change"*** Task 2.2.2: ***"Indirect impacts of human activities on the coastal zone through changes in land and freshwater use that exert significant influences on the biogeomorphological processes occurring in the coastal zone"*** to create a comprehensive mechanism for understanding drainage basin sediment delivery to the marine environment. Focus 1 integrates physical drivers at the drainage basin scale with fluxes of material to the coastal zone, whilst Focus 2 integrates the human dimension of fluxes of material to the coastal zone with biogeomorphological processes. Anthropogenic drivers have been identified as an important focus of this activity where their identification, quantification and simulation over time have been prioritised. However, anthropogenic processes such as agricultural sediment delivery to the river system will be determined by a complex matrix of economic and physical variables. Whilst LOICZ provides a framework for the physical dimension of change, the understanding and subsequent management of processes at local scales demands the further integration of economic processes.

Therefore, within this research, economic drivers of anthropogenic sediment delivery have been treated in the same manner as physical processes (for example, where the spatial and temporal interaction of agricultural practices with suspended sediment delivery to the Belizean coastal zone have been considered in the same way as hydrological drivers). This expansion of the LOICZ theme to economic processes at local – regional scales promotes the ultimate management of system components. However, the physical dimensions of process interactions between the drainage basin and the coastal zone should constitute the framework for *understanding* and potentially *managing* economic drivers.

The LOICZ typology is, therefore, an appropriate framework for sediment delivery investigations within the coastal zone, especially for studies striving to understand anthropogenic interaction with system processes. The framework provides a platform for the understanding of regional process change *prior* to system management. Within smaller-scale initiatives there may however, be some demand to integrate the scientific process with ultimate system management, especially in studies where anthropogenic impacts are concerned.

§2.4.1 Data integration

The use of experimental perturbation studies as a tool for quantifying interactions between catchment land use and sediment delivery to the coastal zone has been emphasised within the literature as a principal device for understanding the intricacies of system response to change (IGBP, 1993). It is clear that this component of coastal system research is an essential pre-requisite to the identification and inference of longer trends and to the understanding of localised anthropogenic drivers of this process. One of the most significant challenges for projects seeking to integrate sediment delivery from the drainage basin to the coastal zone is in the coupling of inter-disciplinary models. If this coupling is achieved through integrating data within the LOICZ typology then system management can subsequently be developed from a firm scientific base.

§2.5 The Belizean coastal zone within the LOICZ framework

Carter's description of the coastal zone (§2.1) is central to understanding the nature of LOICZ change within Belize at the present time. The Belizean coastal zone is characterised by extensive alluvial plains intersected by a complexed network of river systems, mangrove and sea grass environments, and the world's second largest barrier reef. It represents an intricate relationship between human and environmental systems within and across the land – ocean interface. Sediment delivery from anthropogenic activity within the drainage basin to the Belizean coastal system may be conceptualised within the IGBP-LOICZ framework. LOICZ has already been identified as an ideal platform from which to launch sediment delivery investigations, however, the benefits of using this approach for research in Belize are particularly evident.

"Point inputs" of material to the coastal system have been identified within LOICZ as the principal anthropogenic delivery routes between the land and the ocean. The coastal lagoon system of Belize is fed directly by 25 rivers and creeks draining the tropical rainforests of the Maya Mountains and the pine ridge and alluvial plains of the Belize's eastern foothills. This lagoon system divides the coastal drainage basins from the barrier reef complex and the Caribbean Sea.

Anthropogenic activity within the Belizean coastal zone has become an increasingly important issue over recent years. This may in part be attributed to reports of mass "deterioration" and a decline in productivity throughout the Belizean barrier reef system and pollution within the coastal lagoon and mangrove habitats. Changes over the past 40 years have been connected with activities such as over-fishing, tourism, sewage and chemical run-off, mangrove removal and shipping routes through the coastal zone. Environmental disturbances such as hurricane and tropical storm activity, El Nino, changes to sea surface temperature, and natural cyclical events (The Belize Times, 1996) have also been blamed for patterns of disturbance. However, as is the case with the majority of early coastal system research, little connection had been made between activities operating on the land and pollution events within the coastal zone. For example, many of the early articles reporting coral reef degradation, failed to consider fluvial and estuarine systems as a potential source of sediment, nutrients and contaminants within the coastal zone, despite the relative proximity between the two systems, (e.g. Barnes, 1966, contrasted with Birkeland, 1980).

During the early 1990's the increasingly high profile of land-ocean research prompted the realisation that accelerated rates of land clearance and anthropogenic disturbance within the drainage basin may be related in some way to patterns of change within the Belizean barrier reef system (GESAMP, 1994). Of particular relevance was the widening of the United Nations Environment Program (UNEP) during 1993 to continue the preparation of "Inventories on land-based sources of marine pollution from domestic, industrial, and agricultural areas" in Belize. The results were rather alarmist and suggested that:

> ***"The increase in agricultural activity and production has increased the erosion of soil which flows to the coast and marine areas with adsorbed pesticide and fertiliser residues which are impacting on coral reefs and potentially the Barrier Reef..."***
>
> (UNEP, IOC, WMO, WWF, IUCN, 1993)

The subsequent investigation by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 1994) into "Anthropogenic influences on sediment discharge to the coastal zone and environmental consequences" is also of note. Caution was expressed within this study about conclusions made in previous reports based on "insufficient data" and the need for more research into anthropogenic activities within the drainage basin and their subsequent interaction with suspended sediment delivery to the coastal zone was identified. Concern was however, expressed in this report about the nature of anthropogenic sediment and associated contaminant delivery to the Belizean coastal zone and its long-term consequences.

The increasing realisation that there may be a level of interconnectivity between anthropogenic activity within the drainage basin and coastal system processes in Belize has resulted in some severe conflicts between land and environmental managers and misconceptions about the processes at work. In particular agricultural development throughout the fertile river floodplains of Belize has received a hard press with respect to this issue. In light of such confusion it is essential that prior to any research into this area the level of present scientific understanding is outlined with reference to anthropogenic sediment delivery interactions between agricultural development and reef system processes within the Belizean coastal zone.

The majority of this research has been co-ordinated with respect to the influence of agro-chemical usage on the surrounding environment. There have been some attempts to link pesticide and fertiliser usage in banana, citrus and sugar cane agriculture to pollution movement through the coastal zone in Belize (e.g. Hall, 1994). However, although this work has identified that agro-chemicals may be delivered to the peripheral environment under certain conditions, there has been no comprehensive study of the mechanisms by which it may be transferred into the reef zone. Indeed, it has been suggested that many of the pesticides and fertilisers used for tropical plantation agriculture move in conjunction with fine sediments (Windom, 1992), but no comprehensive research had taken place with respect to the movement of agricultural sediments across the land – ocean interface. This is essential if the mechanisms of interaction between banana plantation agriculture and the coastal system are to be fully understood.

The relationship between hydrological forcing functions within the drainage basin and processes occurring within the coastal system are an integral component of any LOICZ orientated research within Belize. Monitoring the interplay between tropical storms, episodic events in hydrological and fluvial systems and patterns of sediment delivery to the coastal ocean, will facilitate the understanding of processes interacting with the anthropogenic dimension of change. LOICZ promotes the use of field plots and contained environments ("experimental perturbation studies") to monitor and predict interactions between a specific component and the peripheral environment. This strategy may be particularly valuable to agricultural sediment monitoring within Belize, and could provide a sound basis for the subsequent extrapolation of system understanding to similar environments. The possibility of linkages between cause and effect would be significantly diminished through integrating data within the LOICZ framework, however caution should still be expressed about the potential for errors when extrapolating results to similar environments.

It is therefore evident that the LOICZ framework provides a platform from which to launch and develop coastal zone research within Belize. An international framework for regional coastal system research facilitates the extension of coastal science to the land management community. The benefits of using a standardised and integrated approach to land-ocean research will be significant for both the scientific and management communities.

§2.5.1 The challenge

The LOICZ typology provides a global context for system research within Belize. High profile international attention must be given to LOICZ Belize, so as to secure regional and international funding for future research and management initiatives. Until recent years, a "catch 22" scenario has prevented land – ocean research from receiving due attention in Belize. The spatial and intellectual gap between cause and effect has promoted both alarmist and dismissive reports of processes responsible for change in the coastal zone and subsequently system managers have received conflicting information. LOICZ provides a framework within which the "middle ground" may begin to be understood.

Within Belize the *effects* of anthropogenic activity may be understood better when set against the *process* of economic and environmental development. In the case of plantation agriculture, understanding may be constructed through balancing cause and effect interactions between land use and coastal zone processes against interactions and change within the economic system. To achieve this level of understanding about the physical *and* anthropogenic cause and effect mechanisms operating within the Belizean coastal zone, will present a significant but meaningful challenge to the development and application of the LOICZ typology. The beginnings of integrating the human dimension into LOICZ research may be seen in attempts to understand the socio-economic aspects of fluxes to the European marine environment (IGBP, 1999b).

§2.5.2 An integrated conceptual framework for Belize

The importance of LOICZ as the scientific framework for a conceptual model has therefore been emphasised. It provides a platform for the integration of the driver, the transfer and the delivery mechanism to the coastal zone within a multi-disciplinary framework. This research uses the LOICZ platform to develop a preliminary conceptual model of interactions between components of the land-ocean delivery system, linking plantation, river and coastal zone within southern Belize. It should, however, be noted that whilst LOICZ provides the conceptual structure of this research it is not a formal LOICZ project. The model has been designed to characterise components based on field observations as a pre-cursor to future definition and further calibration of the model.

Originally it was anticipated that research would seek to characterise processes within this conceptual model during a preliminary field season and calibrate them within a second. However results collected during the first extended field season period indicated that the system was significantly more dynamic than originally thought. Therefore, instead of one set of results facilitating model characterisation and the second, calibration, two field seasons were anticipated to produce two independently characterised data sets for two different years. This concern was reinforced by departmental research in the pro-glacial environment where experience found that because of significant variability within the system, two field seasons returned two independent data sets and therefore whilst conceptual models were characterised, a large number of field seasons were required before calibration was scientifically achievable (Pers. comm., Pro-glacial research group, Department of Geography, University of Southampton, 1999).

To integrate components within the LOICZ framework it was therefore decided that results from one extended field season would be used to characterise key dimensions of the conceptual model for plantation - river - coastal zone interactions in Belize.

§2.6 Background to the study area within the Belizean coastal zone

This section provides a background to the physical characteristics of the study area and an introduction to the climatic characteristics of Belize's southern coastal plains.

§2.6.1 Overview

Belize, located adjacent to the Caribbean Sea, with Mexico and Guatemala bordering the northern and south-western territories respectively (Figure 2.2), is characterised by a tropical climate, tempered by the trade winds. Annual temperatures average 24°C between November and February and 27°C between May and September. Annual rainfall totals of 1290mm have been recorded across the northern districts whilst variants around 4450mm are "typical" in the south (GESAMP, 1994).

For a country no larger than Wales (approximately 22965 km^2), Belize hosts a tremendous diversity of natural environments. The dense tropical rainforests of the Maya Mountains to the westernmost border are set against the vast underwater rainforest, the Belizean barrier reef, only 40km to the east. Longitudinally, the savannahs to the north contrast with the tropical wetlands and marshes to the south. Despite many remarkable features, it may be argued that it is the coastal zone that distinguishes Belize's physical environment from that of any other Central American country. Indeed, the IGBP-LOICZ definition of "the coastal zone" as that area *"...from the coastal plains to the outer edges of the continental shelves..."* (IGBP, 1993) practically encompasses Belize in its entirety.

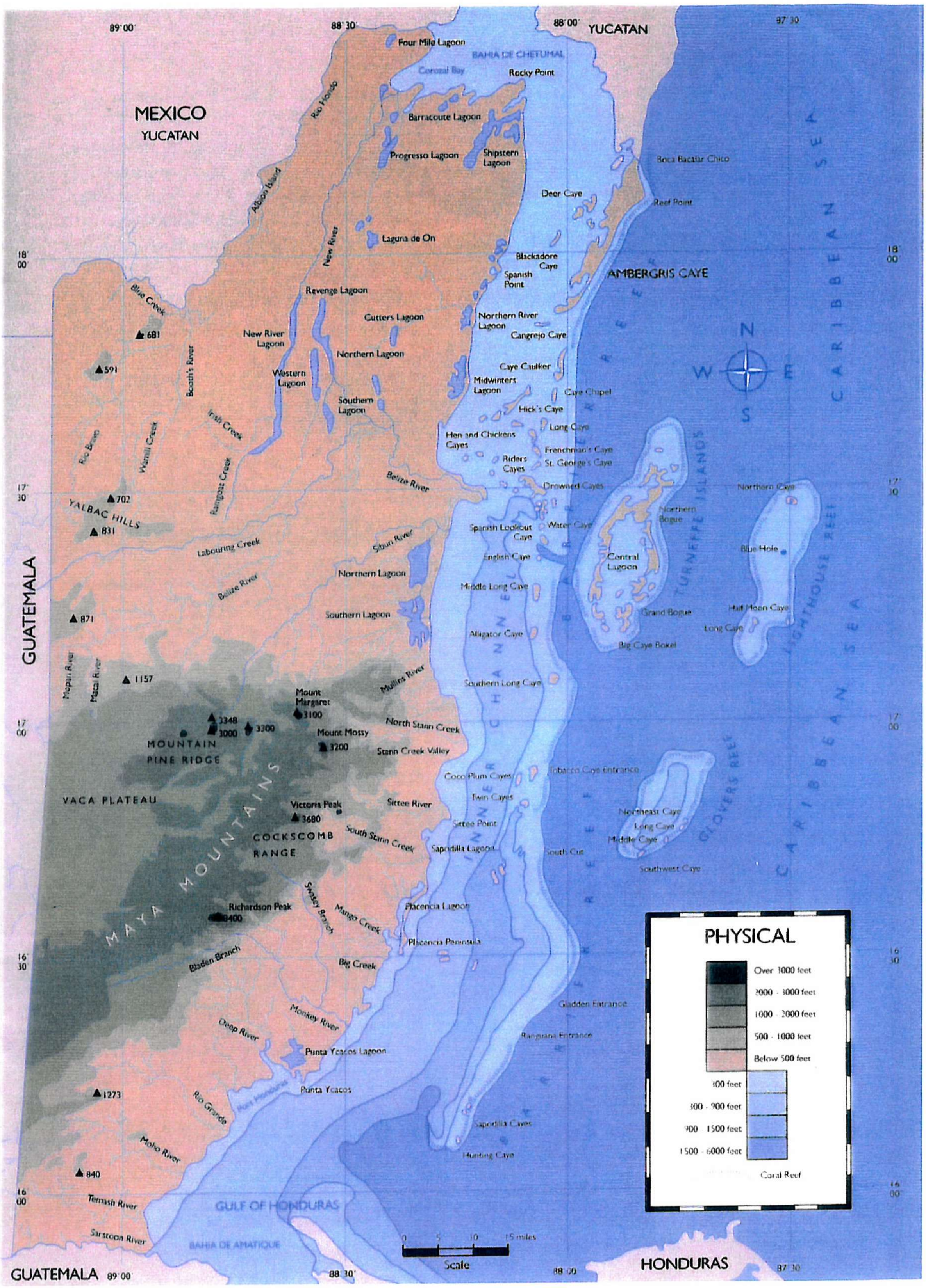


Figure 2.2: The Belizean coastal zone

Belize's coastal ecosystems are comprised of continuous and patch coral reefs, sand and coral atolls, sea grass and reed beds, mangrove swamps and marshlands, coastal lagoons and alluvial coastal plains. The barrier reef complex extends 250km down the length of Belize and has been described by the UNEP as:

> ***"unique in the Western Hemisphere on account of its size, its array of reef types and the luxuriance of corals thriving in such pristine condition"***
>
> (Coral Cay Conservation, 1991)

Citrus, sugar cane, and banana plantation agriculture dominate the terrestrial environment, intersecting primary rainforest, secondary jungle and scrub. There is a strong sense of environmental awareness in Belize, where "ecotourism" has become the "buzz word" of the past two decades (G.O.B., 1991).

§2.6.2 Introduction to the study area

As research has been conducted within the IGBP framework it is most appropriate to introduce the characteristics of the study area within the "coastal zone" as defined by the LOICZ project.

Figure 2.3 highlights the boundaries of the conceptual research area as where the coastal zone meets the continental interior and where the continental shelf meets the open ocean. However, it should be noted that the "physical field environment" is to be further defined still.

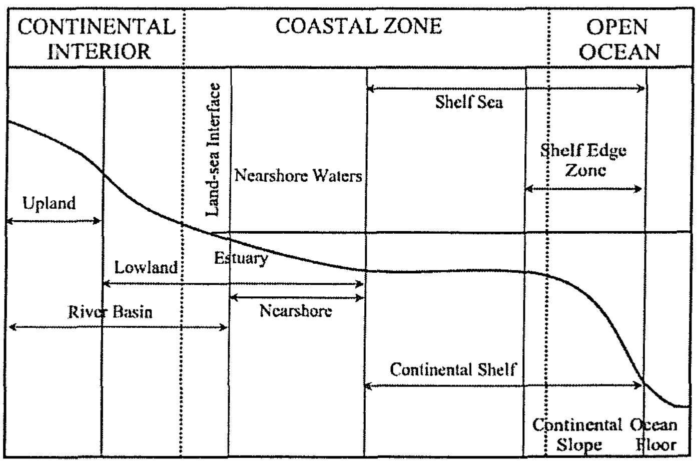


Figure 2.3: The coastal zone as defined within the LOICZ framework (IGBP, 1993)

The banana industry is almost exclusively confined to the coastal plains of the Stann Creek district in southern Belize. Research has subsequently focused on the southerly margins of the Belizean coastal zone. The Stann Creek district is characterised by particularly high rainfall totals during the rainy season (June – October), strongly associated with interactions between the mountain and coastal systems of this region.

Land use activities within the coastal drainage basins of the Stann Creek District are almost exclusively confined to agriculture and forestry. The well-drained alluvial and pine ridge soils, coupled with the high rainfall totals of the south, provided excellent conditions for banana and citrus production. These industries underwent a massive expansion following privatisation in the mid-1980s (Muraro and Rose, 1994) resulting in large-scale land clearance activities and significant improvements to the infrastructural development of the once "forgotten south". The majority of land cleared for expansion by commercial banana and citrus growers has been along the alluvial fans and river floodplains of the coastal plains.

Whilst these southern coastal drainage basins have been rapidly modified by commercial agricultural development, smaller plots, of often less fertile land are dominated by subsistence agriculture. These "plots" are particularly common at the foothills of the Maya Mountains. Traditional "slash and burn" clearance techniques are still very much a feature of the local farming culture, where secondary rainforest and jungle scrub are removed to grow crops such as plantain, rice and beans for basic subsistence. Forest fires are common throughout the coastal plains, which are often started by local deer hunters who believe that the fires drive the animals into clearings where they can be trapped more easily.

Originating in the Maya Mountains, an extensive network of small rivers and creeks intersect the southern coastal plains meandering significantly with decreasing gradient. The clay pan, silicous and mountain pine ridge substrate gives rise to the dominance of fine sand, silt and clay sediments in the transportable load of the south's rivers. Figure 2.2 illustrates the drainage network of the coastal plains.

Although outside the realms of this research, it should be noted that rivers and creeks are of much greater significance to the environmental and social structure of Belize than may be appreciated through monitoring physical processes. They are a vital source of fresh water for rural Mayan Indian communities, providing irrigation for subsistence crops, sanitation and water supply. Perhaps the most classic scene observed when driving through the southern districts of Belize is that of women scrubbing clothes on "washing rocks" along the riverbanks and entire families bathing under wooden bridges (Figure 2.4). It would be inappropriate to attempt an overview of the coastal plain river network without appreciating their role in sustaining human life.

The alluvial plains of the Stann Creek district may be divided into two agricultural areas. The drainage basins of North Stann Creek, Sittee River and South Stann Creek, comprise the first, whilst the Swasey and Bladen branches of Monkey River, make up the second. The blue boxes in Figure 2.5 illustrates the location of these two areas. The Placencia lagoon and surrounding swamps distinguish these zones. This study is primarily concerned with South Stann Creek and the associated catchment and coastal zone.

South Stann Creek is one of the smaller rivers draining the coastal plains of the Stann Creek District. It connects the Maya Mountains to the Caribbean Sea and passes from the mountains through karstic limestone relief, hilly to undulating lowlands and coastal plains before it reaches its estuary at 16°43′N and 88°18′W. During alternating periods of tectonic uplift and sea level rise the Maya Mountains were formed from volcanic and Palaeozoic marine sedimentary rocks (Heyman & Kjerfve, 1999). The fertile soils of the Maya Mountains originate from a limestone parent material. They are thin but particularly fertile and are composed of smectoid clay. The sandstone, mudstone and shale soils of the hilly lowlands are mainly composed from calcareous sedimentary rocks and have been reported to be highly erodible following the removal of sub-tropical forest for slash and burn agriculture and localised subsistence farming development (Harshorn, *et al.,* 1984). The southern coastal plains are primarily composed of alluvial silts, clays and sands, deposited in the valleys cut by the river networks, whilst further south of the plains a wave-cut platform dominates the geology, which is overlain by marine deposits of silt and sands derived from siliceous mountain rocks (Johnson & Chaffey, 1974). The soils of the southern coastal plains have been mapped and classified by Wright, *et al.,* (1989).

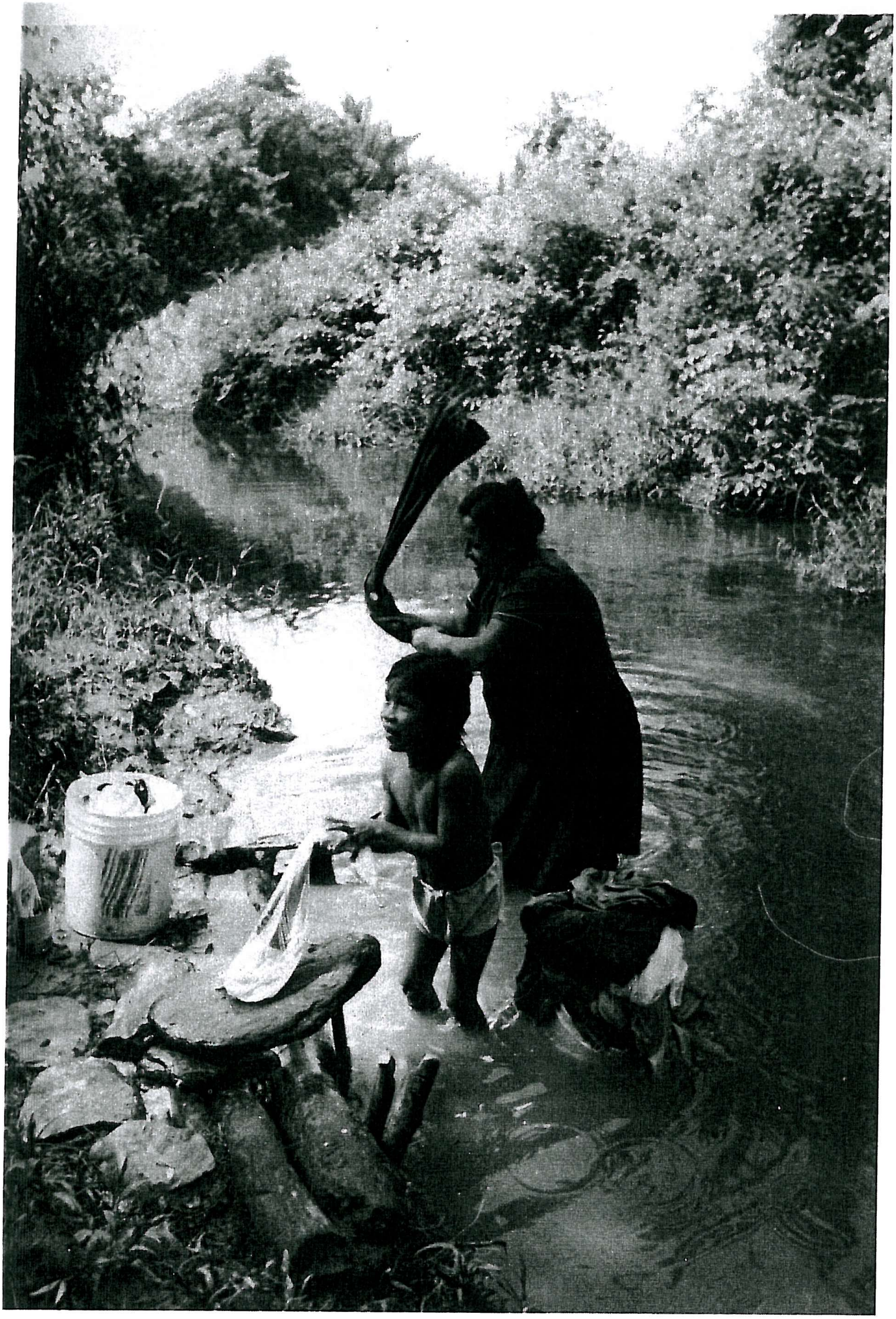


Figure 2.4: A typical Belizean river scene (Rabinowitz, 1986)

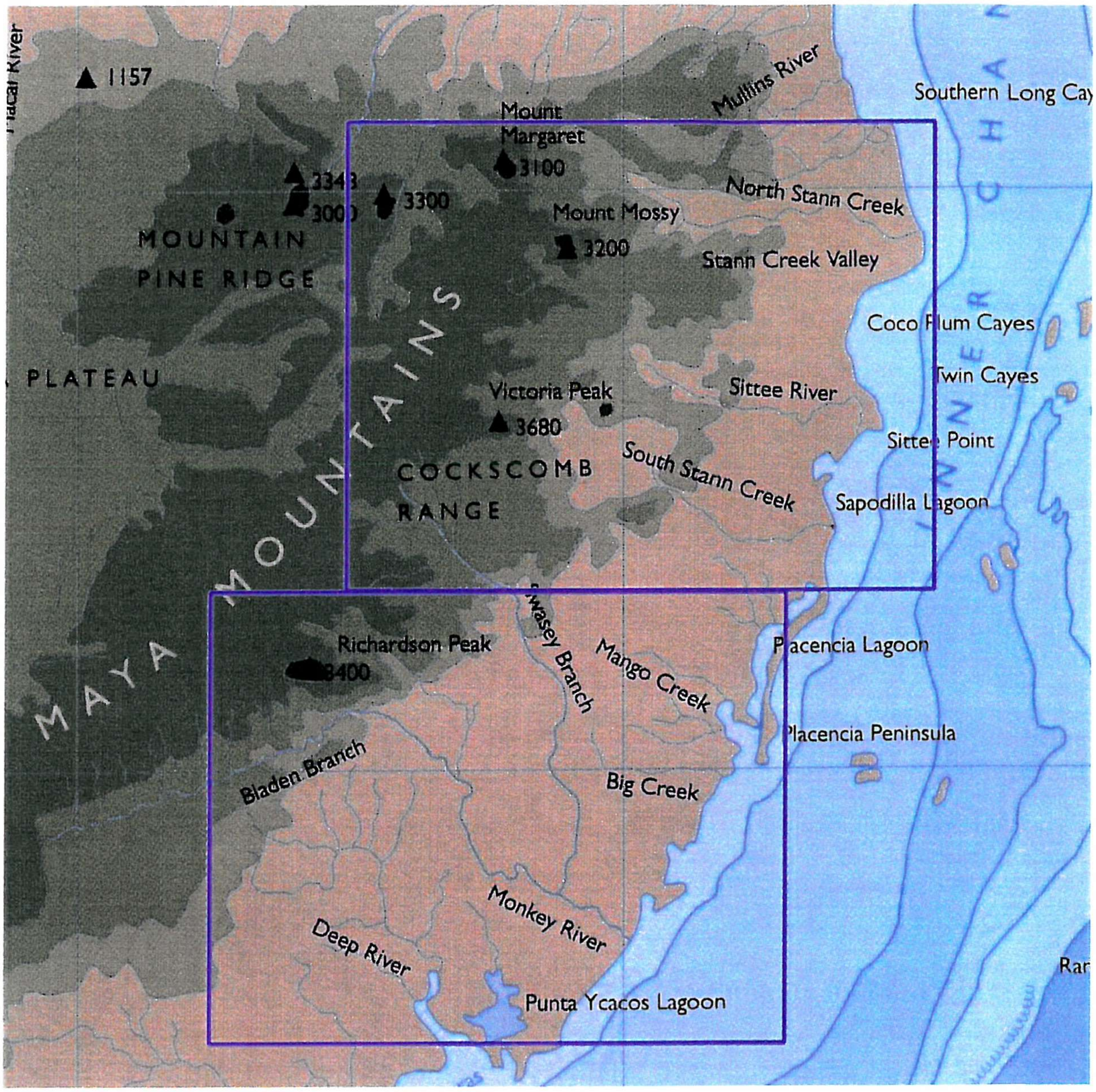


Figure 2.5: The agricultural areas of the Stann Creek District (to the same scale as Figure 2.2)

Banana plantation and citrus agriculture dominate land-use within the coastal plains of the South Stann Creek watershed. Owing to the rich alluvial soils of this region, production has been particularly successful and plantations have extended considerably across the floodplain during recent years. As the river reaches its estuary original sub-tropical forest is replaced by successive mangrove swamps, which have been discussed in more detail by Zisman, (1992).

The coastal zone adjacent to the southern coastal plains of Belize is characterised by the inner channel of the near-shore reef zone. Numerous patch reefs and small mangrove islands are located in this region. Particularly large numbers of manatee (sea cow) and dolphin have been reported within this area. The coastal lagoon (classified on shipping charts as the inner channel) separates the barrier reef from the East Coast of Belize. The lagoon between the reef and the mainland varies between 10 and 20 km (Figure 2.6). Despite the main part of the barrier extending seaward towards the south of the country, the predominance of shallow patch reefs and coral islands increase in number and proximity to the land significantly as they move down the coast.

§2.6.3 The Belizean climate system

The humid tropical climate of Belize's southern coastal plains is characterised by intense rainfall and high temperature (Heyman & Kjerfve, 1999). The dry season tends to occur during the early months of the year and usually stretches between February and May. The remaining months are driven by the dominance of either the moist south-easterly trade winds or cooler, dryer northerly winds (referred to locally as "northers"). The interaction of these winds with Belize's central mountain ridge drives the nature of the climatic regime. Between June and November hurricanes are likely to occur.

§2.6.4 Rainfall

Figure 2.7 illustrates mean monthly rainfall data recorded at Mayan King farm (South Stann Creek) for 1993 to 1997 relative to mean monthly rainfall statistics for Belize (1956-1993). Whilst a full data set for this period was not available due to poor sampling equipment (pers.

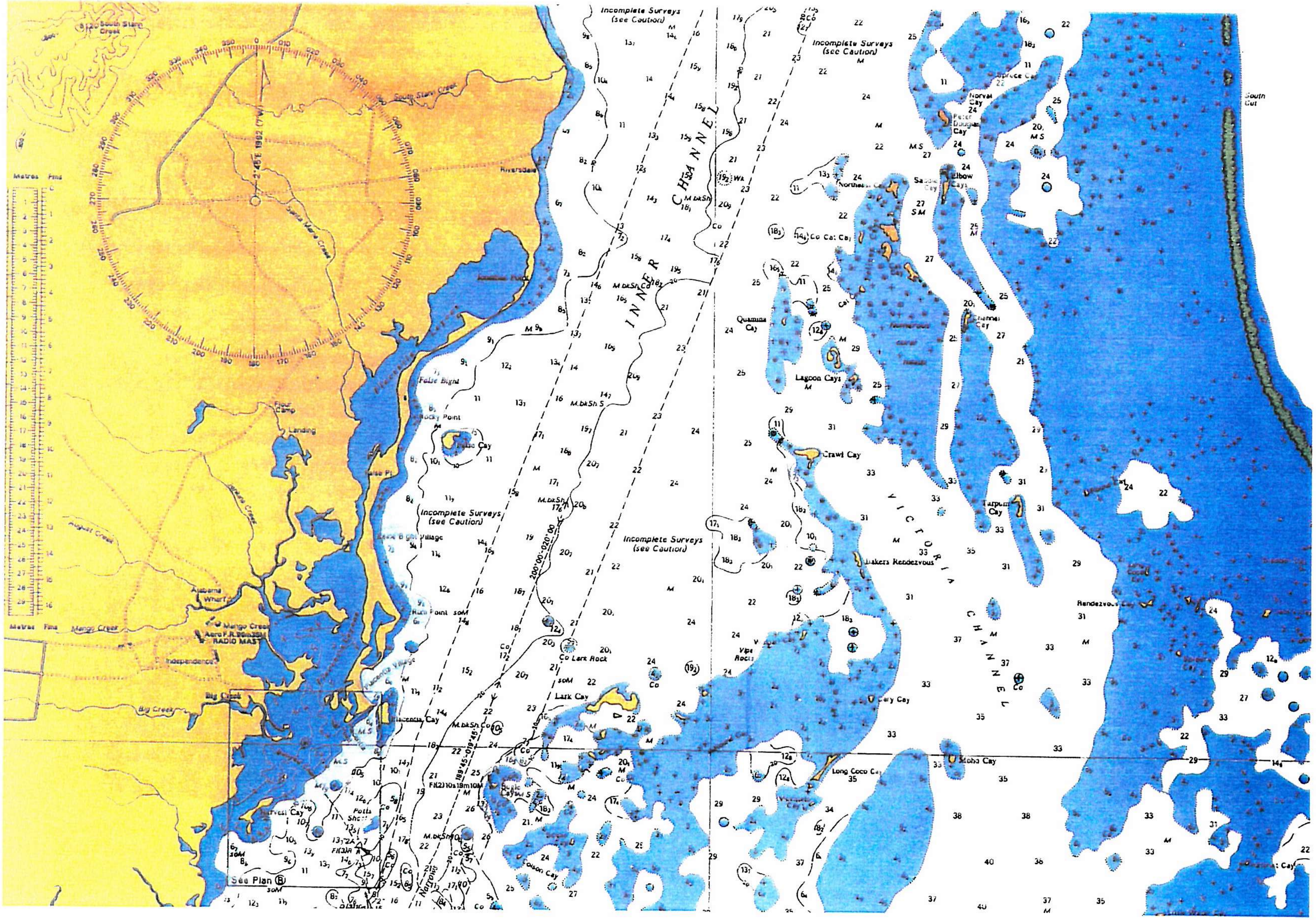


Figure 2.6 The lagoon and reef systems within the southern Belizean coastal zone

comm., National Meteorological Service, Belize, 1998) it is clear that between June and October significant rainfall fell over the south of Belize during most years. During September, mean rainfall over the 5-year period ranged between 279 and 617mm. March and April were characterised by extremely low rainfall totals of between 10mm and 110mm.

The arrival of Belize's rainy season is highly unpredictable and has created significant problems for commercial agriculturalists and subsistence farmers over recent years (National Meteorological Service Belize, 1998b). Of note, what is known as the "false start" to the rainy season has often resulted in farmers having to re-plant crops to achieve a higher emergence rate and subsequently experiencing a shorter and less productive growing season. The median start date for rains across the south of Belize has been reported to be the 22nd of May (143 Julian – hereafter "j") between 1960 and 1995 (National Meteorological Service, Belize, 1998b).

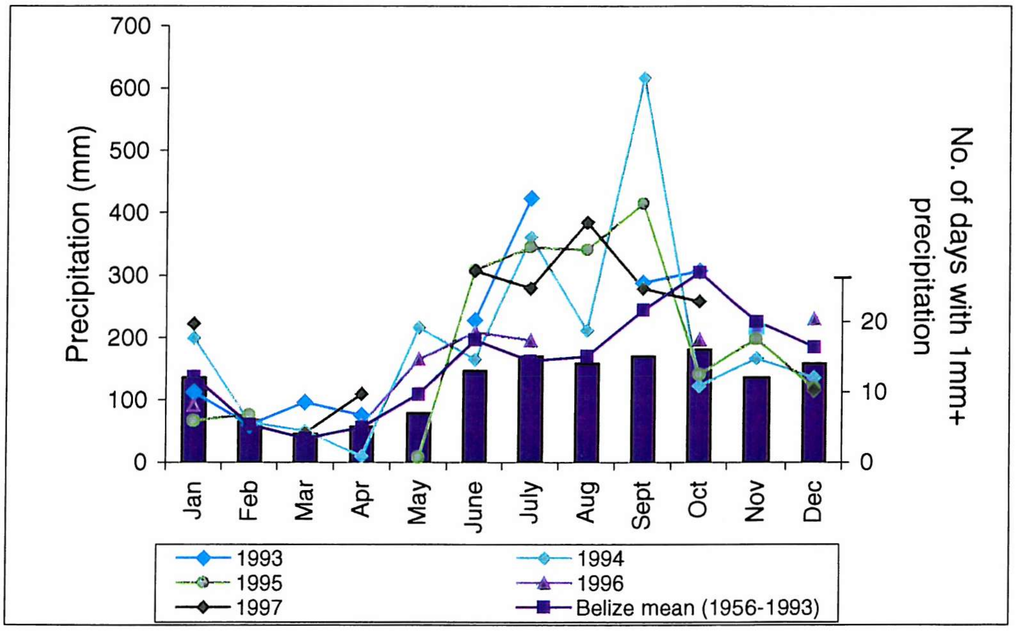
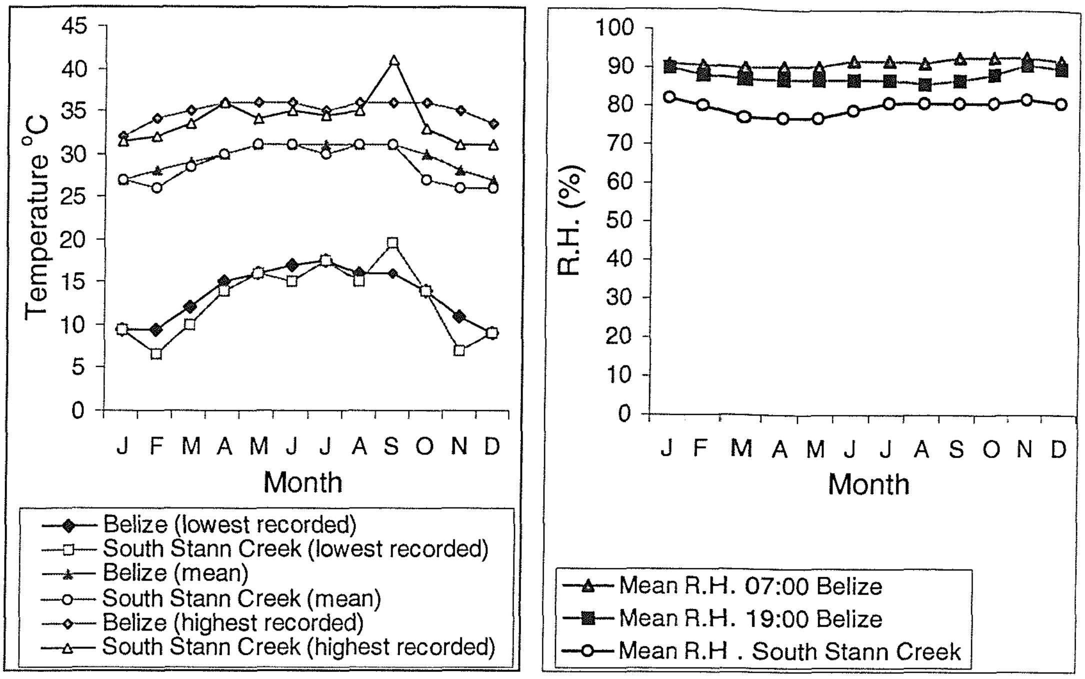


Figure 2.7: Rainfall Statistics for Mayan King Farm monitoring station 1993-1997 against the Belize mean (Pearce & Smith, 1993)

§2.6.5 Temperature and Humidity

Temperature and mean monthly relative humidity for South Stann Creek relative to figures for Belize (1956-1993) have been presented in Figures 2.8 & 2.9.



Figures 2.8 and 2.9: Temperature and humidity at Stann Creek against country figures for Belize (adapted from Directorate of Overseas Surveys, 1974 and Pearce & Smith, 1993)

The data set for South Stann Creek (1933-1970) provides the longest continuous record of temperature and humidity available for the region. The lowest temperatures for the Stann Creek District are between November and February, with maximum temperatures peaking during April and September. Mean minimum and maximum temperature deviated between 18 and 27°C for the monitored period. Mean monthly relative humidity remained relatively constant throughout the year with a deviation of approximately 4% r.h. between 77% and 81%. Between February and July mean relative humidity was at its lowest at approximately 78%, whilst between August and January it was slightly higher at approximately 80% r.h.

§2.6.6 Climate and Agriculture in Belize

The climatic characteristics of Belize's southern coastal plains are somewhat of a mixed blessing for the commercial and subsistence agricultural sectors. Whilst the high rainfall during the wet season months complements the warm climate to provide a rich and productive growing environment, rainfall has always been extremely unpredictable (Figure 2.7) and farmers failing to anticipate the onset of the rainy season period have often encountered economic losses of considerable magnitude.

Whilst the hot, wet climate provides ideal growing conditions, the high erosive power of Belize's tropical rains has been reported to accelerate soil erosion and leaching (King, *et al.,* 1993). In addition, the highly unpredictable nature of rainfall over the southern coastal plain river network has been responsible for extensive flooding of agricultural land, located on fertile flood plains (Pers. Comm., B.G.A., 1996). It should therefore be noted that whilst the climatic environment described above for the southern coastal plains of Belize is typical of a highly productive and fertile environment for agriculture, a fragile balance exists between productivity and large-scale economic loss.

§2.7 Summary

Interactions between anthropogenic activities within the drainage basin and processes operating within the coastal zone have been positioned in this chapter within the context of global change. It has been argued that whilst localised anthropogenic activities may appear to be a "drop in the ocean", cumulative processes such as agricultural interactions with drainage basin sediment delivery to the coastal zone, need to be understood relative to ongoing change. Indeed, the convergence of economic and environmental interests within the coastal zone, serve to illustrate the need to use the LOICZ framework as a base for the subsequent integration of research within local and regional sustainability models. The Belizean coastal zone has been introduced as a particularly challenging area within which to apply this, due to the diversity and wealth of natural resources promoting agricultural and tourism development. It is therefore important that environmental and economic development criteria are considered within an integrated strategy for understanding land-ocean interactions in the Belizean coastal zone to promote future management. The following chapter introduces the banana industry in Belize within this framework. Agronomic and agro-hydrological processes have subsequently been considered as important components of a profitable industry in addition to operating as potential drivers of fluvial suspended sediment to the Belizean coastal zone.

Chapter 3

Interactions at the interface between the plantation and the river: A local driver of suspended sediment to the Belizean Coastal Zone?

§3.1 Introduction

Monitoring sediment delivery from drainage basin agro-systems to the riparian zone has been identified in Chapter 2 as key to understanding how macro-scale sediment fluxes from the land to the ocean interact with localised erosional forces and system inputs (IGBP, 1994). In particular, the relationship between agricultural land management and practice and hydrological forcing functions has been identified as an important one. This chapter may subsequently be sub-divided into three parts.

Firstly, an overview of past research into sediment delivery interactions between agricultural land and the river system is given, where the significant breadth of current understanding has been contrasted against the lack of relevant and usable information presently available for agro-hydrological research in humid tropical environments.

Secondly, the banana industry in Belize is introduced as an economic and physical mechanism for change. A comprehensive overview of plantation practices aimed at directing and controlling agro-hydrological processes has been provided.

Thirdly, physical linkages between the agro-hydrological system and suspended sediment delivery to South Stann Creek are identified and considered. The design plan and methodology for understanding the relationship between local hydrology, the plantation environment and the fluvial system is outlined, prior to the analysis and discussion of results. Consideration is given to realistic and practical strategies for understanding plantation – river interaction given future expansion and change within the industry.

This chapter provides the base level information required for considering the role of banana plantation agricultural practice in Belize as a potential "driver" of sediment mobilisation and delivery from the farm to the river system.

§3.2 Sediment delivery from agricultural land to the fluvial system: a review

Soil erosion from agricultural land has accelerated over recent years (Lal, 1994). The culmination of human and climatic impacts has resulted in the stripping of productive soil from farmland, leading to the depletion of what may be seen as a non-renewable resource. It is well reported in the literature that agro-systems are becoming more frequently destabilised and the subsequent discharge of sediments and associated contaminants to the surrounding environment has generated a wave of concern amongst land and environmental managers (e.g. Walling & Probst, 1997).

Despite the topicality of this issue there is significant lack of information about agricultural sediment delivery to the fluvial system within the tropics. This may be largely attributed to: the logistical difficulties associated with running monitoring programs within the tropical field environment (Douglas, 1996); the lack of a research base to promote advanced calibration studies; and the extent of hydrological system dynamics often being of far greater magnitude than those experienced within temperate environments (e.g. Arenas, 1983).

Relative to the development of croplands, humid tropical environments have been found to experience very high rates of soil erosion, with future projections suggesting that this trend will accelerate (Lal, 1983). Extreme climatic conditions, coupled with dramatic hydrological events provide a rich but difficult growing environment. The insertion of agricultural land-use practices into this system has been reported to intensify sediment loss problems and threaten the very nature of what they are designed to sustain (Webster &Wilson, 1980).

In particular, dual-purpose systems designed to control hydrological inputs and reduce soil erosion have often failed to do either. Hudson, (1981), explains that whilst soil and water management practices may appear to be inter-related, agronomic and mechanical systems designed to control both have frequently underestimated the nature of interaction between hydrology, slope, vegetation and soil.

The high erosivity of tropical rains is clearly an important determinant of agricultural soil erosion and reports suggest that these regions are characterised by a 1-hour maximum precipitation intensity of up to 50-75mm (Jansson, 1982). In particular, catastrophic precipitation events "flush out" sediments from tropical agro-systems with large quantities of productive soil subsequently being lost to the surrounding environment. This system loss may

be understood and potentially managed if it is seen as a function of the relationship between agricultural land use practice and the dynamics of the physical environment.
Practices employed on tropical banana plantations have generated much concern regarding the loss of nutrients and agro-chemicals to the surrounding environment (Hall, 1994). Although it is widely understood that this process is inextricably linked to the movement of fine sediments through erosive pathways, little research attention has been given to this issue. Studies in Costa Rica (Guzman, 1991) suggest that banana plantations are particularly vulnerable to episodic sediment loss during storm events. There has been some discussion in the literature as to the nature of interaction between the incision and collapse of drainage pathways and hydrological events (International Commission on Irrigation and Drainage, 1969). However, little attention has been given to process dynamics within a tropical context or to the role of banana plantation drainage networks in transporting available sediments away from the field to the river system.

Plantation drainage channels are designed to quickly and effectively remove excess surface and sub-surface water away from the plant roots. Bananas require extremely well drained soil (Holder and Gumbs, 1982). Any standing water will result in extensive crop damage and in some cases total crop failure (Banana Operations Manual, 1972). Drainage networks serve to buffer the impact of extreme hydrological events by dispersing excess water away from the plantation into nearby rivers and creeks.

These channels are, however, frequently subject to incision and bank erosion and regularly require maintenance and re-working. By emptying directly into surrounding rivers and creeks they act as a transfer route by which eroded soil and associated contaminants may enter the fluvial system. Hall (1994) discusses this process in some detail with respect to the potential flux of agro-chemicals to the riparian and coastal systems of Belize. Agricultural contaminants were identified as particularly transferable due to their ability to sorb to suspended sediments. It was discussed that due to the mobility of fine suspended sediments, sorbed agro-chemicals could travel greater distances from citrus, sugar and banana plantations to adjacent fluvial and coastal systems. However, a lack of research into the movement of suspended sediment from the farm to the fluvial system has, to date, prevented the insertion of project recommendations into agricultural system management.

At the same time, in other sensitive environments around the world, inter-connectivity between agricultural sediment and chemical run-off and coastal water quality has become a high profile issue. For example, in the Florida Everglades sediment transfer from citrus and sugar plantations via primary drains to rivers and creeks has been connected with severe coastal water quality problems (NARMAP, 1994), where plantation practice modifications designed to reduce soil erosion have been enforced by the state. It is in some ways surprising, that given the sensitivity and diversity of the Belizean coastal environment, where the coral, mangrove and sea grass habitats are recognised to be of global heritage, water quality research into agricultural - coastal interactions, is still very much in its infancy. However at the same time, researchers, scientific and governmental bodies and non–government organisation's (NGO's) all recognise the urgent need for this to change (Natural Resources Institute, 1993).

Further attention has been given to the mechanics of interaction between climate and agriculture as drivers of processes linking the plantation to the river in Chapter 6: Figures 6.10 and 6.11.

§3.3 Economic and physical development of the Belizean banana industry

The physical and economic development of the Belizean banana industry over recent years represents a series of trade off mechanisms between its environmental and economic sustainability. The "size" and "shape" of the industry has been reactive to the demand for production, where existing farms have expanded and intensified practices to meet their quota for export, or during times of sustained demand, plantation managers have cleared additional land for new plantation development (Pers. Comm., Fyffes 1996). At the same time the demand for production has in part been a function of fruit quality. At a local level, the ability of the physical environment to sustain a specific quantity and quality of fruit has related directly to plantation practices and *vice versa.* The initial location and design of plantations has been determined by the suitability of the environment for development, however, management has evolved to respond fluidly to local variations in physical conditions through practice adaptation (Pers. Comm., B.G.A., 1998). Local, national and international economic forces have therefore been inextricably related to the physical development and management of the banana industry in Belize (European Commission, 1995). It is subsequently essential that these factors be understood prior to any analysis of practice management.

§3.3.1 Brief history of the development of the banana industry in Belize

The economy of Belize is primarily based on agricultural exports where sugar, citrus and bananas are the three principal export crops. Agriculture provides approximately 70% of all foreign exchange earnings and employs over 30% of the workforce (Harbourne, *et al.*, 2000). The banana industry developed in response to the carefully planned macroeconomic policies of the Belizean government and the European Development Fund. However, the economic climate over the last two decades has been increasingly unstable, exacerbated by difficulties with the physical growing environment.

During the 1970's Belize was heavily encouraged to diversify into the production of bananas. It was thought that the industry would provide steady jobs for a large workforce and secure foreign exchange throughout the year. Unfortunately during the middle 1970s two major hurricanes, Fifi and Greta, ripped through Belize, seriously damaging plantations and stunting the fledgling industry. However, the potential advantages of a strong banana industry in Belize outweighed this temporary set-back and aid from the European Development Fund, the World Bank, and the Commonwealth Development Corporation was invested heavily in removing road and infrastructure constraints and improving the efficiency of production (B.G.A., 1993). Subsequently the 1980s saw a massive expansion in banana plantation agriculture and by 1986 the industry was privatised.

In 1990 a privately financed port facility was opened in Big Creek on the basis that production would continue to develop, reaching an export quantity of 100,000 tonnes of bananas by 1996. As a result an export quota of 100,000 tonnes was sought for Belize that would ensure the long-term sustainability and viability of the industry. Unfortunately in 1993 with the commencement of the European single market, the "banana regime" (Regulation (EEC) 404/93) capped Belize's exports to 40,000 tonnes to increase only to 55,000 tonnes in 1995. As a result the banana industry underwent a period of significant losses where measures were taken to curb production and large quantities of surplus fruit were dumped. The industry is presently waiting for an urgent review of the quota situation where it is anticipated that within the next year the 1995 quota will be increased to prevent the economic base of the industry being completely undermined. The intensity of agricultural practices and the rate of plantation development will strongly reflect the nature of the "banana regime" and future practice modifications should be seen within this context.

At the present time the banana industry in Belize is the single largest employer, providing steady work for 45% of the work force in the South and generating over 21% of the country's foreign earnings (G.O.B, 1999). Since privatisation approximately 300km^2 of bananas have been planted or rehabilitated in Belize with the development of a further 200km^2 set for the next few years pending the future of the "banana regime" (Pers. comm., B.G.A., 1999).

The link between the intensification of practice, development and expansion of the industry and the economic policy of the government and European Union is clearly of great importance to any research attempting to understand practice interactions between the physical environment of

Belize and banana plantation agriculture. There is significant potential for reasonable practice modifications to be inserted into the management of existing and new plantation areas.

§3.3.2 Structure of the industry

There are presently 24 plantations in Belize that produce bananas for export, with an un-reported number of small subsistence "Milpa" farms (Pers. Comm., Fyffes, UK, 1996). Following privatisation, foreign entrepreneurs heavily invested in a number of these farms, whilst the Fyffes Group Ltd (UK) and local land-owners formed the remaining sector. The Fyffes Group Ltd (UK) has a contract to purchase all fruit and fruit by-products from all farms exclusively until the year 2002. Sales are conducted through the Belize Banana Growers Association (B.G.A.). The B.G.A. and Fyffes at different levels of the production process conduct quality control jointly. Agro-chemical residence monitoring takes place on a small scale by a subset of the B.G.A called "Sigatoka control", in accordance with Fyffes group requirements. Figure 3.1 illustrates the structure of the industry in more detail:

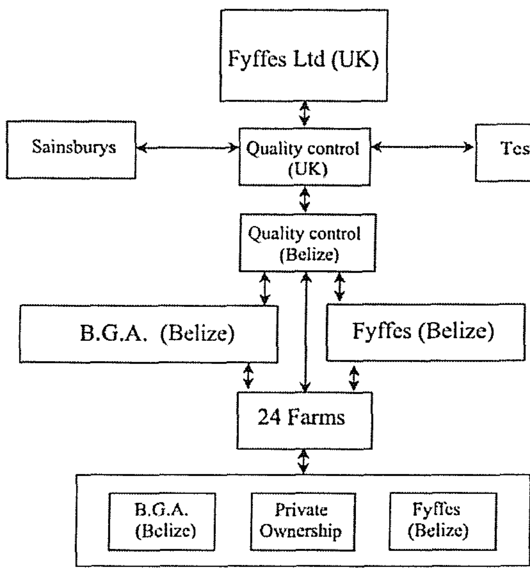


Figure 3.1: The structure of the Belizean banana industry

§3.3.3 Physical Characteristics of the industry

Banana production in Belize tends to be concentrated on the low-lying coastal plains of the south. The Stann Creek District and the northern part of the Toledo District are the principal areas for banana production (Pers. Comm., Fyffes, UK, 1996). These effectively constitute the same agro-climatic region. Average annual precipitation is approximately 2800mm and temperature ranges between a minimum of 15 and 20°C and a maximum of 26 and 31°C (King, 1989). Total precipitation exceeds the water requirements of the banana by a massive 800mm/year, but between February and May when precipitation often averages less than 150mm/month, irrigation is required (Pers. Comm., B.G.A., Belize, 1998).

The 24 commercial farms of Belize are located adjacent to South Stann Creek and Swasey River, with subsistence Milpa farms located in the watersheds of Bladen River, Sennis River and Indian Creek (Hall, 1994). The total acreage of the South Stann Creek banana plantations is approximately 1200 hectares. Commercial farms vary enormously in size with the smallest being only 10 hectares and the largest, 209 hectares. The average plantation unit is approximately 70ha (European Commission, 1995). Initial cultivation requires the large-scale clearance of land, the construction of irrigation and drainage pathways and the input of large quantities of agro-chemicals. All farms are located adjacent to a river system, which is essential for cost-effective irrigation and efficient drainage (Pers. Comm., Fyffes, UK, 1996). Figure 3.2 illustrates the network of plantations in southern Belize relative to classified land-use for the region.

In addition to climatic factors the proximity of plantations on the southern coastal plains to "Big Creek" shipping port and a large Guatemalan immigrant workforce fixes the industry firmly in the south.

§3.4 The plantation environment

This section explores the characteristics of and inter-connectivity between, plantation practices, environmental conditions and agro-economics within the banana industry of southern Belize:

§3.4.1 Plantation practices

Specific procedures employed in banana plantation agriculture vary between farms and growing regions (Pers. Comm., B.G.A., Belize, 1998). There are, however, some practices that are uniform across most producing areas and that are relatively uniform across the industry and should be given some attention in any attempt to understand process interactions between the plantations and the peripheral environment. Consideration should be given to these procedures prior to studying plantations on an individual basis. Any extrapolation of the research framework to parallel environments throughout Belize or in growing regions such as Jamaica and Suriname, will involve an appreciation of the similarities and differences in plantation practices and the nature of process interactions between physical parameters. Table 3.1 summarises the nature of plantation practices in Belize.

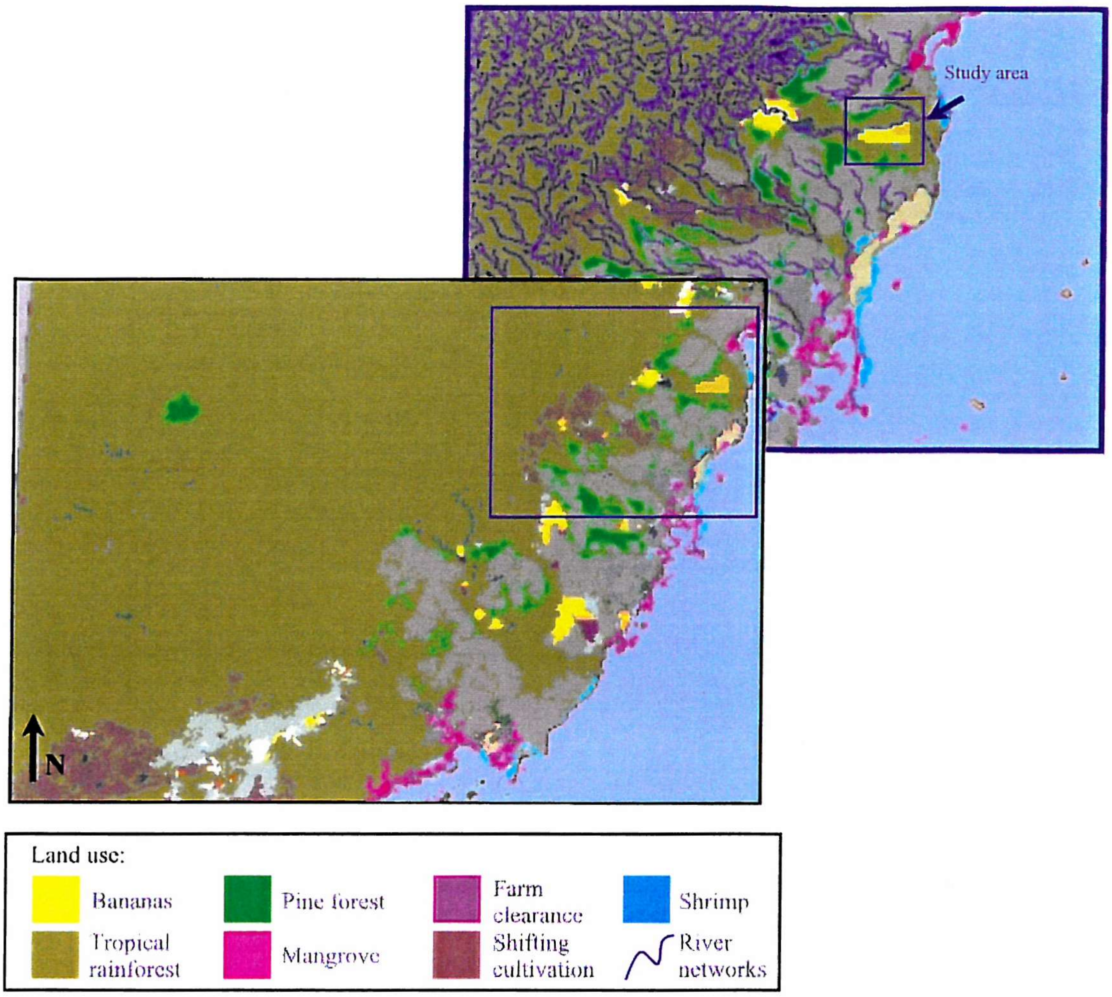


Figure 3.2: Land use in the Stann Creek district (adapted from The World Bank Group, (2000), 1:200,000)

Table 3.1: A summary of plantation practices

Practice	*Procedures*	*Industrial specifications & field observations (Fyffes/B.G.A., 1998/1999)*
Land clearance	Removal of natural land-cover (usually primary and secondary rainforest (Field notes 1998/1999))	
	Construction of drainage & irrigation systems	Based on topography and proximity to the river system – topographic maps are usually constructed to determine the direction of flow and most plantations are designed to slope towards the river system.
Cultivation practices	Bananas are farmed throughout the year (Simmonds, 1966). Cultivation will take place for 3 days in 7.	Fruit will be produced within 12 months of planting. Agro-chemical application, pruning, bagging and ditch construction will take place during days when fruit is not being harvested (although they are not mutually exclusive).
	• Spacing	Essential to the success of the crop & the economic efficiency of the plantation. A function of plant size, precipitation, soil properties & winds. Spacing is inter-related to the design of the drainage network and will be reduced if soils are particularly heavy and increased in lighter conditions.
	• Irrigation Water is pumped from the river system and distributed systematically through the plantation.	Requirements can vary considerably. Irrigation is the single largest cost to any grower, subsequently plantations are located in areas with high precipitation. Bananas are highly vulnerable to stress from insufficient water – resultant crop damage is likely to result in large economic losses.
	• Drainage	Fruit is best produced in well drained light sandy soils. Excess water within the root zone for a short period (hours - days) will result in crop damage. Drainage design is determined by the relationship between plant physiology, soil characteristics and system inputs.
	Fixed drainage (Figure 3.3)	Standard dimensions specified for the Valery plant (bank angle – not specified). Primary: Berm width = 6 m; base width = 2 m; depth = 3 metres. (Rule of thumb – 1ft depth for every 1ft of width). Secondary: Berm width = 6m; base width = 1m; depth = 2.5m. Tertiary: Berm width = 1m; base with = 0.3m; depth = 0.3m. (tertiary channels are required to drain approx. 1m of soil and are spaced every 10m.)

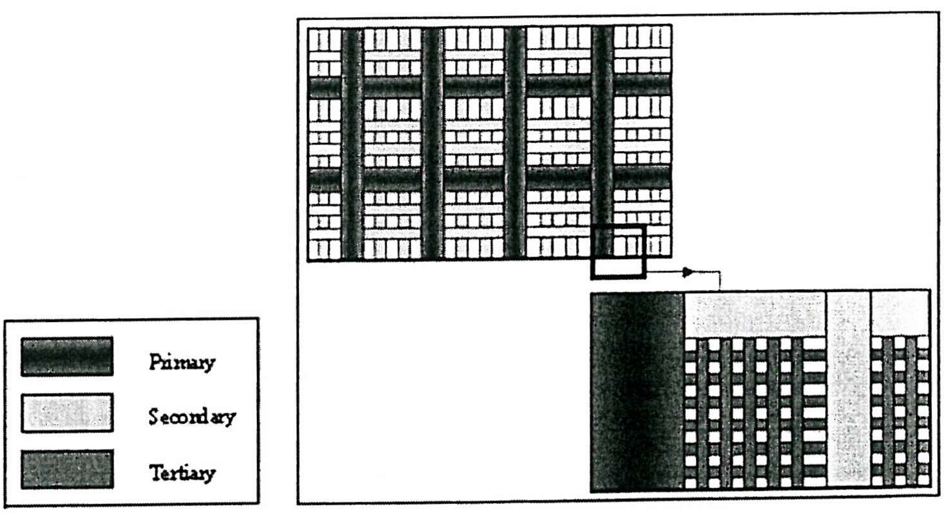


Figure 3.3: Banana plantation drainage channel networks

Practice	*Procedures*	
	Responsive drainage	Cut as a last resort to remove standing water away from the plants during or directly after a storm. Plantation workers place stakes in areas of standing water and cut a trench along the contours of the stakes to the nearest drain. This is particularly common on farms where the percentage soil composition of clays and silts is high.
Rehabilitation	Removal of plants following saturated root conditions for 3 or more days.	Plant removal using *macanas*‡ and the re-seeding of a new crop. Considerable soil erosion and sediment loss problems are experienced following re-habilitation.

§3.4.2 Physical conditions

Although bananas can grow within a very wide range of climatic and environmental conditions, profitable cultivation of the fruit requires specific physical parameters (Simmonds, 1966). Such conditions are especially important for the Valery Plant (the principal commercial crop of the banana industry at the present time (Pers. Comm., Fyffes, 1996)). Three environmental variables are of key importance to the location and maintenance of profitable plantations, precipitation, temperature and soil/drainage (Fyffes, 1972). A summary of conditions and requirements has been provided in Table 3.2:

Table 3.2 Summary of physical conditions required for banana cultivation

Control	*Requirements*
Precipitation	For the commercial growth of bananas should total 1270mm to minimise irrigation costs (Fyffes, 1972). Precipitation should ideally be distributed relatively evenly over the year with the soil not remaining dry for more than two weeks at one time. Cultivation within the tropics has needed to adapt to seasonal patterns of precipitation, resulting in particularly high irrigation costs over lengthy dry seasons (Field Notes, Belize, 1998/99).
Temperature	The normal temperature range for the crop is between 15°C and 32°C although there is some flexibility around these temperature margins, usually resulting in a decline in the rate of growth or some deterioration in the quality of fruit (Simmonds, 1966). Temperature exerts control over crop water availability determining irrigation & drainage demand (Fyffes, 1972).
Soil and Drainage	Soil and drainage are not only important in the initial location of farms, but are essential to the design of plantation practices (Field Notes, Belize, 1998/99). Commercial banana cultivation is almost exclusively restricted to flat alluvial plains. Ideal soils will be of a loam composition with approximately no more than 85% sand, 75% silt and 40% clay (Fyffes, 1972). Prime cultivation characteristics include, excellent internal drainage, good water holding capacity and a good depth of soil (approx. 1.5 meters) (Pers. Comm., Fyffes, Belize, 1998). Variability of these parameters will clearly take place between plantation areas; however, physical disparities will be counteracted by modifications in plantation practice.

‡ A cultivation tool similar to a machete

§3.4.3 Practice response to environmental conditions

Changes to physical parameters required for banana cultivation pose serious problems for the industry. Direct measures are subsequently employed to counterbalance environmental conditions and restore the plantation to its most productive state (Field Notes, Belize, 1998). Under some circumstances, such as hurricanes or tropical cyclones, little can be done to prevent significant damage of the crop (Fyffes, 1972). However, precipitation, temperature and soil/drainage variations have been adapted to by modifying plantation practices – often at considerable expense to the growers (Pers. Comm., Fyffes, 1996). The decision to act represents a trade off between potential economic loss and the cost of response.

The most frequent practice response to environmental conditions is the modification of surface and sub-surface drainage networks (Field Notes, Belize, 1998). This takes place following high intensity or high duration precipitation events where it is essential that water be removed from the growing area quickly and cost-effectively to prevent economic loss (Pers. Comm., B.G.A., 1998). Resultant soil erosion and sediment loss problems have been tackled by allowing debris and vegetation to collect in the drains during the dry season and the "stepping" of drains with a reverse grade to reduce bank angle and bank failure (Fyffes, 1972). However, restricting the rate of surface water removal has been found to exacerbate drainage problems and such methods have largely been avoided (Field Notes, Belize, 1998). Ironically, existing soil conservation techniques create the very same problems that drainage modifications have been designed to counteract.

Sub-surface drainage problems relating to the height of the water table have been more costly to address (Field Notes, Belize, 1998). Original drainage ditches (constructed when the plantation was initially seeded) require regular maintenance (Pers. Comm., B.G.A., Belize, 1998). Channel siltation, bank vegetation, leaf debris dams and occasionally plastic bags accumulating in ditches[‡] restrict efficient water transport (Personal Communication, Fyffes, UK, 1996). Whilst such processes constitute environmental adaption to the unstable relationship between water, sediment and vegetation within the plantation, they inhibit the rapid removal of water away from the plant roots and subsequently threaten profit margins.

§3.4.4 Practice response to consumer and market quality requirements

Aside from environmental conditions, the consumer and market demands on fruit quality may be of equal if not greater importance as a mechanism for driving the nature of plantation practice.

[‡] Used to protect the skin of the banana during growth.

Whilst environmental conditions largely drive the *design* of practice, consumer demand is highly related to the *intensity* of practice. Rigid controls on fruit quality, regulated at numerous control stages, restrict the shipment of anything but "perfect" fruit (Pers. Comm., Fyffes/B.G.A., Belize, 1998). The individual farmer's quota is attained by the supply of exclusively "perfect" produce to the distributor. Natural variations in the quality of fruit have increasingly been managed over time through species modification and the use of agro-chemicals at various stages of the production process (Marriott, 1980). However, improvements in field quality control have been accompanied by an associated rise in the demand for an even higher standard of produce from the consumer. As a result farmers have needed to intensify plantation inputs and produce greater quantities of fruit to achieve their quota (Pers. Comm., B.G.A, Belize, 1998). Approximately 30% of fruit entering the packing process will be discarded for not meeting distribution standards whilst a further 20% of fruit will be lost during subsequent quality control stages (Pers. Comm., B.G.A, Belize, 1998). Agricultural land is therefore farmed to attain maximum output to reduce the costs of over-production. Practice intensification procedures such as reducing the spacing between plants, maximising nutrient and fertiliser applications and fine tuning the relationship between precipitation, drainage, irrigation and evapo-transpiration are all symptomatic of quality restrictions, where economic survival relies on achieving the highest possible output per hectare.

In some cases large quantities of fruit discarded during the production and packing process have been used as fertiliser, however the cost of employing man-power to perform this task, has been reported to outweigh the economic benefits of reducing agro-chemical applications (Green Gold (Interview), 1998). Increasing consumer and market demands on the quality of fruit are therefore likely to have significant control over the intensity of practice, where land is more intensively farmed to meet the quota of "acceptable" produce. It is essential to consider in any process-based study of plantation interaction with the physical environment that practice modifications may be equally responsive to economic as well as environmental drivers.

§3.5 Characterising sediment production from the plantation unit

The first part of this chapter overviewed the physical and economic development of the banana industry in Belize. It is clear that the cost-effective production of bananas in Belize is intrinsically related to the fast and effective removal of storm water away from the plantation area. Indeed, the industry balances precariously between the need for large quantities of precipitation to feed a high input – high output system and the need to remove large quantities of excess water away from the plantation environment to produce a prime product. Drainage channels are the key to sustaining this balance. However it has also been identified that such channels may serve to accelerate the delivery of suspended sediment from the plantation to the river system, where it may subsequently be delivered to the coastal zone. Fluvial sediment dynamics have been considered with respect to conceptualising a characterisation of this process in Chapter 4. However, within the LOICZ framework it is now important to characterise the plantation and coastal components of the model, where key building blocks are given preliminary values. Such data will enable subsequent calibration and parameterisation studies to assign specific attention to areas that are little understood and/or require further modelling over space and time.

This section presents data collected within the plantation unit between May and August 1998. The physical characteristics of the plantation drainage system have been illustrated prior to the characterisation of channel sediment delivery to the fluvial system with instantaneous sediment load data. Information for a monitored storm event has been provided in addition to a temporal summary of plantation practice to facilitate initial understanding of driver dynamics.

§3.5.1 Research base

To date, there has been very little reportage in the literature as to the process of banana plantation soil erosion and sediment loss within Belize. The majority of research has concentrated on the fate of agro-chemicals and the movement of pesticides and fertilisers along drainage pathways to the riparian and coastal systems (NARMAP, 1994). However, all reports have recognised that to manage agro-chemical movement through the system, sediment movement requires monitoring and understanding. Six of the seven agro-chemicals used in banana cultivation in Belize strongly sorb to fine sediments (Hall, 1994). A collaborative project between the Sustainable Agriculture Production Program and the B.G.A. (NARMAP, 1994) concluded that:

> ***"...attention needs to be focused on sediment movement as this is the principal means of pesticide and phosphate movement.."***
>
> (NARMAP, 1994)

However, it has also been recognised that sediment in significant quantities can become a water quality pollutant, regardless of agro-chemical sorption (GESAMP, 1990). Sedimentation has been understood over recent years as a fundamental threat to the health of Belize's marine habitats (Foer & Olsen, 1992), although the relative importance of different sediment sources and transport mechanisms are still largely un-quantified. Sediment delivery from banana plantation agriculture in Belize via drainage channels to the fluvial system therefore constitutes a significant research gap. It is for this reason that the present study adopts a reconnaissance approach, seeking to scope and structure the system rather than provide verification of detail. Additional focus has been given to the regional dimensions of this research gap within the WRIScS (Watershed – Reef Interconnectivity Scientific Study) project, which has existed in parallel to this study with open communication but without close interaction.

§3.5.2 Site selection

To conceptualise plantation – river interaction with a view to characterising the processes involved, the identification of a "plantation unit" was required. The notion of a "unit" was central to creating a fluvial sediment budget for understanding the system at the simplest possible level and for characterising contributions to the budget from plantation drainage channels. The budget was important for understanding the net change in river suspended sediment load between a site upstream and downstream of a banana plantation unit.

The "simplicity" of the plantation unit relative to other plantation systems in Belize, enhanced the potential for research findings to be extrapolated to wider scientific and management frameworks. To select the most appropriate unit, the following Ordnance Survey 1:50,000 maps were analysed:

Table 3.3: Ordnance Survey maps detailing plantation networks in southern Belize

Ordnance Survey International Maps of BELIZE 1:50,000 (contoured) *Universal Transverse Mercator Grid (revised in 1991/2 from field photography taken in 1998)*		
D.O.S. (Series)	Sheet number	Edition
649 (E552)	35	4 – GSGS
649 (E552)	36	4 – GSGS
649 (E552)	39	4 – GSGS
649 (E552)	40	4 – GSGS
* Maps Published by Directorate of Overseas Surveys		

Three farms, located in a strip along the south bank of South Stann Creek (Sheet number 36, Figure 3.4) were selected to comprise the plantation unit for this research. Fyffes International and the B.G.A., Belize (B.G.A.) classified these plantations as Farm 8: Arnold Brothers, Farm 16: Green Gold, and Farm 7: Sagitun (**Sal**va, **Gi**na, **Tun**).

The total farm acreage for plantations 8, 16 and 7 was approximately 5.5 sq km. The reach of South Stann Creek adjacent to the plantations was ideal for the budgeting exercise due to there

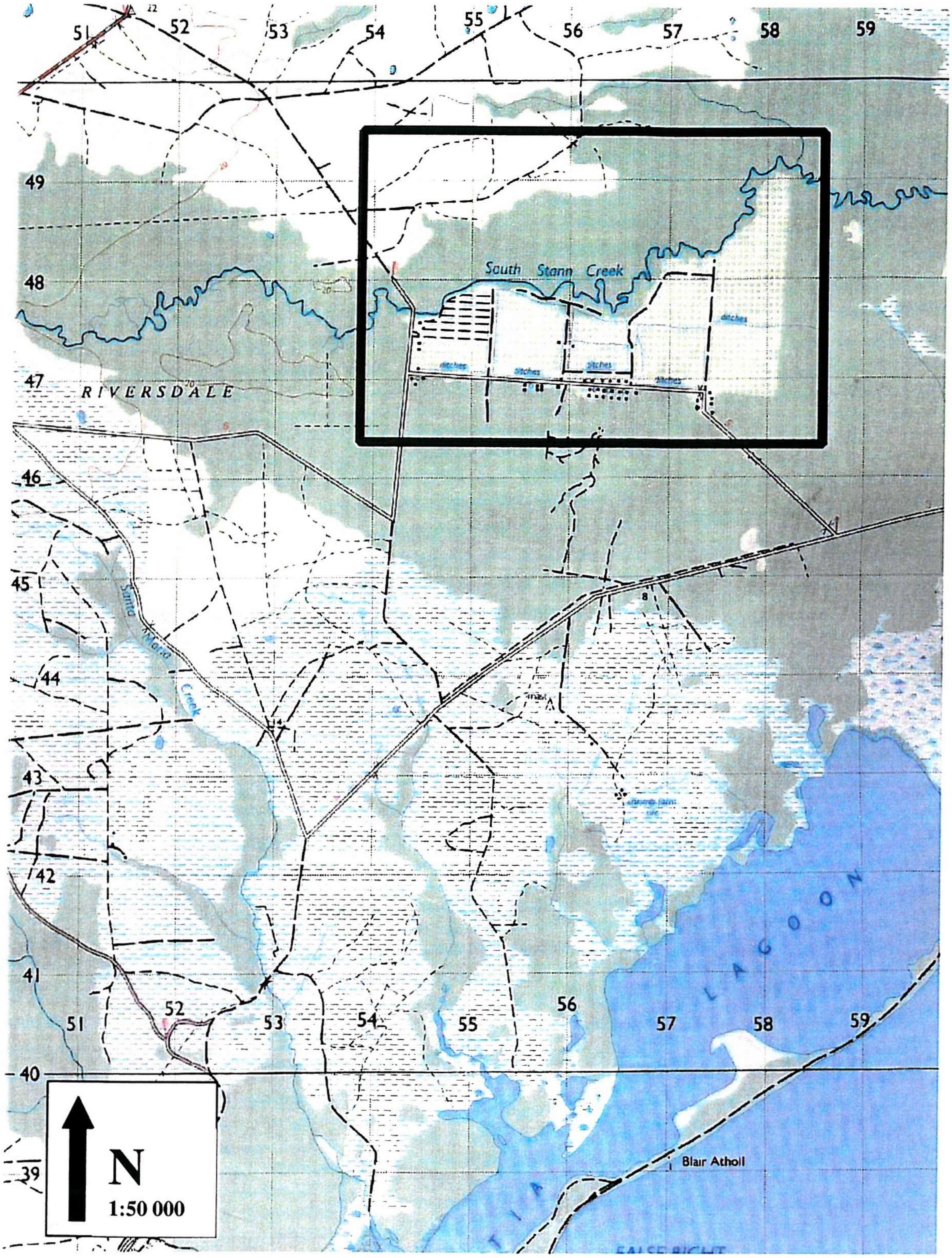


Figure 3.4: OS Map No. 36. The Souh Stann Creek plantation unit

being no intersecting tributaries apart from those associated with the plantation unit.

The plantation unit was located on the Stann Creek coastal floodplain. Table 3.4 illustrates a full pit profile, with laboratory analysis carried out at the Melinda Agricultural Station on the South Stann Creek coastal floodplain during 1988. The profile illustrates a well-drained soil derived from river alluvium but with considerable variety of parent material, grain size and age. Studies report that the alluvium within these soils is old and that they have not been regularly replenished due to sustained periods of leaching and weathering (Hall, 1994).

The vegetation on the opposite (North) bank of the river was dense un-disturbed jungle (although this area was being surveyed during field research for the expansion of the banana industry in 2000/2001 (Pers. Comm., B.G.A., Belize, 1998)). Field observations confirmed that there were no tributaries or point sources of material entering the river from this bank.

§3.5.3 Physical characteristics

A graphical representation of drainage channel order and dimensions has been provided in Figure 3.5 and Figure 3.6 whilst Table 3.5 presents the average dimensions of drainage channels recorded for the three farms comprising the plantation unit and illustrates the spread within the data.

Weather: The Ministry of Energy, Science, Technology and Transportation's National Meteorological Service, Belize, recorded precipitation, maximum and minimum temperature and evapo-transpiration data during the field season from May 1st (121(j)) to July 31st (212(j)) 1998. Precipitation was recorded at Mayan King farm on South Stann Creek. "Mayan King" was the closest hydrological monitoring station to the field site (Figure 3.7). Precipitation data collected at this station for the duration of the field season have been illustrated in Figure 3.8.

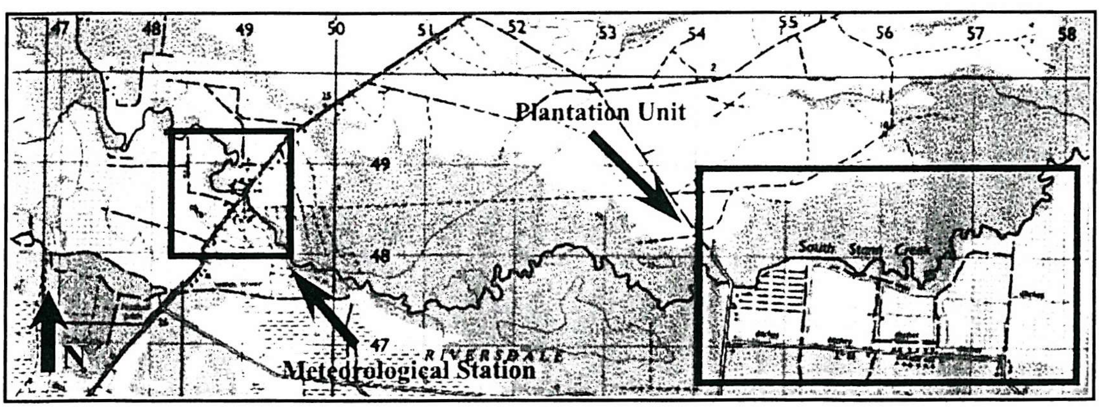


Figure 3.7: Location of the hydrological monitoring station relative to the field site (1:50,000)

Table 3.4 Pit profile for South Stann Creek, 1988 (Adapted from Hall, 1994)

		Particle Size Class														
		Sand %				Silt%		Clay%	pH	pH	Electrical Conductivity	Moisture % o.d.s	Total N %	Org C o.d.s	Av P ppm	W/V g/cm2 a.d.s
Depth (cm)	Lab. No.	Coarse	Medium	Fine	Very Fine	Coarse	Fine		1:5 H_2O	1:5 1M KC1	1:5 H_2O					
0-13	8102	0	1	1	2	17	49	30	5.0	4.2	0.10	2.8	0.32	2.93	20	0.86
25-35	8103	0	0	1	9	20	40	30	5.1	4.1	0.04	1.5	0.08	0.61	3	1.00
35-85	8104	1	0	1	4	15	45	34	5.1	4.1	0.04	1.6	0.08	0.47	3	1.04

		Exchangeable cations Me/100g/a.d.s					*TEB me/100g o.d.s*	*Cation exchange capacity me/100g*	*Base sat. %*	*Total content ppm*				*Trace elements ppm*		
Depth (cm)	Lab. no.	Na	K	Mg	Ca	Al				P	K	Mg	Ca	Cu	Mn	Zn
0-13	8102	0.1	0.4	0.7	2.6	2.0	3.8	13.0	29	740	13 000	3600	900	20	710	100
25-35	8103	0.0	0.1	0.5	1.1	2.6	1.7	8.1	21	250	12 500	3950	600	20	230	80
35-85	8104	0.1	0.0	0.5	0.9	2.5	1.5	7.7	10	200	14 800	3200	450	20	160	80

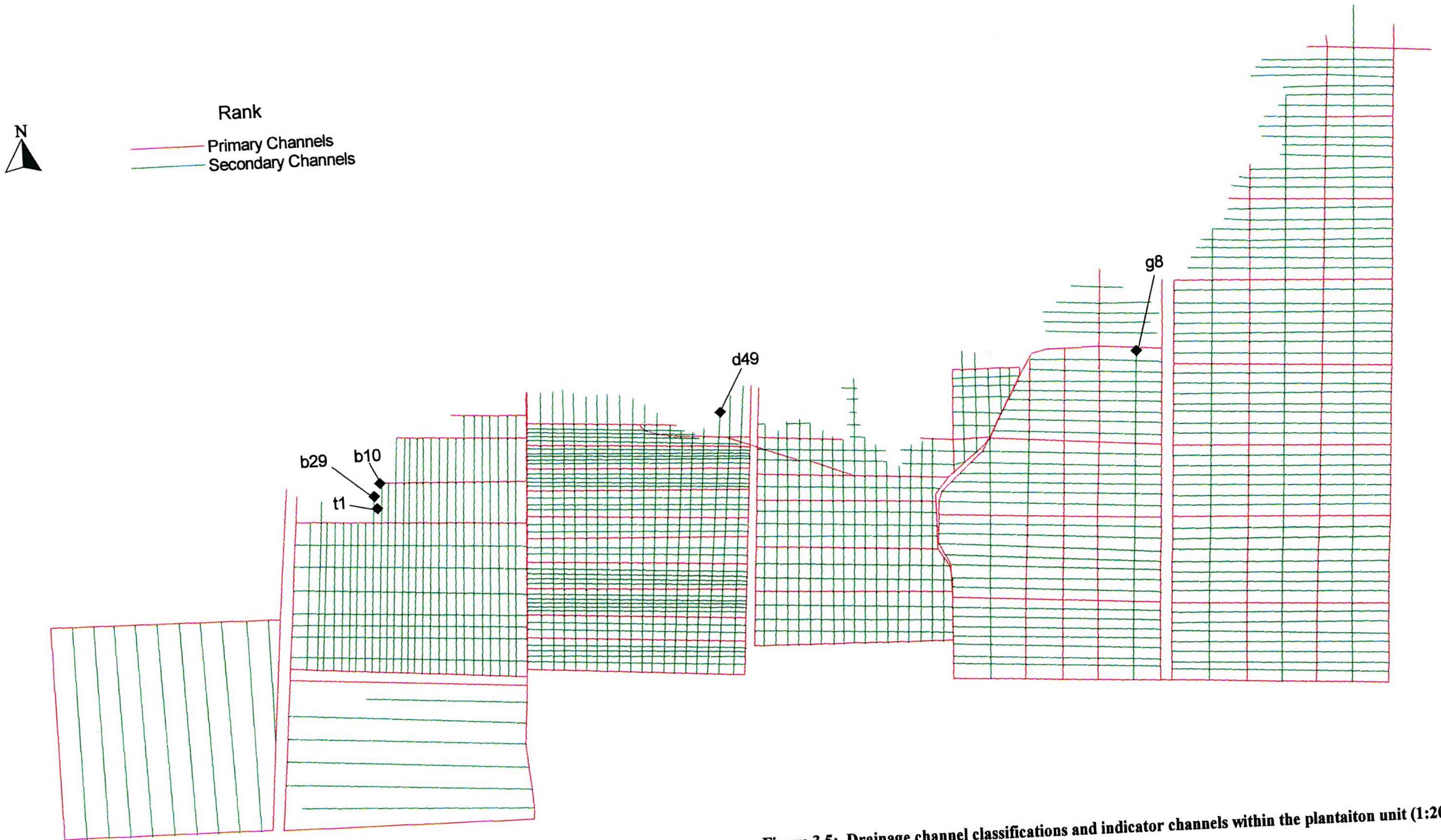


Figure 3.5: Drainage channel classifications and indicator channels within the plantaiton unit (1:20,000)

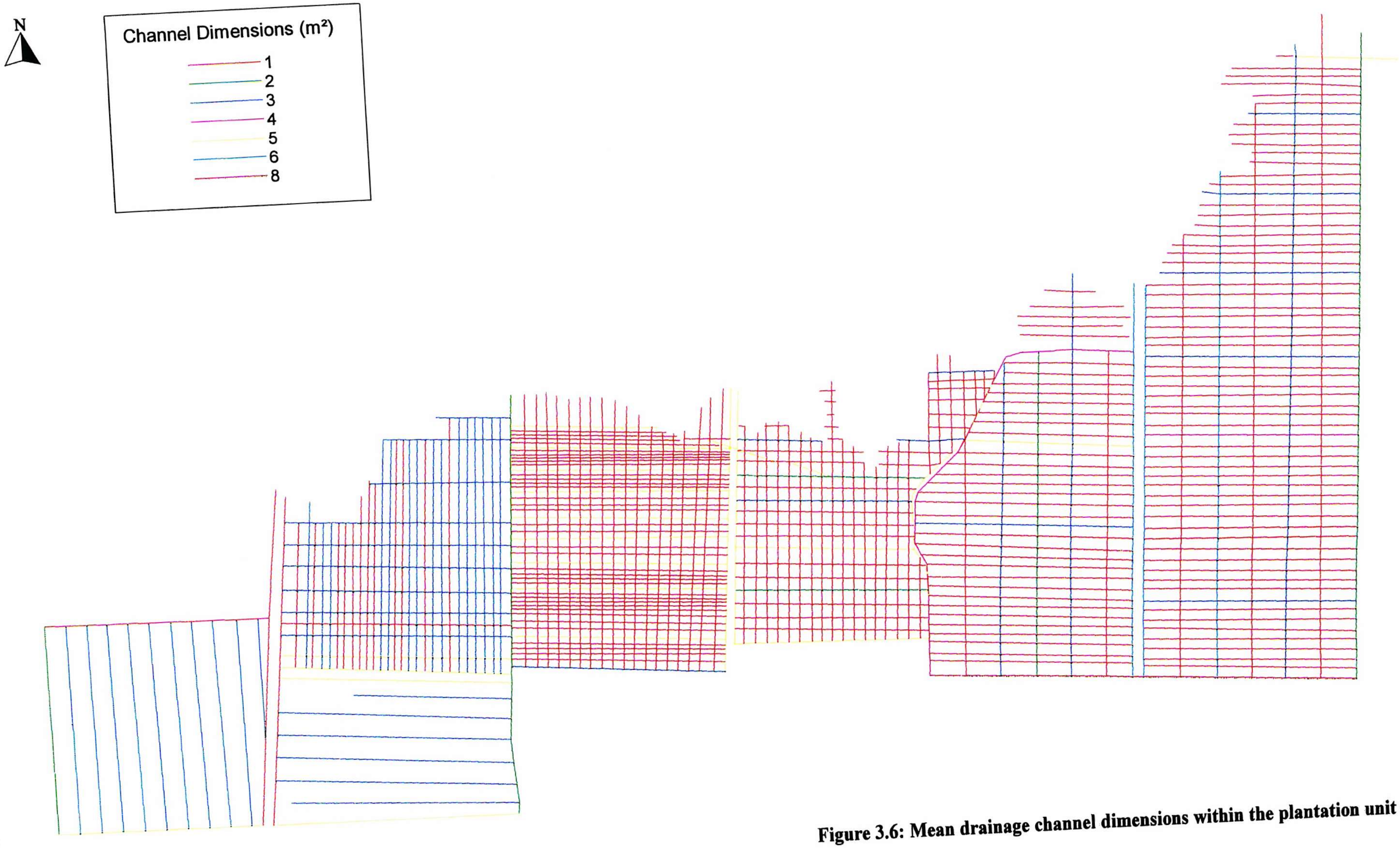


Figure 3.6: Mean drainage channel dimensions within the plantation unit (1:20,000)

Table 3.5: Drainage channel dimensions and indicator channels within the plantation unit

Plantation	*Drain Classification*	*Sample Size*	*Mean Base Width (m)*	*S. DV*	*Mean Height (m)*	*S. DV*	*Mean Top Width (m)*	*S. DV*	*Mean Bank Angle (°)*	*Mean Drainage Distance (m)*	*Number of channels discharging into the river system:*
8	Primary	7	1.4	0.7	1.3	0.4	2.6	1.0	115	932	6
Indicator:	*b29*		1		1		1.5		117	945	
8	Secondary	65	1.0	0.5	1.0	0.4	2.0	1.0	118	827	4
Indicator:	*b10*		0.5		0.5		1		106	800	
8	Tertiary	5	0.3	*	0.3	*	0.5	*	108	*	*
Indicator:	*t1*		0.3		0.3		0.5				
16	Primary	25	1.4	0.3	1.8	0.4	2.3	0.4	104	424	6
Indicator:	*d49*		1.5		2		2.5		124	495	
16	Secondary	98	0.5	0.1	0.5	0.1	1.0	0.1	115	441	32
16	Tertiary	5	0.3	*	0.5	*	0.9	*	119	*	*
7	Primary	20	1.5	0.4	1.6	0.4	2.7	0.5	121	1013	8
Indicator:	*g8*		1.5		2		3		108	1368	
7	Secondary	90	0.6	0.2	0.9	0.2	1.1	0.2	106	698	27
7	Tertiary	5	0.3	*	0.5	*	0.9	*	120	*	*

*No data

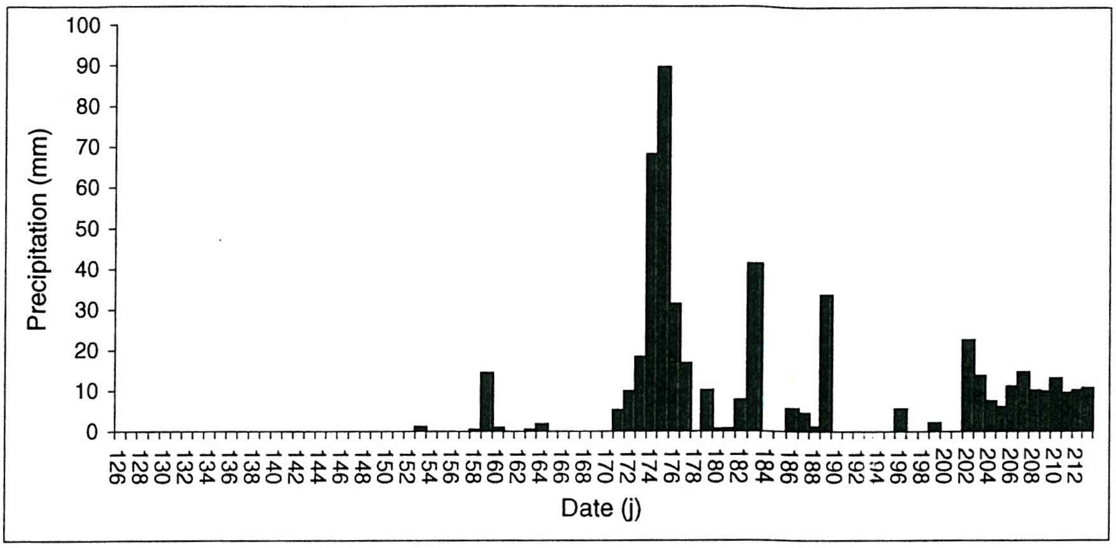


Figure 3.8: Precipitation May – August 1998 (Mayan King)

The beginning of the field period coincided with the end of the 1998 dry season. Early May was one of the driest periods recorded in Belize to date (National Meteorological Service Belize, 1998b). Whilst the rains did begin at the end of May as expected, a two-week dry spell during June prior to a period of continuous precipitation, was unusual. The "false start" to the rainy season at the end of May was particularly costly for agriculture across Belize. Although the first event took place on the 1st of June (153j) it is clear that the sustained precipitation associated with the onset of the "rainy season" did not take place until the 19th of June (171j). Sustained precipitation during June was within the long-term monthly mean for Belize. At Mayan King station, precipitation was approximately 50mm less than the average monthly mean (National Meteorological Service Belize, 1998c).

The period between the 3rd of June (154j) and the 15th of June (166j) was characterised by relatively low precipitation values, intersected with a few coastal showers and afternoon thunderstorms. On the 9th of June (160j) the weather deteriorated across Belize during the development of heavy convection currents in the north associated with a weak transient low-level trough over Central America. Between the 20th and 21st of June (171 & 172j) conditions became increasingly unstable due to the presence of an upper level trough running from the Gulf of Mexico to Yucatan. This was exacerbated by the intersection of a tropical wave that resulted in the significant increase in precipitation between the 21st and the 25th of June (172-176j). The maximum precipitation recorded during the field season on the 23rd of June (175j) was 89.5mm. This event effectively marked the beginning of a continued period of rain in the Stann Creek District for the remainder of the field season. The subsequent period of unsettled precipitation and thunderstorm activity towards the end of the month was that associated with a second tropical wave moving through the southern districts of Belize. Between the 10th and 15th of July a more stable dry period took place associated with a sustained easterly airflow. However, following this, the rains returned and widespread storms and showers took place across southern Belize through to the end of the field season on the 31st of July.

§3.5.4 Methods

During field research in 1998 a plantation-monitoring programme was co-ordinated to characterise the conceptual framework for plantation interactions with fluvial suspended sediment delivery. The framework, discussed earlier in this chapter is elaborated on further in Chapter 6, where a feasibility assessment is performed for the fluvial sediment budget using the characterised plantation data set.

To characterise the plantation system, the aims were to:

- Obtain initial data on the spatial characteristics of sediment load in drainage channels
- Identify, and obtain initial data on processes that interacted with plantation sediment delivery to the fluvial system

Implementation involved the sampling of suspended sediment in selected active drains. Sampling took place using standard techniques that have been detailed in Table 3.6 along with procedures used to classify the dimensions and location of drainage networks.

During field research is was clear that plantation sediment delivery to the river system interacted significantly with local hydrology and plantation practice. Subsequently a three-tier drainage network (at the interface between a primary, secondary and tertiary drain) was monitored during a storm event (Table 3.6) to provide base-level data about the dynamics of the delivery process. Plantation practices associated with soil conservation, runoff and drainage were also noted during the field season, where field managers and plantation workers were interviewed and the timings of soil, irrigation and drainage management procedures were obtained.

§3.5.5 Logistics

A number of logistical problems arose during data collection. The primary challenge was co-ordinating the monitoring of plantation processes with fluvial sediment monitoring. Both programmes required a significant input of time, especially during periods of high precipitation when plantation run-off in drainage channels was monitored and automatic river sampling equipment required calibration. This resulted in a somewhat flexible monitoring programme where prioritisation was governed to a large extent by logistics. The challenge of working "solo" in the field accentuated such difficulties.

Table 3.6: Methods for characterising the plantation unit

Plantation characteristics	*Method*
Drainage channel characteristics: mapping	Surveyors' maps of plantation drainage channel networks were obtained in the field from individual farmers. These were digitised, classified according to rank (i.e. Primary, Secondary, Tertiary) and projected onto a NAD 27 Universal Transverse Mercator Grid (Zone16) within a Geographic Information System (GIS) (MAPInfo[**]) to facilitate the multi-level integration of drainage channel data. Plantation drainage channels discharging directly to the river system were noted during a walking survey.
Drainage channel characteristics: dimensions	Primary and secondary drainage channel dimensions were classified according to base width "*b*", berm width "*c*" and height "*a*". Bank angle was calculated using the following equation: $$D^\circ = {}^{Tan}\left\{\frac{c-b}{2}\Big/a\right\} + 90^\circ \qquad (3.1)$$ Where D^o = mean bank angle, c = berm width, b = base width and a = height. This method assumed a symmetrical channel where bank angle was equal on both sides of the drain. The dimensions of primary and secondary drainage channels formulated the second layer of channel network data within the GIS. This information was used to determine the mean dimensions of primary and secondary drains on each of the farms. The tertiary drainage network was not classified, as there were too many drains to obtain detailed measurements for each site. The dimensions of tertiary drains were therefore assumed to be those specified in the Banana Operations Manual (Fyffes, 1972). These dimensions were confirmed by a small number of field measurements.
Drainage channel instantaneous sediment loads (Primary & Primary, Secondary, Tertiary)	• A representative primary channel was identified (dimensions and location) on each plantation (Plantation 8 = *b29*, Plantation 16 = *d49* and Plantation 7 = *g48* (Figure 3.5)). • A representative secondary (*b10*) and a representative tertiary channel (*t1*) were identified on plantation 8 (Figure 3.5). • Instantaneous suspended sediment concentration and discharge were measured daily for these "indicator channels[††]". • Instantaneous sediment loads (kg sec^{-1}) were estimated for each channel by multiplying suspended sediment concentration by discharge. (Indicator channels selected for instantaneous sediment load sampling have been highlighted in blue on Table 3.5 and all are within 1 standard deviation of mean channel dimensions for respective farms.)

[**] MAPINFO: Version 4.1.2

[††] The extent to which "indicator channels" were representative of plantation channel characteristics was further defined in the UK following GIS analysis.

<table>
<tr><td>Storm characteristics</td><td>Sediment load data was collected during one storm event within a primary secondary and tertiary channel over the time frame illustrated in Table 3.7 to obtain initial data on the temporal relationship between precipitation and drainage channel run-off.

Table 3.7: Sampling frequency for monitoring a storm event
<table>
<tr><th>Variable</th><th>Frequency (minutes after initial storm onset)</th></tr>
<tr><td>SSC</td><td><u>Primary</u>:00,10, 20, 30, etc <u>Secondary</u>:00, 05, 10 etc
<u>Tertiary</u>:00, 01, 02, 03</td></tr>
<tr><td>Stage (m)</td><td>00, 10, 20 etc</td></tr>
<tr><td>Velocity (m/sec)</td><td>05, 15, 25, etc</td></tr>
</table></td></tr>
<tr><td>Suspended Sediment Concentration (SSC)</td><td>SSC was estimated through the filtration of water samples obtained using the USDH-48 hand-held suspended solids monitor (Figure 4.2, §4.5.2).
• Pre-field
Whatman-40 glass fibre and Cellulose Nitrate filter papers were numbered and pre-weighed to the nearest 0.0001g. Papers were placed in sealed plastic wallets.
• Field
The USDH-48 was lowered into the direction of flow close to the centre of channels actively draining the plantation. Samples were well shaken and passed through filter papers using suction based filtration device in the laboratory. Papers were returned to respective plastic wallets. On occasions where sediment loads were particularly large more than one filter paper was used and some samples were taken to the UK in plastic bottles for filtration using an automatic suction device in the laboratory.
• Post-field
Filter papers were oven dried at 80°C for 30 minutes[‡‡] and placed in a desiccator to stabilise for a further 30 minutes prior to re-weighing.</td></tr>
<tr><td>Velocity</td><td>Velocity was recorded using the Braystoke BFM001 current meter and was calibrated in accordance with BS3680 to m/sec (Valeport 2000).</td></tr>
<tr><td>Discharge (Q)</td><td>The x-sectional areas of indicator channels were measured at the beginning of the field season. During the following months, x-sectional area was estimated from daily stage readings, identified by lowering a weighted measuring tape into the channel or measuring against a known unit. Velocity was calculated using the Braystoke BFM001 current metre and conversion tables (§4.5.2). Discharge was subsequently estimated using the continuity equation detailed in §4.5.2.</td></tr>
</table>

§3.5.6 Preliminary results - primary channels

Figure 3.9 presents sediment-loading data for the field season recorded within the indicator primary drains on plantations, 8, 16 and 7. Instantaneous sediment loads have been expressed in kg sec^{-1}.

[‡‡] It was found that drying the papers for longer than 30 minutes accelerated the probability of combustion in the oven (§ 4.5.2).

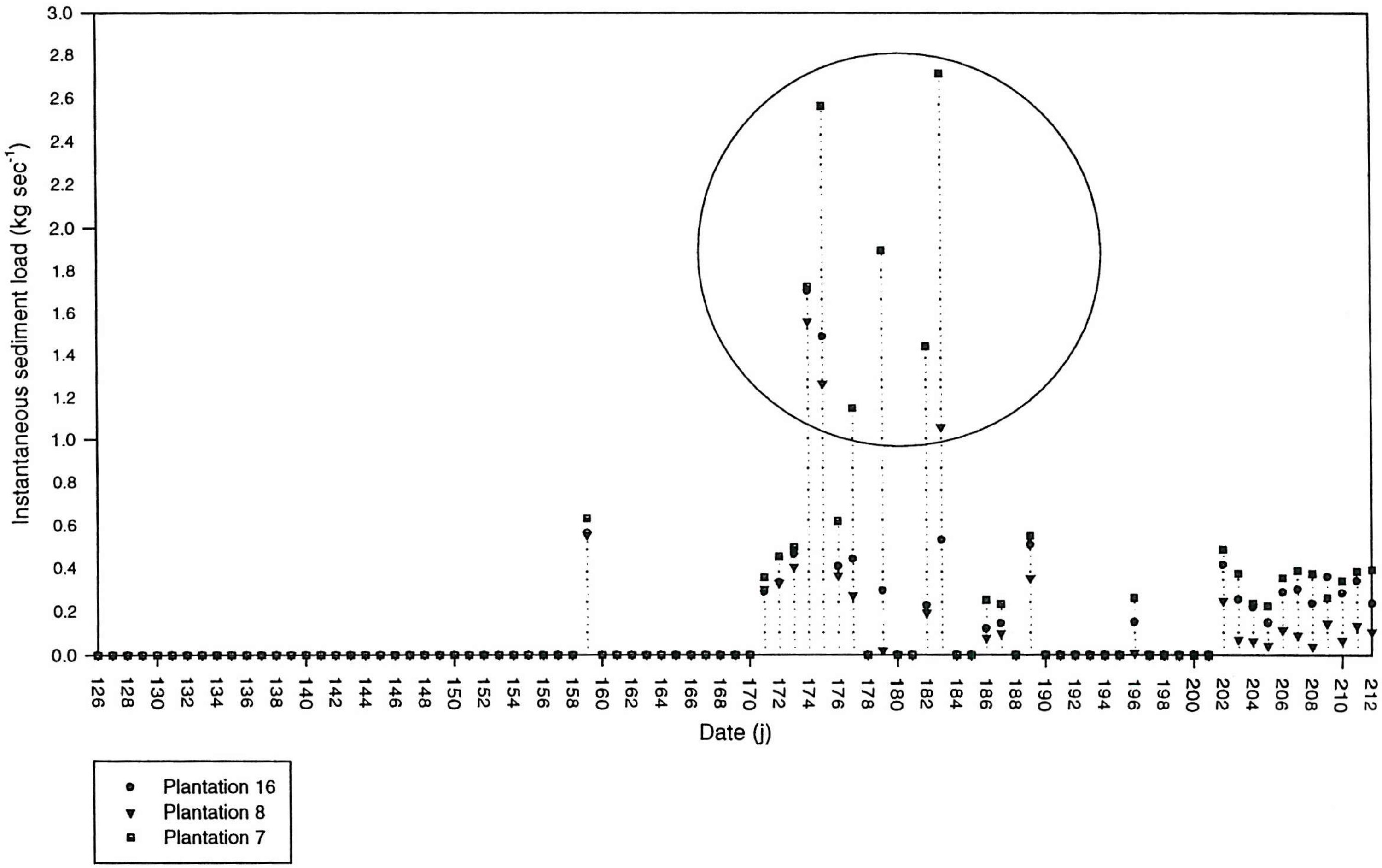


Figure 3.9: Instantaneous primary sediment load time series, Plantation 8, Plantation 16 and Plantation 7

During the field season there were two marked periods of drainage sediment yield activity, the first taking place between 170 and 189(j) and the second between 202 and 213(j). The magnitude of loadings varied for the most part between 0.05 and 0.6 kg sec^{-1}, however between 174 and 183(j) a period of sustained activity (marked by a circle on Figure 3.9) was characterised by sediment yields of between 1.1 and 2.7 kg sec^{-1}. If results are examined relative to precipitation, a hysterisis effect does not appear to have taken place over the field season. However additional information relating to the temporal dynamics of daily sediment loads would be required to explore this further. Two patterns are however, particularly evident. Firstly that there was a strong relationship between daily precipitation and instantaneous sediment loads (R^2=0.88, 0.86 and 0.69 for plantations 8, 16 and 7 respectively). Secondly that sediment load magnitude was definable on a per-plantation basis. Namely, where plantation 7 consistently returned higher sediment yields than plantations 8 and 16 and plantation 16 consistently returned lower yields than on plantations 7 and 8. The continual repetition of this pattern throughout the field season over a range of loads and input variables indicates that changes to plantation sediment yields over space and time may be an interesting focus for model calibration.

§3.5.7 Preliminary results – primary, secondary, tertiary channels (plantation 8)

Figure 3.10 illustrates daily instantaneous suspended sediment loads measured for the indicator primary, secondary and tertiary channels on plantation 8.

The magnitude of sediment load varies in the primary drain between 0.15 and 2.20 kg sec^{-1}, whilst secondary and tertiary loads fluctuate between 0.10 and 2.10 kg sec^{-1} and 0.01 and 0.75kg sec^{-1} respectively. It is again clear that if data are examined relative to precipitation in there is a strong correlation between instantaneous sediment loads and total daily precipitation (R^2=0.88, 0.91 and 0.95 for respective primary, secondary and tertiary channels). Hysterisis over the field season was not evident in either the primary, secondary or tertiary drain suggesting that if the instantaneous loads were representative of total daily sediment load for each channel and not affected by large monitoring errors, the sediment system was not exhausted following the two key periods of precipitation and subsequent drainage channel activity.

The general trend appears to suggest that sediment loads were highest in the primary drain and lowest in the tertiary drain over the monitoring period. However, during 4 of the 6 largest peaks, loads in the secondary channel exceed those monitored within the primary channel. This order reversal may be related to a larger proportion of erosion taking place within the secondary drain during periods of heavy precipitation rather than on the plantation surface, perhaps resulting

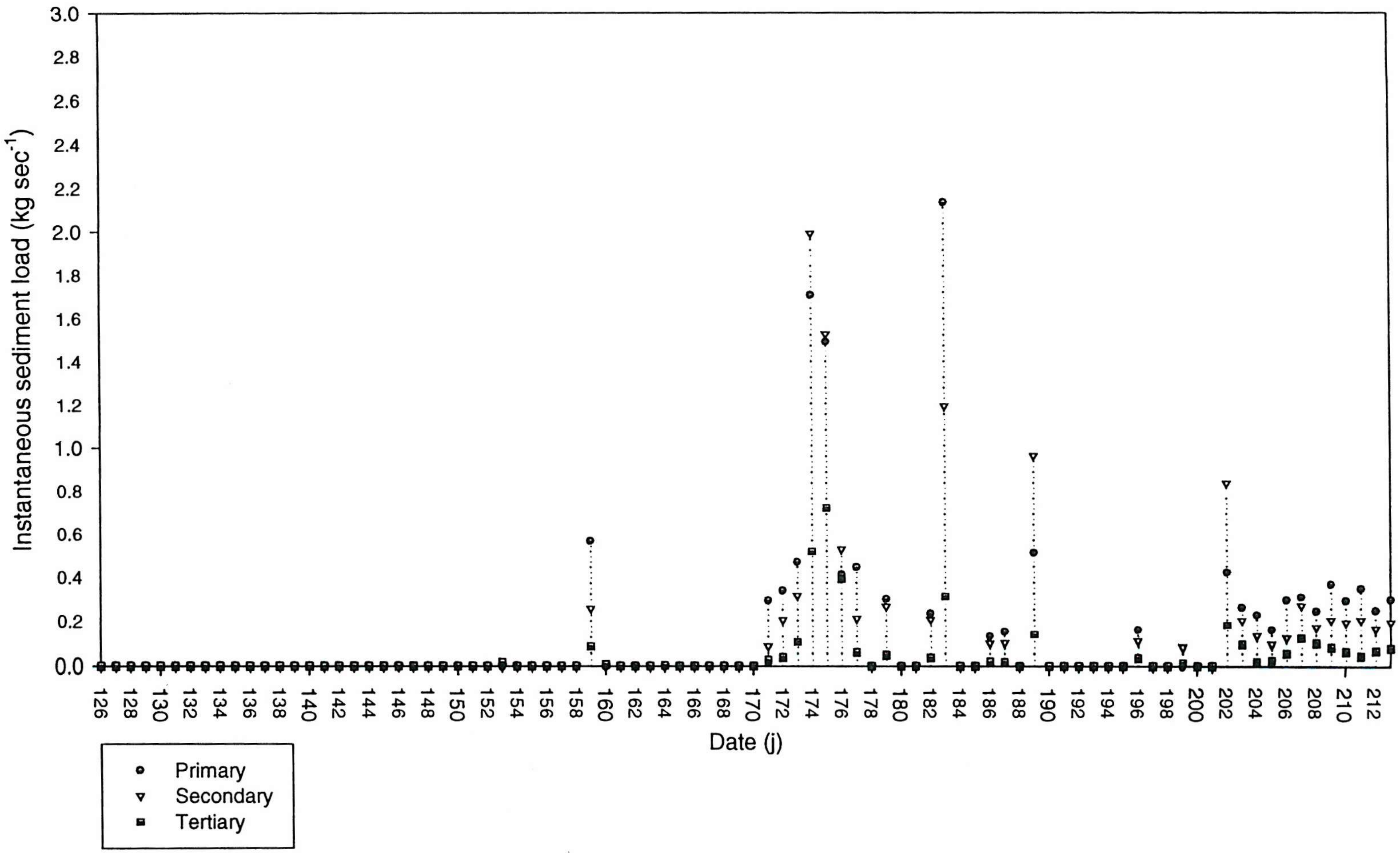


Figure 3.10: Instantaneous primary, secondary and tertiary sediment load time series, Plantation 8

from processes such as bank collapse. On the other hand the order reversal may be related to monitoring errors in large channels over storm events and the lack of temporal information. This is again an important area for model calibration where high-resolution temporal and spatial information would enable the response dynamics of various sediment sources to be distinguished and illustrate how they change with system inputs.

§3.5.8 Preliminary results – storm response

Figure 3.11 illustrates the response of a primary (*b29*) secondary (*b10*) and tertiary drain (*t1*) to a storm event on the 2nd of July 1998 (183j). The storm lasted 44 minutes and the point at which precipitation ceased has been marked by intercept R1. Whilst it would not be appropriate to make any assumptions about system behaviour on the basis of one event it is clear that suspended sediment was mobilised either on the plantation or within the drainage channel in all monitored channels during the storm period. Indeed, the behaviour of tertiary channel "t1" during precipitation was particularly interesting. Sediment load increased almost immediately after the initial storm onset and ceased within a minute of storm cessation. This pattern was observed in the field and has been well recognised within the industry to be an indicator of effective drainage (Pers. Comm., Plantation Managers (Farms 8, 16 & 7), Belize, 1998).

Another interesting pattern was the pulse of sediment transported in the secondary drain between 45 and 65 minutes after storm cessation. Sediment load rose to exceed that of the primary drainage channel. This may have been related to significant sediment transport and mobilisation within interconnected tertiary channels. Sediment load within the primary drain was less transient but still varied significantly between 0.3 and 0.95 kg sec^{-1} throughout the monitored period. It is clear from Figure 3.11 that sediment yield behaviour over a storm event was extremely dynamic in the primary, secondary and tertiary drainage channels monitored. This suggests that whilst the temporal dimension of instantaneous sediment yield for monitored channels can be characterised, to calibrate the plantation system effectively, a significant number of drains would require monitoring over a wide range of spatial and temporal scales.

§3.5.9 Error

Error margins identified for the plantation monitoring programme have been reviewed in Table 3.8:

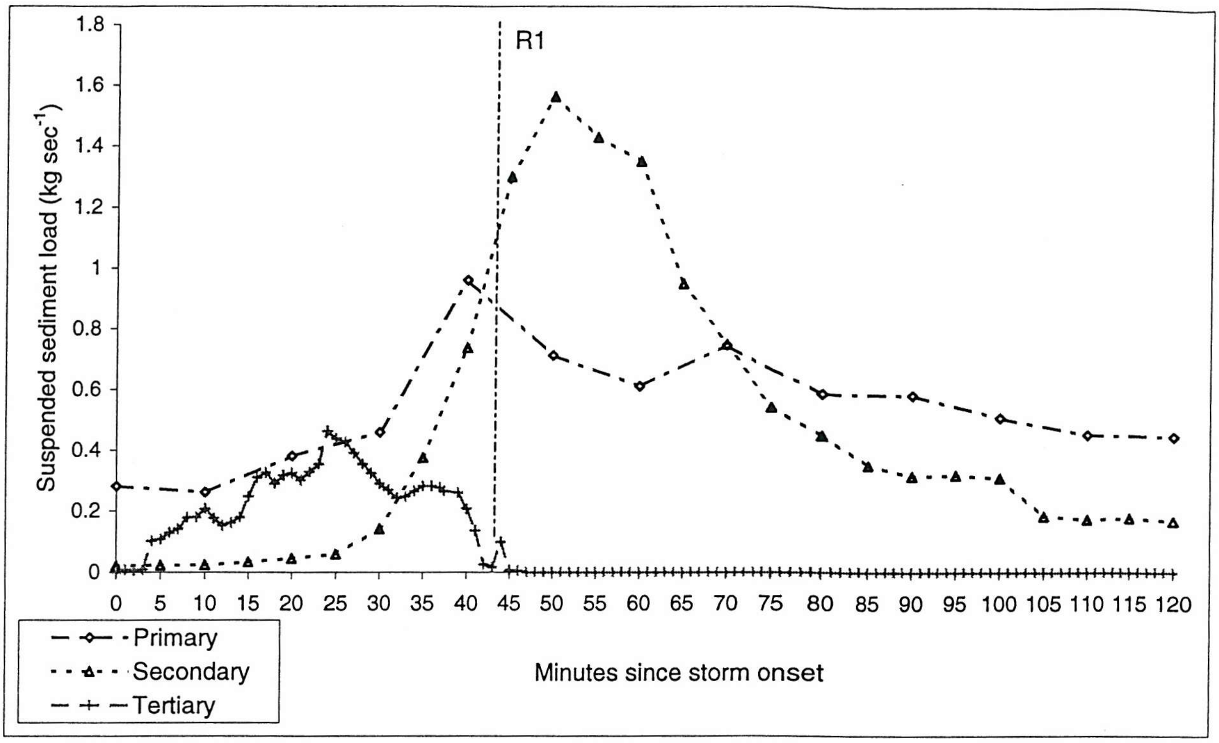


Figure 3.11: The response of a primary, secondary and tertiary drain to a storm event (Plantation 8)

Table 3.8: Estimated error margins for the plantation monitoring programme

Method	*Procedure*	*Description of potential errors*	*Estimated error Margins*
a) Suspended sediment sampling	USDH48 Hand held sampling of suspended sediment	Field sampling	Negligible due to robust equipment but likely to result in a net underestimation of large sediment loads
		Laboratory procedures	Negligible (+/- 0.0002g – based on fluvial data, although lab. errors are likely to have been up to +/- 0.001g during the handling of filter papers containing large quantities of sediment)
b) Discharge Estimation	Calculation of velocity using the Braystoke current meter	Calibration – conversion procedure from revolutions/second to metres/second	≈ +/- 1% of estimated velocity (Braystoke Current Meter User Manual, Undated)
	Measurement of stage	Random Error	Negligible (≈+/- 3cm)
	Measurement of channel dimensions	Random Error	Negligible (≈+/- 0.3m^2)
c) Estimation of instantaneous sediment load	Multiplication of instantaneous SSCs (mg/lt) by discharge derived from velocity and stage recorded at the same time(m^3/sec)	a) Multiplication of errors identified in sections a) and b) above	Negligible but likely to result in a net underestimation of instantaneous sediment loads.

Whilst it is clear that many potential errors are likely to compromise data quality within such preliminary reconnaissance research, a reasonable level of confidence may be attributed to the methods used. However to extrapolate this information to estimate a net sediment yield for the plantation unit would generate large errors unless temporal and spatial dynamics were stringently calibrated. The robust equipments facilitated the collection of a crude characterised data set on the magnitude of processes involved for subsequent insertion into a conceptual framework, providing base level information on the characteristics of the plantation system; practice and hydrological drivers and sediment yield dynamics. Further attention has been given to characterising the conceptual framework in Chapter 6.

§3.6 Practices

During field research, plantation practices were recorded. Figure 3.12 details the temporal characteristics of six key plantation management activities relative to agro-hydrological processes. Irrigation, drainage clearance, harvesting, fluid drain construction, drain re-passing and vegetation removal have been overviewed in §3.4 and identified as activities important to understanding agricultural interactions with the fluvial system. These activities have been designed to interact with climatic and hydrological system drivers to sustain a profitable plantation environment.

Given the unusually long dry period prior to the 1998 rainy season in Belize (§3.6) continuous plantation irrigation took place during the early part of the monitoring programme. In stark contrast to the subsequent rainy season, significant problems were experienced given dry, cracked soils, poor nutrient transfer, disease and pests and the economic drain of running the irrigation system over this sustained period. Unlike the drainage network the irrigation system has been designed to siphon river water from upstream of the plantation unit and distribute it across the plantation environment. The irrigation system was disabled on 22nd June (173j) despite a "false start" to the rainy season at the beginning of the month.

Drainage clearance (i.e. the physical maintenance of existing drainage channels) took place consistently throughout the early part of the field season. Clearance took place as a regular plantation practice in conjunction with harvesting every Monday to Wednesday of the year. However after the rains began, resources were channelled towards the re-passing of failed drains and construction of fluid channels to transport excess water away from the plantation system as rapidly and effectively as possible.

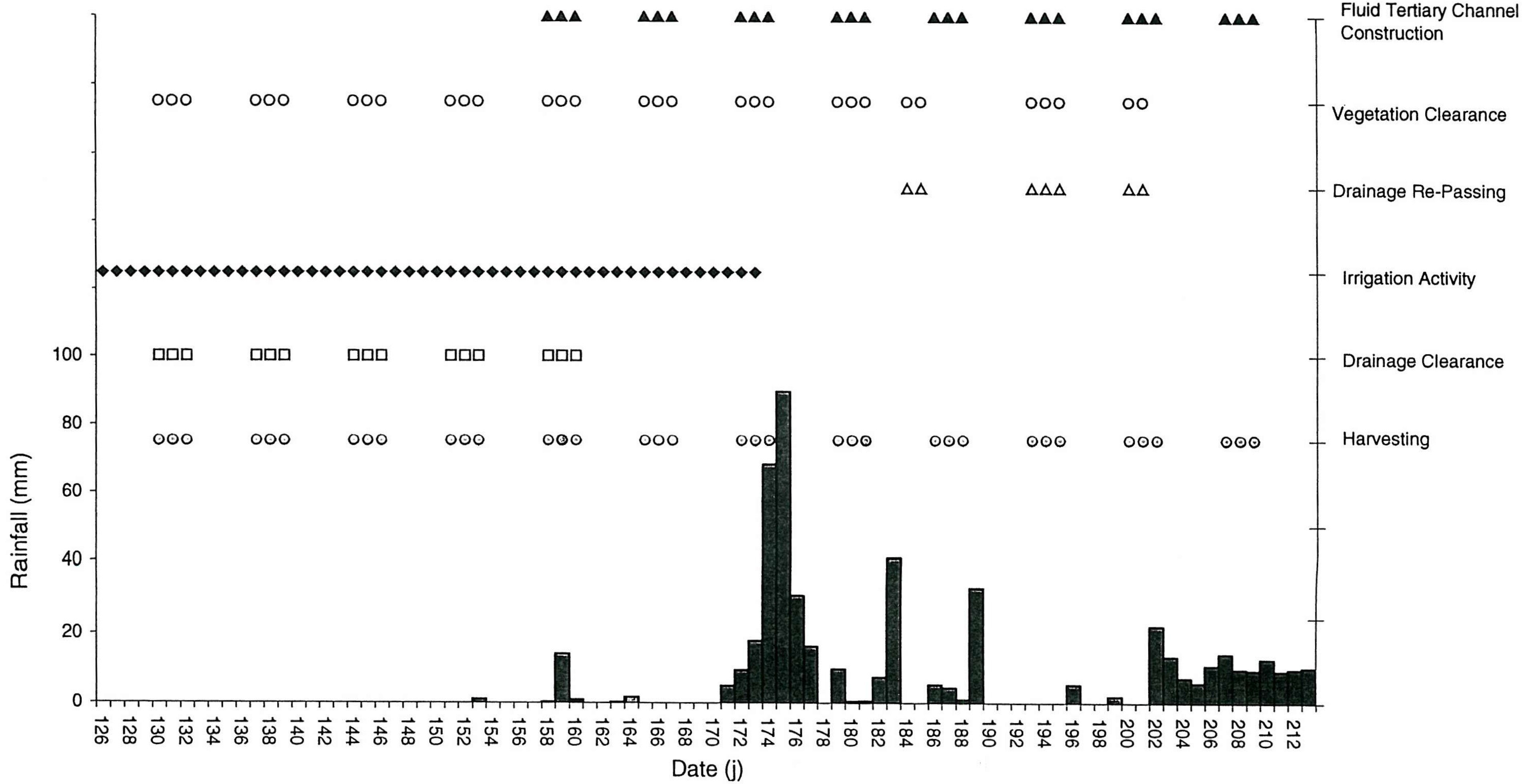


Figure 3.12: Temporal distribution of plantation management activities associated with drainage

Fluid tertiary channel construction has been discussed in §3.4.5 as an essential surface and sub-surface drainage management practice for reducing standing water and saturated soil conditions within the plantation area. This took place following the initial onset of rains within the plantation area and became a regular working practice on the plantations throughout the remainder of the field season. Plantation managers identified where new channels were to be constructed at the beginning of each week or following torrential storms.

At the same time as response tertiary channel construction took place in areas with saturated soil conditions, existing channels experienced bank failure and collapse following major storms. Subsequently during drier periods when the drains were not transporting storm water, plantation workers rejuvenated existing drains by re-stabilising banks and transporting eroded soil back onto the plantation. Often this soil would be re-located to areas within the farm where local topography was impeding drainage efficiency.

Vegetation clearance on the banks of the drainage channels and within the plantation area took place regularly throughout the dry season and during drier periods of the wet season. Vegetation growing within the drainage channels and around the root zone presented two key problems to plantation production. Firstly vegetation within the drains prevented excess storm water from being removed away from the plantation unit as quickly and effectively as possible. Secondly this vegetation competed with the banana plants for key physiological requirements for growth such as nutrients and water. Therefore whenever possible, within the day-to-day management of the plantation, vegetation within drainage channels and the plant root zone was removed using machetes. However, in some instances it was recognised that the roots of vegetation growing within drainage channel banks were effective stabilisers and subsequently were left in place and only the external limbs of vegetation that restricted effective drainage were removed.

§3.7 A guide to the interpretation of results

It is clear that a strong relationship exists between agro-hydrological parameters and sediment delivery in drainage channels to the fluvial system. Importantly it appears that precipitation inputs interact with plantation drainage channel design to *drive* sediment delivery, whilst agronomic and management practices *react* fluidly to change. Characterised processes suggest that large sediment loads are discharged to the fluvial system during periods of activity, but these periods of activity require further definition due to the nature of variability identified for the system. Subsequent research will need to calibrate specific components of the processes conceptualised within this chapter. Two specific areas have been defined: Firstly on a plantation-by-plantation basis, high-resolution temporal and spatial sediment loading information would facilitate the discrimination of plantation management practices from more uniformly distributed drivers (across the plantation unit) such as precipitation and temperature. Secondly, sediment loads in primary, secondary and tertiary channels would require calibration with high temporal resolution data to facilitate the definition of plantation sediment sources and the evaluation of their relative contribution over time and space to drainage channel sediment delivery to the fluvial system.

This chapter may be summarised by two key observations. Firstly that the physical and economic environments of banana plantation agriculture interact with hydrological forcing functions to drive suspended sediment into the fluvial system via plantation drainage channels. Secondly, that the temporal and spatial dimensions of this process are significant, where dynamic components will each require high-resolution data sets to calibrate the characterised conceptual framework presented here.

Within the LOICZ framework banana plantation agriculture has been identified as a physical and economic driver of suspended sediment to the river system. It is subsequently important to identify the mechanisms by which this driver interacts with the drainage basin system to understand potential linkages with the coastal zone. The following chapter seeks to achieve this by using a fluvial suspended sediment budget to calibrate the conceptual model at the point of transfer between the plantation and the coastal system.

Chapter 4

Monitoring suspended sediment delivery from a plantation unit to the fluvial system through a sediment budget: characterising the transfer system

§4.1 Introduction

This chapter approaches the conceptual framework from within the fluvial system, where process interactions characterised in Chapter 3 are explored from a different catchment perspective. It sets out to characterise productivity as indicated by a suspended sediment budget to further understanding of interactions between the plantation and the river.

Suspended sediment output from the drainage basin has increasingly been recognised as a moderator of coastal change, where fluxes in fluvial sediment are thought to have significant impact on the coastal environment. The interaction of human activity with this process has attracted immense research attention and monitoring programmes have been set up in fluvial and coastal environments across the globe to facilitate understanding of man's influence on system components and *vice versa* (Peters & Walling, 1991). The strong association reported in the literature between suspended sediment and contaminant movement (e.g. Chapman, 1982) has further promoted the demand for water quality research in fluvial and coastal systems. Sediment loss from the drainage basin has also become a pressing issue at the local scale, where soil erosion, particularly from agricultural land has been associated with economic as well as environmental loss. To understand how this process fits into the broader sediment delivery framework, monitoring programmes have increasingly used sediment budgeting as a technique for linking processes operating within the drainage basin to those taking place at the land-ocean interface (IGBP, 1999).

Initially this chapter examines the importance of sediment budgeting for characterising the transfer of suspended sediment from the land to the ocean within a dynamic tropical environment. Consideration is given to past research within this area and important gaps in understanding are highlighted. In particular attention is drawn to the value of robust monitoring for the implementation of programmes within unpredictable environments. The second part of this chapter presents methodologies and results from a characterised fluvial suspended sediment budget of South Stann Creek. The budget is used to facilitate understanding of net changes to suspended sediment loadings within a reach adjacent to the banana plantation unit identified in the previous chapter. Consideration has been given to the value of characterising the conceptual framework within the fluvial system for integrating agricultural, fluvial and coastal processes within a unified system model.

§4.2 Developments in suspended sediment monitoring programmes

Significant advances in the capabilities of monitoring equipments to record accurate data over long time periods have promoted the establishment of research programmes in remote and challenging environments (e.g. Gurnell, *et al.,* 1992). Together with this, improvements in the capabilities of data handling and spatial analysis technologies have shifted sediment-monitoring programmes towards the cutting edge of water quality science and management.

There has been some discussion in the literature relating to the role of sediment monitoring programmes as a scientific tool for subsequent management (e.g. Olive & Reiger, 1992). Significant attention has been given to the detail and accuracy of such programmes; however, in many cases the rationale behind their design appears unclear and research findings have seldom been applied to related sedimentation issues. Despite the capability of sampling devices to record over long time periods, the general trend seems to be moving towards that of shorter monitoring programmes (Day, 1988), focussing on increased accuracy and the temporal and spatial extrapolation of findings to infer longer trends. Some progress has been made over the last few years and the tentative extraction of "meaningful" data from short term monitoring programmes has pushed their design and application into the domain of applied science. There is, however, a risk when using short-term data to identify processes and patterns in the fluvial environment that significant errors may occur if findings are applied to larger spatial and temporal scales (Summer, *et al.,* 1992). This consideration is particularly important when project findings are applied to system management. Programme design is, therefore, central, to the accuracy and applicability of sediment monitoring programmes.

Sediment monitoring programmes for water quality usually focus on three core variables, discharge (Q), suspended sediment concentration (SSC), and particle size, which are normally estimated within relatively small error margins (Ongley, 1992). The challenge is however, in the estimation of sediment sources, sinks and transport mechanisms, especially when linking erosional processes within the drainage basin to patterns in the fluvial environment. Significant literature has evolved discussing the difficulties and uncertainties surrounding this issue (e.g. Walling, 1990) and subsequently highlighted the need for more research. The overwhelming importance of managing drainage basin land use and understanding links with off site effects in parallel environments has accelerated the establishment of monitoring programmes in sensitive and stressed regions (e.g. Zeldis & Smith, 1999).

The interface between agricultural land and the fluvial environment is a particularly sensitive region. Agricultural land is frequently located within the riparian zone and there is often significant interplay between the river and the farm in terms of agricultural practices and process interaction across the fluvial/agricultural interface. There are however, significant difficulties in differentiating agricultural sediments from those derived from in-stream erosion and transportation processes or from elsewhere in the catchment. Clearly, there will also be a degree of interaction between these processes, where in-stream material may be deposited on agricultural land (usually occupying the floodplain) and agricultural sediments may be transported to elsewhere in the catchment. Sediment delivery to the river system from agricultural land poses significant challenges in terms of monitoring design and management considerations. The increasingly understood link between sediment delivery to the river system and off-site effects such as sedimentation in the downstream/coastal environment has directed large-scale research attention to the interaction of agricultural activities with this process (e.g. Oliveira & Kjerfve, 1993). Clearly, the challenge of understanding, quantifying and addressing this potential link is considerable in terms of pure and applied science.

There has been much discussion in the literature relating to the problems involved with linking soil erosion and run-off from agricultural land to river sediment yield (Walling, 1990). Perhaps the most significant monitoring difficulty is that of the temporal discontinuity between soil erosion and sediment run-off in the agricultural area and down-stream suspended sediment behaviour. A number of studies have attempted to understand catchment sediment delivery mechanisms by exclusively examining processes from a soil erosion perspective (e.g. Kirkby, 1980). Research at the sub-basin level, involving the monitoring and modelling of soil erosion from the land surface has generally been very successful in understanding the contribution of sediment lost from small plots (Olive, *et al.,* 1988). Research involving the mechanics of sediment delivery in rills gullies and drains and soil loss equations such as the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE), (Renard, *et al.,* 1997) encapsulate only one dimension of the link between the field and the river. Direct plot measurements are of more value in determining the variables that govern erosional processes. An alternative perspective has seen a number of studies approaching the issue from a sediment yield perspective (e.g. Walling, 1984). These studies have used a basin approach to understand the contribution of delivery processes operating within the catchment such as agricultural practice. The response of the fluvial system to erosional events is however, likely to be determined by a vast range of internal and external forces. The spatial, temporal and scientific gap between agricultural soil erosion and basin sediment yield is too great for any meaningful relationship to be derived from attempting to correlate their individual behaviour and properties. Instead there is a need for alternative means of linking the farm to the river.

One such method is that of sediment tracing or "fingerprinting". This method links the individual physical and chemical properties of a potential source material with suspended sediment particles in the river. In particular the "fingerprint" of caesium-137 (^{137}Cs) has been used to effectively determine the contribution of sediment sources in a number of agricultural drainage basins (Peart & Walling, 1986). Caesium-137 was distributed evenly across the globe as a result of nuclear weapons tests and may be used as a tracer of soil and sediment movement. Its principal advantage over techniques such as the USLE for understanding sediment movement is that it uses real data opposed to an equation with calibrated variables (Cambell, *et al.*, 1988). However, as with other sourcing techniques, the error margins in using this method to identify quantitative budgets from sediment delivery processes have still to be identified and its value presently lies more in identifying qualitative boundaries of source material location rather than in defining the size and shape of its contribution. The issues relating to sediment fingerprinting as a tool for understanding drainage basin sediment delivery mechanisms have been discussed in considerable detail in the literature (McHenry & Ritchie, 1977). However, it should be noted that the present cost of the technique is a major limitation for monitoring programmes lacking substantial funding and access to specialist equipment.

Over the past decade there has been an increasing awareness that the monitoring of erosional processes and sediment yield need to be integrated to achieve a meaningful understanding of sediment sources within the drainage basin. The study of sediment budgets is a useful tool for developing this. There is, however, no definitive strategy for monitoring sediment budgets and the final result is unlikely to provide an absolute account of system behaviour but rather contribute to an understanding of the link between on-site erosion and downstream sediment yield. Determining the contribution of a suspected source of suspended sediment has proved to be a challenging task and significant errors, uncertainties and assumptions have distorted the accuracy of some results (Parker, 1988). Such uncertainties largely result from sampling error, natural variability and inaccurate interpolation or extrapolation of data over time. The science of sediment budgeting is still developing and more research is required to develop the necessary monitoring and modelling strategies for understanding and predicting the intricacies of system behaviour. The value of constructing a sediment budget in identifying sediment delivery to the river system from agriculture has been noted by a number of authors (e.g. Bordas & Walling, 1988). Programmes utilising strategies for monitoring the periodicity of SSC upstream and downstream of an agricultural area have been relatively successful in identifying the nature of interaction across the field/riparian interface over a limited time period (Al-Ansari & Al-Sinawi, 1988). However, some caution should be expressed when using data from very short programmes (i.e. 7-14 days) to infer conclusions about the relationship between the field and the river over longer time scales. On the other hand, long-term sediment monitoring programmes have often needed to trade off between temporal and spatial coverage, especially when cost has been a limiting factor (Parker, 1988). Concern about the errors involved in constructing a sediment budget from insufficient data has been expressed in the literature (e.g. Olive & Reiger, 1988), although providing error margins are adequately defined crude data sets can provide meaningful sediment budgets (Day, 1988). The concept of sediment budgeting a drainage basin land-use area to link soil erosion with river sediment yield is, in itself, a relatively new science and in some respects, particularly innovative. Its value lies in providing a framework to merge the science of sediment monitoring with the management challenge of controlling agricultural interactions between soil erosion and sedimentation within the catchment.

An important consideration when applying sediment budgets to sediment delivery investigations is the size of the drainage basin. It has been suggested that smaller rivers deliver disproportionately large quantities of sediment to the coastal zone with respect to their catchment size (IGBP, 1995), and the interaction of anthropogenic forcing functions with this process has been increasingly recognised as a key area for new research. The value of sediment budgeting can, therefore, be seen within the IGBP - LOICZ context as an excellent means for understanding the dynamics driving the catchment sediment delivery continuum from different sized drainage basins to the coastal zone.

The interactions of annual and seasonal climatic variations with processes occurring within the catchment sediment system and basin geology play a key part in the delivery process. In particular, tropical environments experience significantly high rates of soil erosion and weathering within the drainage basin (Lal & Russell, 1981). The availability of sedimentary material coupled with the episodic nature of climatic and hydrological regimes make the tropical environment particularly demanding with respect to monitoring and managing transfer processes. To date, relatively little is known about sediment delivery mechanisms in tropical basins. Research in this area has been relatively fragmentary and there is a need for more studies investigating the extent to which the tropical drainage basin works as a delivery system to the associated coastal zone. Sediment monitoring programmes established in tropical environments have often needed to be rather fluid in their design. The unpredictability and versatility of the tropical environment does not lend itself to systematic monitoring with standard equipment. Perhaps the greatest challenge in logistical and scientific terms is in responding appropriately to tropical storms. Dramatic events have been known to wash entire monitoring stations downstream loosing valuable data and equipment. It is a well reported that storm "flashes" of suspended sediment often contain a considerable proportion of the catchment sediment yield (White, 1988) and it is therefore of great importance that data are not lost over this period and that the sampling programme is modified accordingly. Sediment concentrations in tropical rivers will tend to respond in a more "flashy" manner to storm events than most other environmental systems (excluding the pro-glacial environment), especially in small drainage basins (Olive & Reiger, 1988). As a result of this, particular emphasis should be placed on the role of storms in shaping tropical drainage basin dynamics and the subsequent response of the sediment system to such. The design and representativeness of a sampling programme will be strongly affected by the temporal relationship existing between suspended sediment and discharge, especially over the storm sedi-graph. The dynamism of the tropical environment clearly restricts the nature of field research and presents a considerable challenge to its subsequent application. The multitude of challenges associated with this environment may, in part, explain the research gap between global developments in sediment monitoring programmes and the relatively sparse literature surrounding such research in the tropical world.

Few sediment-monitoring programmes have given attention to the role of the river in transporting suspended sediments from agricultural sources to the coastal zone. This may be due to uncertainties in the quantities of sediment involved. Walling, (1990), suggested that only a rather small proportion of sediment eroded within a river basin would find its way to the basin outlet. Monitoring quantities of sediment held in storage has proved extremely difficult and Meade & Parker, (1986), offered a cautionary note to projects failing to understand temporal discontinuities in sediment delivery from the field to the ocean. A number of studies have tackled this problem by adopting watershed models to support agricultural sediment monitoring programmes and Dickinson & Bolton (1992), discuss this method in more detail. Sediment output from the watershed is, however, thought to reflect the recent erosional history of the basin rather than synchronous erosion and sediment transport within the basin. This has considerable bearing on the nature of the sediment-monitoring programme as if system output responses are muffled by catchment behaviour it is extremely difficult to ascertain direct forcing functions. At the same time if "flashes" of suspended sediment mobilisation and delivery are characteristic of the tropical sediment system then there may be some scope for linking instantaneous mobilisation and delivery to a budgeted source and catchment sediment yield.

There are a number of key questions that need to be addressed prior to the design of a tropical sediment-monitoring programme, if results are to be representative and meaningful in terms of pure and applied science. Linking sediment delivery to catchment yield *via* a sediment budget may constitute a simple and effective means for achieving this. However, the limitations of this method must be identified in each case and subsequently accounted for. Providing the sediment budget is contextualised within the research framework and recognised for what it actually represents, it may provide a useful tool for understanding agricultural interactions with sediment dynamics in the tropical drainage basin.

§4.3 The value of a sediment budget for linking the plantation to the river within the research framework

The potential for integrating erosion-transfer-deposition components of the fluvial system within a sediment budget has been identified. Within this research it offers a mechanism for linking plantation sediment delivery to the fluvial transfer system and facilitates the understanding of processes within the wider scale of change. The conceptual framework for linking plantation and coastal zone interactions may be characterised at the "transfer" stage through budgeting the upstream/downstream change in suspended sediment yield in the reach of South Stann Creek adjacent to the banana plantation unit (§3.5.2). Through characterising the framework the budget provides a structure and focus for future calibration where dynamic and gross patterns of change over the field season period may be used to direct research towards areas where further attention is best concentrated.

§4.4 Estimating a sediment budget for South Stann Creek

The sediment budget therefore may be seen to provide a mechanism for integrating on-site erosion within the plantation unit and basin sediment yield within South Stann Creek. It facilitates not only characterisation at the plantation river interface but also enables conceptualisation of processes within the wider basin delivery system. The sediment-monitoring programme has subsequently been designed to meet two objectives:

1. To characterise a fluvial suspended sediment budget for South Stann Creek upstream and downstream of a banana plantation unit.
2. To provide a downstream sediment yield time series for South Stann Creek to integrate with the characterised spatial conceptual model of fluvial suspended sediment delivery from South Stann Creek to the associated coastal zone.

   (Only the first of these objectives has been discussed within this chapter, the second is discussed in Chapter 5.)

All standards within this study have been developed within the framework of the LOICZ Data System Plan (IGBP, 1995). Wherever appropriate, existing internationally agreed standard protocols have been applied.

§4.4.1 Field and laboratory design strategy

This section describes the design and implementation of the research programme conducted during the 1998 field-season and discusses laboratory and field methodologies. Monitoring programmes undertaken in similar unpredictable and challenging environments have highlighted the importance of good field-calibration procedures for achieving accurate and reliable results (Gurnell *et al.,* 1992). This sediment-monitoring programme was designed within such guidelines to minimise systematic errors in data collection and analysis. A more detailed discussion of data quality and related issues has been conducted later in this chapter.

In designing an effective monitoring programme for research in the tropical environment, the appropriateness of standard apparatus and techniques for monitoring under extreme physical conditions, required careful consideration. Rainfall in the banana growing areas of Belize may be compared to that of other tropical areas by using values of mean rainfall per rainday (Heyman & Kjerfve, 1999). In the south of Belize rainfall intensity has been recorded to average around a mean of 20 mm per rainday during the rainy season (Walker, 1973). The intensity, quantity and frequency of hydrological events within this region presented a number of limitations to the design of the fluvial monitoring programme, as a large proportion of standard equipments were unsuitable for monitoring effectively under such conditions for a sustained period. The monitoring programme and equipments were subsequently required to work efficiently within the physical environment whilst sampling systematic and accurate data over the field season.

Data requirements

The most pertinent data requirement was a suspended sediment yield time series for two sites on South Stann Creek, upstream and downstream of a banana plantation unit. A reasonable level of accuracy was required over time and space where a field-calibration procedure was essential for assessing the accuracy of monitoring techniques. This involved the monitoring of the following variables over time:

- SSC
- Q (stage/velocity/x-sectional area)

Data were also required for assessing errors involved in sampling these variables.

Equipment requirements

Sediment monitoring equipment was required to be particularly versatile for a successful field research programme. The following aspects were considered important:

- Reliability
- Mobility - enabling changes to programme design and the effective removal of equipment during hazardous conditions.

- Durability - waterproof materials, unaffected by high levels of humidity, temperature resistant and inexpensive.
- Cost-effectiveness - relatively inexpensive and discrete equipments – to prevent theft and vandalism but fulfilling the above criteria.

On the basis of past successful sediment monitoring programmes in the tropics, the best policy has been identified to be the utilisation of simple, robust, cost-effective and reliable equipment. Experience in the equally challenging setting of the pro-glacial environment suggested that the automatic ISCO pump-sampling device was ideal for producing a time-series of SSC data with a view to estimating sediment load at a river cross-section (Gurnell, 1987).

The ISCO pump sampler (Figure 4.1) has been used in a vast range of sediment budgeting studies, particularly for the monitoring of agricultural soil erosion and sediment delivery (Hasholt, 1992). The device is however, heavy and requires programming. The point/depth integrated USDH48 hand-held suspended sediment sampler (Figure 4.2) is equally robust and would be an ideal calibration device for the ISCO automatic pump sampler. A comprehensive review of suspended sediment monitoring equipments and strategies may be found in Bogen *et al.*, (1992).

The representativeness of automatically collected point sample SSC data
Sampling stream suspended sediment at one fixed point may not be the most accurate means for establishing SSC across the entire river x-section. In particular, samples collected at the river bank may by distorted due to mixing functions (Feltz & Culbertson, 1972). The standard procedure for handling this discrepancy is the determination of a "box equation", or the calculation of the most appropriate cross-section versus point sample coefficient (Inland Waters Directorate, 1988). The equations derived will relate SSC under a number of conditions to individually collected point or depth-integrated samples. The subsequent mathematical expression will facilitate the conversion of single point or depth samples to cross-sectional suspended sediment concentrations for the same temporal interval. This technique has been found to be particularly useful for identifying annual variations in the fluvial suspended sediment flux, however the technique has been less useful in detailed temporal investigations (Horowitz, *et al.*, 1990).

Automatically collected point SSC samples for sediment budgeting investigations may be corrected spatially by using this procedure through obtaining detailed cross-sectional information on stream SSC at a range of discharges during the field season. However, it should be noted that whilst the implementation of this technique is preferable to deriving total cross-sectional SSC from individual point samples, it is not without its critics and detractions. Clearly the temporal and spatial coverage of calibration samples will affect the real "accuracy" of the depth and width integrated cross-sectional data. It is therefore important, that consideration be given to the acceptability of error margins in the application of this method to sediment budgeting investigations.

Site requirements

The location of the monitoring site for effective and representative monitoring of SSC has been identified to be of key importance in sediment budgeting investigations (Gibbs, 1974). For fluvial sediment monitoring in Belize the following factors were considered important:

- A stable and inconspicuous monitoring platform.

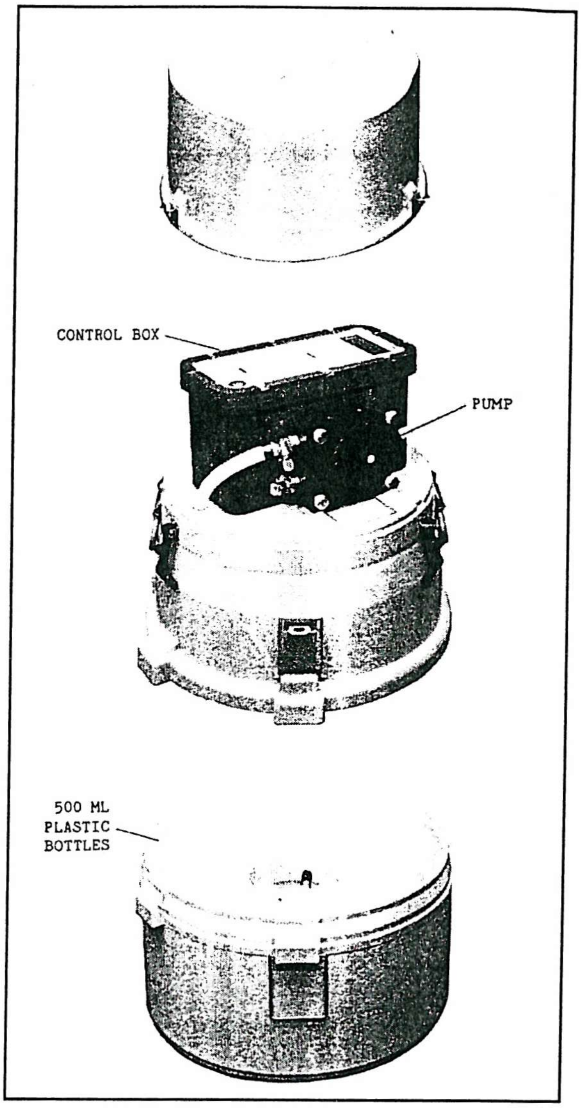


Figure 4.1: The ISCO Automatic Pump Sampler (ISCO, 1986)

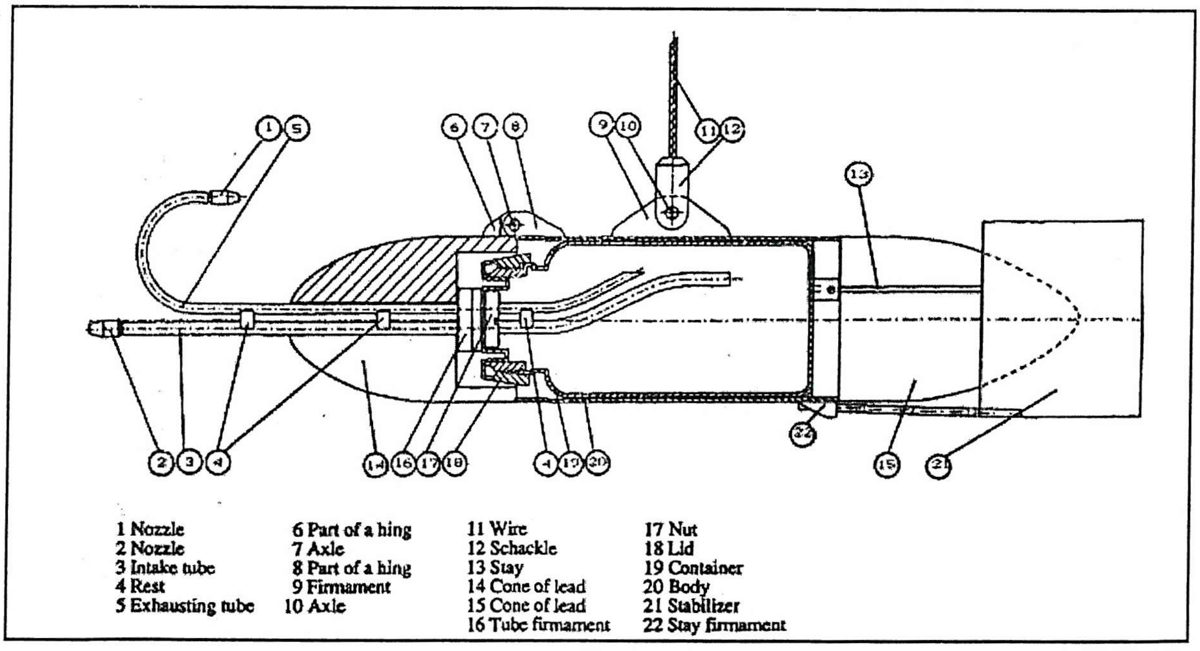


Figure 4.2: The USDH hand-held suspended sediment sampler (Nillison, 1969)

- The positioning of equipment above the maximum anticipated level of river flow to reduce the possibility of data and equipment being lost.
- Accessibility - especially with apparatus that required maintenance and re-programming.
- Location on the boundary between the farm and the peripheral environment (although caution was exercised with respect to tampering and vandalism).
- The positioning of monitoring equipments relative to sediment sources (especially fluvial and agricultural tributaries) due to the level of mixing in stream and the relationship of such with river inputs. (Despite the level of turbulence generally being quite high in tropical streams (Arduino, 1992) SSC was still likely to vary over the cross-section and be affected by suspended sediment inputs proximate to the sampling apparatus).

It was also preferential that the field site was located in close proximity to a fluvial gauging station and a hydrological monitoring site on the same river to facilitate the interpretation of dynamics relative to local and regional system drivers.

§4.4.2 Site selection

Two sites were chosen to budget in-stream and delivered suspended sediment to South Stann Creek. The strategy was to monitor sediment concentration at set intervals throughout the field season encompassing the initial energy flux at the onset of the rainy season. Similar monitoring programmes in the pro-glacial environment have varied tremendously in their design with sampling frequencies depending on a series of factors ranging from programme length to the particular properties of suspended sediment being investigated (Gurnell, 1987).

Two monitoring sites were chosen, upstream and downstream of three banana plantations (Farms 8, 16 & 7) located on the banks of South Stann Creek. The first site (hereafter, Site A) was chosen primarily due to its location upstream of any influence from these plantations whilst the second site (hereafter, Site B) was located directly downstream of the study area (Figure 4.3). Both sites were located on the boundary between the plantation and the external environment. Site A was particularly ideal as an iron bridge crossed the river at this point (Plate 4.1). Logistically this facilitated positioning the sampling apparatus above the influence of flood conditions and away from human or animal interference with the sampling programme. Hand-held USDH readings could be taken relatively easily in-stream and from the riverbank or by lowering a weighted sampling bottle from the bridge during flood conditions. The bridge was approximately 20ft above the water during low flow conditions, which fortunately was the

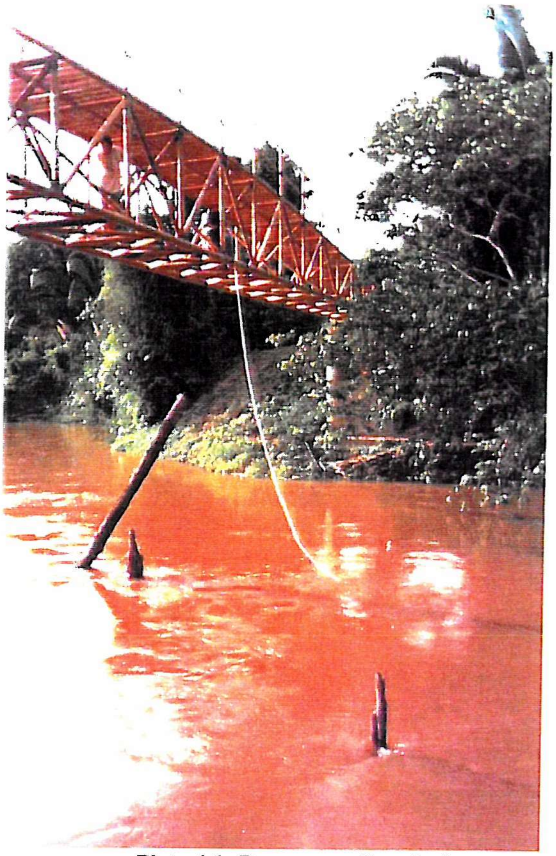


Plate 4.1: Pump sampling device attached to the steel bridge at site A

Plate 4.2: Transportation of pump sampling apparatus to field site B

maximum sampling height over which the automatic ISCO pump sampler could pull under the power of a 12V battery.

The second site was considerably less accessible and created a considerable challenge logistically. Unlike the upstream site A, where the station was positioned on the interface between managed land and the plantation, site B was located at the interface between the banana plantation and secondary rainforest/jungle. Accessibility was limited to bicycle and cableway transport or alternatively a shorter trip by canoe. The site did not have any solid structure against which to tie apparatus, so a wooden platform was required to be constructed to prevent equipment being lost during peak flow. The monitoring apparatus required for site B needed to be light and extremely robust as equipment was either towed on cableways or carried through the farm.

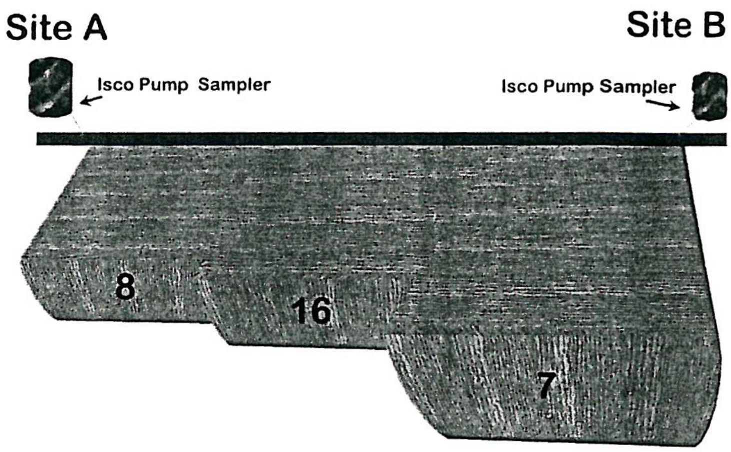


Figure 4.3: Simplified Design Strategy

Plantations 8, 16 and 7 have been described in more detail in Chapter 3, however it is important to note that they formed a simple plantation unit that fulfilled the criteria for the characterised study of interactions between banana plantation agriculture and the river (§3.5.2). The plantation occupied one bank of the river continuously from monitoring site A to monitoring site B (Figure 4.3) and encompassed an area of approximately 5.5 square kilometres.

§4.5 Methodology

This section details the procedures implemented during the fluvial sediment budgeting programme.

§4.5.1 Monitoring suspended sediment concentration

SSC was estimated through the filtration of water samples. Table 4.1 describes the pre-field, field and post-field methodologies for the estimation of this variable.

Table 4.1: Methodologies for monitoring SSC

Methodology	*Procedure*
Pre-field methodology (filter-papers)	Prior to field research laboratory tests were executed to determine the most appropriate methodology and apparatus for sediment weighting. Millipore 0.45μm cellulose nitrate membrane filter papers were selected for their non-hygroscopic properties (i.e. they will not absorb humidity in a tropical environment), small pore size, and resistance to clogging. They were selected on the basis of research undertaken in the pro-glacial environment (Gurnell, et al., 1992) where cellulose nitrate papers were ideal for the filtration of large quantities of fine cohesive suspended sediment. There has been some discussion in the literature with respect to field and laboratory methodologies for handling cellulose nitrate filter papers (Threfall, 1986). Errors generated using coarse glass filter papers such as the Whatman 40 have been assessed in the alpine pro-glacial context (Gurnell, et al., 1992) and have been attributed to finer sediments passing through the pores. Past studies have identified that the transportable material of the Stann Creek coastal plains and the suspended load of South Stann Creek is predominantly fine cohesive sediment (Hall, 1994). Given such, cellulose nitrate papers were identified to be more appropriate for field research than coarser glass papers. Appendix 4 highlights pre-field and post-field laboratory procedures for handling cellulose nitrate papers. The following method was selected for handling samples: 1. Primarily, each cellulose nitrate paper was numbered with biro and weighed prior to storage in a sealed plastic wallet[§§]. 2. Water samples were filtered through the cellulose nitrate papers, and the wet papers subsequently returned to the sealed plastic wallets for storage until returning from the field. 3. Papers were oven-dried at 80°C for 30 minutes in the laboratory[***]. 4. Papers were placed directly in a desiccator 5. Papers were re-weighed. NB: Papers were handled with forceps to prevent contamination. In addition, ten "control" filter papers were pre-weighed in the UK, taken to the field site, wetted, and once back in the laboratory, dried and desiccated under the same conditions as the sediment sample papers.
Pre-field methodology (monitoring equipments)	Prior to fieldwork in Belize, a number of tests were carried out on suspended sediment sampling equipments. Two ISCO automatic pump samplers (model 2900) were chosen to be the principal device for monitoring sediment concentrations in the field. This model is a portable device, which has been designed to collect up to 24 samples, concurrently or at set intervals. The sampler collected at equal

[§§] Research using Whatman 40 filters in the filtration of sediments, found that the pre-drying stage was necessary to account for the hygroscopic nature of the glass papers (Threfall, 1986). However the resistance of cellulose nitrate papers to humidity adsorption eliminated the necessity of this procedure.

[***] 80 degrees Celsius is the recommended temperature for drying cohesive sediments without deforming their properties (Pers. comm., Whatman, 1999) and 30 minutes was found to be the correct drying time as 1 hour as recommended by manufacturers sometimes resulted in paper combustion.

	time intervals due to its internal timing circuitry and also sampled whenever manually triggered. The sampler is encased in a plastic container, which may be detached to remove the collected samples at any time during the cycle. An adjustable length hose is attached to the barrel that suctions water via a small pump into the bottles. The interval between samples could be programmed for between 1 and 9999 minutes (approximately 7 days). The sampling design could therefore be pre-determined through keying in parameters to specific steps on a liquid crystal display. Slight variations between the two samplers available for field research meant that one would sample up to a maximum volume of 500 millilitres and the other up to 1000 millilitres. However, providing readings were calibrated with standard equipment, representative SSC could be determined and results comparable for both sites.
Pre-field methodology (monitoring equipments) cont.	The two ISCO pump samplers were run for one week concurrently in the laboratory to test their response to the programmed sampling instructions. Each ISCO pump sampler responded as required to the sampling programme specified, although it was impossible to accurately simulate field conditions in the laboratory. Aspects such as sampling height and the hose length were not simulated, as field specifications were uncertain. At the same time it was also impossible to predict the type of programme required during fieldwork as this clearly depended on environmental conditions during fieldwork. The ISCO pump samplers were run off 12V car batteries as previous research using the pumps found that the encased battery failed to run for longer than a few days (Personal communication, laboratory technician, University of Southampton, Department of Geography). In a humid environment it was anticipated that the ISCO pumps would sample approximately three times a day over a week on one 12V car battery before it required recharging. Two additional car batteries were charged prior to fieldwork, facilitating an efficient changeover between the two power sources.
	Sampling equipment such as the USDH 48 suspended solids sampler required little pre-fieldwork testing providing the sample bottle remained clean and attached during research.
Field methodology	During the 1998 field season, the two ISCO 2700 automatic pump samplers were run continuously upstream and downstream of the research area at sites A and B. The frequency of samples was increased at the beginning of the rainy season from 1 x 1000ml/24hrs upstream and 1 x 500ml/24hrs downstream to 3 x 1000ml/24hrs and 3 x 500ml/24hrs respectively. Variations in sample volume at the two sites were due to different sized pump-samplers where a fault with the upstream pump prevented sample volume from being programmed to only sample a volume of 500ml. During large storm events sampling frequencies were occasionally increased to 6/24hrs. USDH readings were taken whenever possible to calibrate this data with the majority of readings taken at the exact same time as the ISCO was sampling. The ease of using the USDH during the dry season enabled this operation to be conducted frequently and effectively, however, as the discharge of South Stann Creek increased dramatically during storms the implementation of this sampling strategy became increasingly difficult and dangerous. It was therefore found that the best means for achieving similar data in these conditions upstream was to lower a weighted plastic bottle into the creek from a bridge. Unfortunately downstream there was no bridge so USDH readings were taken from a canoe tied to the riverbank adjacent to the pump sampler.
	Changing the length of the hose at site A from that originally attached in the UK to a 20ft hose was necessary at the beginning of the field season due to the gap between the bridge and the water level being higher than anticipated. This procedure was relatively simple and involved un-clamping the

original tubing and replacing it with the longer version. The sampling specifications programmed into the CPU unit required modification accordingly. Due to the excess power necessary for pulling water over this added distance, the battery at site A was found to last for shorter periods than that at site B and subsequently required replacing more frequently.

Field methodology cont.

§4.4.3 discussed the representativeness of automatically collected point sample SSC data and the value of deriving the cross-section versus point sample coefficient for subsequent data quality enhancement. In-field methodologies for this procedure involved hand – held USDH48 depth and width integrated sample collection across the cross-section at low, medium and high discharges at both sites. To calibrate accurately with ISCO automatic pump sampler SSC measurements USDH48 readings were taken within the same time frame as automatic sampling took place.

The 24 ISCO pumped samples were collected immediately at the end of the sampling programmes at sites A and B. The samplers were programmed so as to avoid their cycles ending at the same time. The 24 samples were then decanted into numbered 500ml plastic bottles and carried back to the field base. The sampling programme was then re-set to either the original or a modified sampling programme. During periods when river stage rose and the sampling programmes were in mid cycle, water samples were collected manually and the programmes were adjusted to a higher sampling frequency.

USDH48 hand–held water samples and automatic pump samples were shaken well and filtered through Whatman 0.45μm cellulose nitrate papers using hand-operated pumps. These pumps worked on the principle of creating a vacuum below the filter paper through manually extracting air from the container. Each sample took approximately 5-10 minutes to filter manually. Alternative tests were conducted with Whatman 40 glass fibre filter papers, but these were found to be equally slow and tended to block more quickly. Approximately two Whatman 40 filter papers were capable of holding the same quantity of fine sediment as one Cellulose Nitrate paper. The sediment-laden papers were subsequently replaced in respective plastic pockets and sealed.

Post-field methodology

Following return to the laboratory the handling procedure for cellulose nitrate papers was resumed. Samples were removed from their plastic wallets and placed in a drying oven at 80°C for 30 minutes. Papers were subsequently placed in a desiccator for a further 30 minutes to facilitate cooling without moisture re-absorption. Each filter paper was individually re-weighed to the nearest 0.0001g.

The concentrations of some water samples were too high to be filtered manually through cellulose nitrate filter papers. These samples were left in the sample bottles brought back to England and filtered using a vacuum pump in the laboratory. Care was taken to ensure that residue did not remain inside the original sample bottle, especially after they had been left standing for considerable time periods. Additional sediment was washed out with clean water and vacuum-filtered through the same filter paper.

Filter paper weights for the 500ml samples (site B) were doubled to ascertain their representative weight per 1000ml so they were comparable with site A sediment-weights. On a few occasions the pump failed to sample the programmed volume of either 500 or 1000ml. For such instances volumes of less than 100ml were discarded, as error margins have been found to significantly increase as sample volume decreases to this extent (Threfall, 1986). Filtration weights for under-sampled volumes greater than

	100ml were multiplied by the appropriate factor to represent the standardised 1000ml volume of water and sediment.
Calibration Calibration cont.	All SSC weights were corrected by the mean variation in the weight of the ten control papers to allow for slight variations in humidity and local conditions. The mean variation between the "pre-field" and "post-field" weights of ten control filter papers was calculated to be 0.0002g, returning a standard deviation of 0.0001g. The SSC data set was corrected accordingly. Calibration of the automatic pump sampling device (the ISCO 2700 pump sampler) took place in the field using the USDH48 hand-held suspended sediment sampler (Figure 4.2). Only USDH readings taken at the same time as the ISCO pump was sampling were used in this calibration process. The relationship between the ISCO pump sampler and USDH hand – held readings at sites A and B returned strong R^2 values of 0.98 and 0.94 respectively. The regression relationships for site A and site B were subsequently applied to the ISCO sediment concentration data for sites A and B to standardise values. Standardisation procedures for hand-held against automatically collected sediment weighting data have been discussed further in Gurnell, (1987).

§4.5.2 Monitoring Discharge

Discharge was estimated for site A using the continuity equation:

$$Q = A.v = w.d.v \qquad (4.1)$$

Where A = area, v = mean velocity, w = width, d = mean depth and s = stage. Daily measurements of stage were obtained for site A using a weighted tape measure attached to the steel bridge. Velocity was recorded daily at site A using the Braystoke BFM001 current meter and was calibrated in accordance with BS3680 to m/sec (Valeport 2000). Cross-sectional area was measured over a range of discharge conditions throughout the field season. A strong stage / discharge relationship was determined for site A ($R^2 = 0.89$) and has been illustrated in Figure 4.4 below:

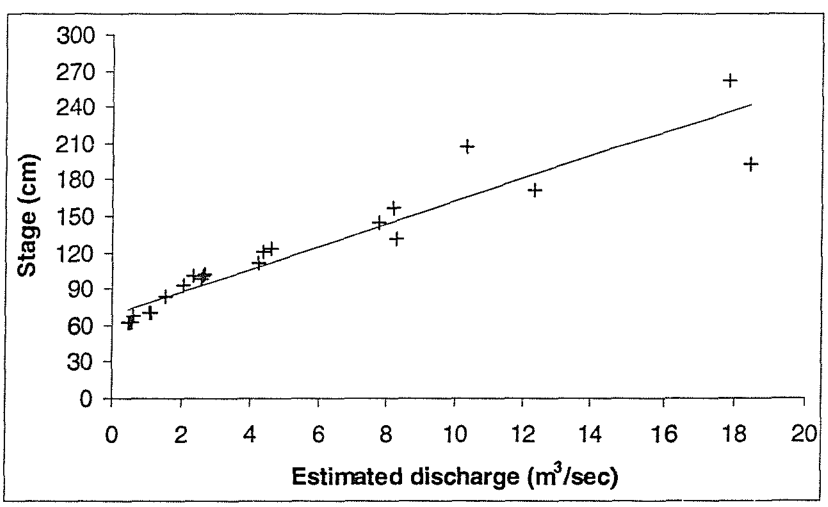


Figure 4.4: Stage discharge relationship site A

The temporal resolution of discharge data for site A was sharpened with high-resolution stage information from an upstream site (site W) using the following procedure:

Stage at site W was logged at 15-minute intervals on South Stann Creek throughout the field monitoring period as part of a regional monitoring initiative (Watershed-Reef Interconnectivity Scientific Study (WRIScS, 2000)). Velocity measured at site A was used to derive the time at which stage data from the same period was originally logged at site W. Stage at derived times for site W was subsequently plotted against recorded stage for site A. A strong linear relationship between the two variables ($R^2 = 0.91$) facilitated the use of regression to estimate site A stage with the site W stage time series (on the basis of velocity recorded at site A). The stage / discharge relationship identified for site A was then applied to the estimated stage data to obtain a high-resolution discharge time series.

This procedure assumed that velocity measurements for site A were representative of mean velocity during the time of monitoring between sites W and A. The method was reliant on the similar cross-sectional profiles and close proximity of the two sites. Maximum errors associated with this procedure were included in an assessment of error margins for the budget.

Discharge for site B was assumed to be essentially the same as that estimated for site A since there were no tributaries within this reach. However, discharge timings were adjusted on the basis of a velocity-weighted time lag for the 6.1 kilometre section between site A and site B. This procedure assumed that velocity recorded at site A was representative of mean velocity during the time of monitoring between sites A and B and was again reliant on there being no fluvial tributaries between the two sites. Again, maximum error margins were defined within the sediment budget.

§4.5.3 Calculating upstream/downstream sediment yield

To derive field season sediment yield for both sites the following equation was used:

$$\int_{O}^{t} Q(t)S(t)dt \qquad (4.2)$$

Where, Q = Discharge (m^3/sec) and S= Suspended Sediment Concentration (SSC) values (kg/m^3).

§4.5.4 Estimating the sediment budget

The suspended sediment budget was calculated from the net difference between field season suspended sediment yield at site A and site B.

§4.5.5 Logistics: some considerations

Co-ordinating the monitoring programme within the humid tropics presented a range of challenges that require brief attention. Environmental conditions coupled with logistics resulted in a particularly flexible and improvisational field season. Initial logistical constraints involved the transportation of equipment to the field sites. The two ISCO pump samplers were more bulky than heavy but transporting these to sites A and B resulted in considerable improvisation! The ISCO pump sampler was attached to the bridge at site A with rope and positioning the pump under the main frame of the bridge was particularly cumbersome. Reaching site B was not possible by road and therefore the pump was attached to a series of pulleys (designed for towing bananas) with rope and wooden boards and towed by bicycle for 2-3 km through the plantations to the river (Plate 4.2).

Each subsequent calibration reading and sample collection involved cycling for approximately one hour. Car batteries were transported in a rucksack to the sampling sites, although, in the humidity this was particularly challenging whilst balancing on a bicycle. The equipment attracted some attention whilst being transported to the monitoring sites and it was, therefore, necessary to explain why they were being used and for what, to the local residents. Misconceptions about the monitoring of water quality in Belize could have resulted in the sabotage of equipment and so it was important to explain that the monitoring programme would not affect local utilisation of the river for washing, drinking and other such day to day uses. A significant difference between the approach to monitoring programmes run in the UK and those operating in the developing world is the role of the river in community life. This distinction was particularly important when explaining the purpose of research to the community. There appeared to be a fine line between not explaining enough and explaining too much. One particular local became concerned, after the monitoring programme was explained, that the river-water his family had been drinking and washing in for years was no longer safe! The task of explaining the monitoring programme to the local community was therefore quite a challenging one.

The ISCO pump samplers were camouflaged with green and black paint and subsequently attracted little attention after they had been positioned at the monitoring sites. Unfortunately the 12V car batteries used for operating the pump samplers did not fit inside the plastic casing of the pump. Torrential rainfall and various creatures threatened to damage the batteries if they were exposed. The batteries were therefore placed on top of the control panel and attached to the pump with electrical tape. Thick plastic sheeting was then wrapped around the pump to prevent any leakage. This procedure worked particularly well, although a tree frog managed to enter the casing under the plastic and couldn't escape!

Another problem with the ISCO model 2700 pump samplers was that they were not equipped with a stage altered sampling device. Therefore, modifying the sampling frequency in response to variations in river stage was somewhat difficult. However, the majority of the time the river responded rapidly to rainfall events in the mountains and on the farms and hence the sampling programme was increased following significant rainfall in these regions. The logistical advantage of living on the plantations facilitated this degree of control over the monitoring programme. A stage-altered automatic pump-sampler would though, be a desirable addition to any future monitoring programme.

Although the USDH 48 hand – held suspended sediment samplers were a robust and valuable calibration tool, some problems were experienced when using this device during flood conditions. The short handle of the sampler restricted monitoring from the bridge at site one with this device. Although improvisation resulted in the utilisation of a 500ml weighted sampling bottle and rope the standard intake nozzle of the USDH 48 could not be replicated. At the same time, calibrating automatic readings with the USDH 48 at site B encountered similar problems. Calibration readings therefore involved using a dug out canoe (*dori*) fixed to one side of the bank with rope to reach the centre of the river.

The ISCO pump samplers were extremely robust and ideal for use under such challenging field conditions. However, some of their components required regular maintenance throughout the field season. The positive and negative pins, which connected the car batteries to the pump were prone to rusting and required frequent cleaning. The hose required cleaning frequently as the wire mesh attached to the end of the hose – designed to prevent debris from blocking the tube, would sometimes become swamped with algae or leaf litter. The USDH 48 and Braystoke current meter required regular cleaning to prevent sediment and algae from blocking the intake nozzle and restricting the rotation of the propeller blades.

§4.6 Results

Further to methodologies outlined earlier in this chapter this section presents results obtained during the 1998 fluvial sediment-monitoring programme.

§4.6.1 Suspended Sediment Concentration (SSC) time series

The methodology for determining suspended sediment concentrations in the field at site A and site B has been discussed in §4.5.1

Standardised concentration data for site A and site B recorded over the field season have been presented in Figure 4.5.

On day 175 (j) of the field season the automatic pump sampling interval was increased from 1/24hrs to 1/8hrs. Sampling frequency was increased due to the onset of the rainy season towards the end of June 1998. There were a few incidences during which the automatic pump failed to sample and for which USDH calibration data was not available. These cases have been outlined in Table 4.2.

Table 4.2: Failed sampling intervals

Date (j)	Site	Sample interval (hrs)
126	Site 2	1/24
177	Site 2	1/8 (Sample Number 3)
187	Site 1	1/8 (Sample Number 2)
192	Site 2	1/8 (Sample Number 2)
192	Site 2	1/8 (Sample Number 3)
211	Site 2	1/8 (Sample Number 3)
212	Site 2	1/8 (Sample Number 1)
212	Site 2	1/8 (Sample Number 2)
212	Site 2	1/8 (Sample Number 3)
213	Site 2	1/8 (Sample Number 1)
213	Site 2	1/8 (Sample Number 2)
213	Site 2	1/8 (Sample Number 3)
214	Site 2	1/8 (Sample Number 1)
214	Site 2	1/8 (Sample Number 2)

§4.6.2 Discharge (Q) time series

Figure 4.6 illustrates the discharge time series calculated for site A and site B.

Main features:

The lag calculated through the derivation of sampling time from site W relative to velocity measurements at sites A may be seen clearly particularly during the dry season months when velocities were noted to be especially low. Of note, between 127 and 172(j) particularly low discharge levels characteristic of the dry season months were recorded. Mean discharge during this period was recorded to be approximately 0.72 m^3sec^{-1}. The initial response of South Stann Creek to the onset of the wet season took place on 172(j) where a rapid increase in discharge reached a peak at 16.9 m^3sec^{-1}, exceeding average dry season discharge by over a multiple of 23.

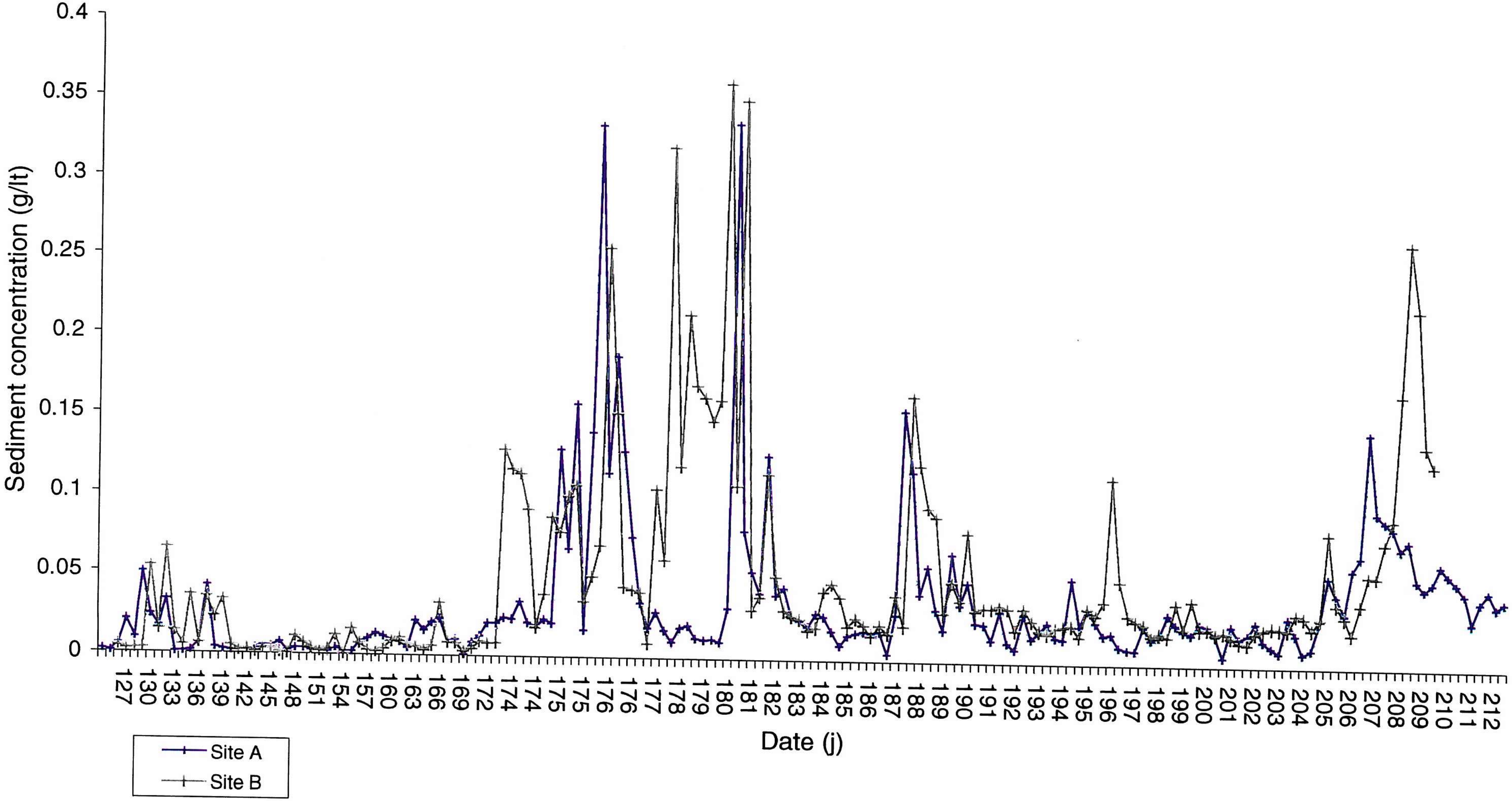


Figure 4.5: Site A / Site B standardised concentration time series

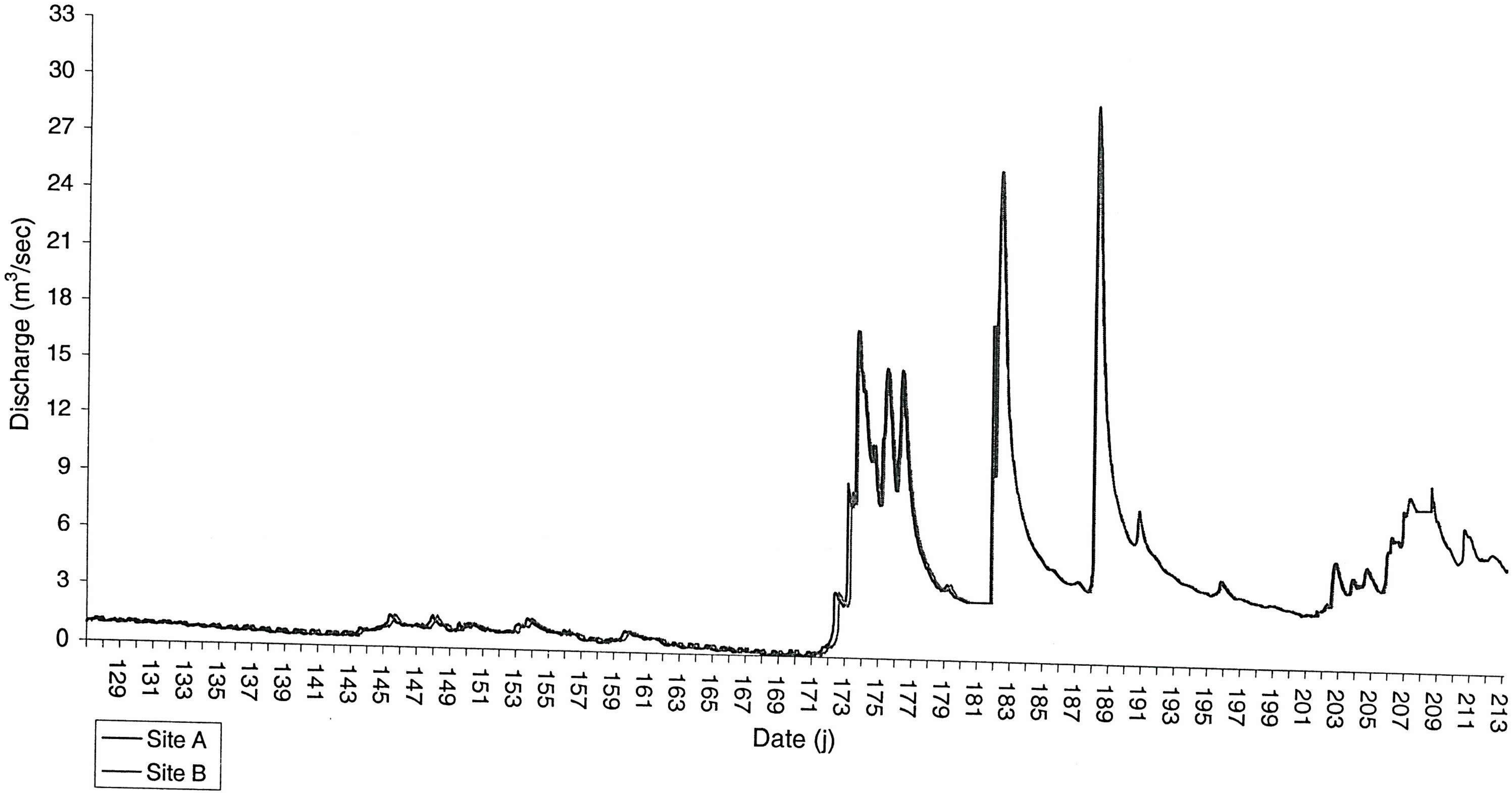


Figure 4.6: Time series discharge estimations for site A and site B

Discharge continued to remain at a high level for the following week with two distinct periods where discharge dramatically fluctuated, possibly associated with storm activity within the Maya Mountains in the upper catchment. Discharge began to drop between 177 and 180(j) where the falling limb stabilised at 2.79 m^3sec^{-1}. On 182(j) discharge again increased rapidly to an initial peak after 4 hours at 17.5 m^3sec^{-1} followed almost immediately by a second peak of 25.6 m^3sec^{-1}. Whilst not fluctuating as much as the first stage of activity the falling limb declined at a similar rate to the first period bottoming at 3.52 m^3sec^{-1}. The third peak looked to be almost identical to the second except the peak discharge was the highest experienced during the field season reaching a level of 28.9 m^3sec^{-1}, which was over a 42 times the dry season average. The falling limb declined for a longer period than the second peak with ten days of steadily declining discharge only broken by two small peaks on days 191 and 196(j). Between 201 and 213(j) discharge fluctuated between 2.46 and 9.29 m^3sec^{-1} with 4 notable periods of activity on 202-204(j), 206(j) 207-209(j) and 210(j).

Assumptions:

Whilst consideration has been given to error in §4.7 it is important that key assumptions made during the calculation of discharge for site A and site B be outlined. These were that:

- No significant increase in Q took place between site A and site B (plantation drainage channels were estimated to contribute a maximum of 1% to total discharge).
- Velocity recorded at site A represented a constant throughout the reach between the field site and the automatic monitoring station.
- Point velocity readings were representative of velocity across the fluvial x-section.

The assumption that Q did not increase within the monitored reach was based on the comparably short length of the reach within the basin system and that no fluvial tributaries entered the river between site A and site B. Whilst, plantation drainage channels exited into the reach between the two monitoring sites it is anticipated that gross changes to discharge as a result of such were minimal. Further consideration has been given to the potential impact of this assumption on accuracy in Table 4.3.

Likewise, the assumption that velocity was constant throughout the reach and between site A and site W may also have introduced some error into the calculation of Q. In particular, the temporal distribution of the time series at sites A and B may have been affected. However, this assumption would only have altered discharge timings by an order of minutes rather than hours and subsequently have had little affect on sediment loading calculations based on SSC samples every 24 or 8 hours.

Point velocity readings were assumed to be representative of velocity across the fluvial x-section. This assumption was based on two factors. Firstly that the samplers were positioned within the centre of the channel at a point where flow was well mixed and secondly that whilst calculated loadings were important, their principal value was for insertion into the differential equation for the upstream/downstream budgeted yield. Subsequently the small net over/underestimation of loadings as a result of this assumption was likely to have negligible influence over budget output.

§4.6.3 SSC/Q dynamics

The SSC and Q time series for sites A and B have been illustrated in Figures 4.7 & 4.8 respectively, to facilitate a brief overview of upstream/downstream sediment dynamics.

A number of trends may be observed in dynamics between Q and SSC at both sites that require brief discussion to detail potential drivers. In particular, the overall flux of sediment through the system took place in association with discharge, characterised by three periods of activity around 175, 183 and 189(j). However, closer examination identifies that despite similarities in overall trends a number of SSC peaks were not associated with discharge activity. Indeed, on a number of occasions SSC activity at sites A and B increased on the falling discharge limb. Likewise peaks in SSC were recorded at site B, but were less evident at site A and *vice versa*. Whilst it is recognised that many interrelated processes may drive SSC/Q dynamics over time – especially within the humid tropics, several consistent trends emerged during the field season that warrant brief attention.

A number of Q events were not mirrored by high SSC. This may be explained by a number of theories, two of which appear likely based on the nature of the system. Firstly, exposed cohesive banks, vulnerable to shear failure, were maintained during periods of high stage. However, as stage fell, the forces counteracting the failure mechanism were reduced and a threshold was exceeded whereupon bank collapse occurred (Ashbridge, 1995). Similarly a form of bank armouring may have been operating where coarser less erodible material was guarding fine cohesive bank sediments against erosional processes until a critical threshold was crossed whereupon erosion took place (Bogen, 1995). Examples of these trends are between 171 and 173(j) where peak Q was associated with low SSC until the falling limb whereupon SSC activity was recorded at both sites. This trend was also particularly evident on 179 and 180(j).

A second major trend associated with this was the prevalence of SSC peaks on the falling Q limb. Whilst both theories help to explain this process, a third theory is that local agro-hydrological drivers interacted with the fluvial system at a different time to regional climatological drivers controlled Q within the fluvial system. Subsequently peaks in SSC took place within the reach

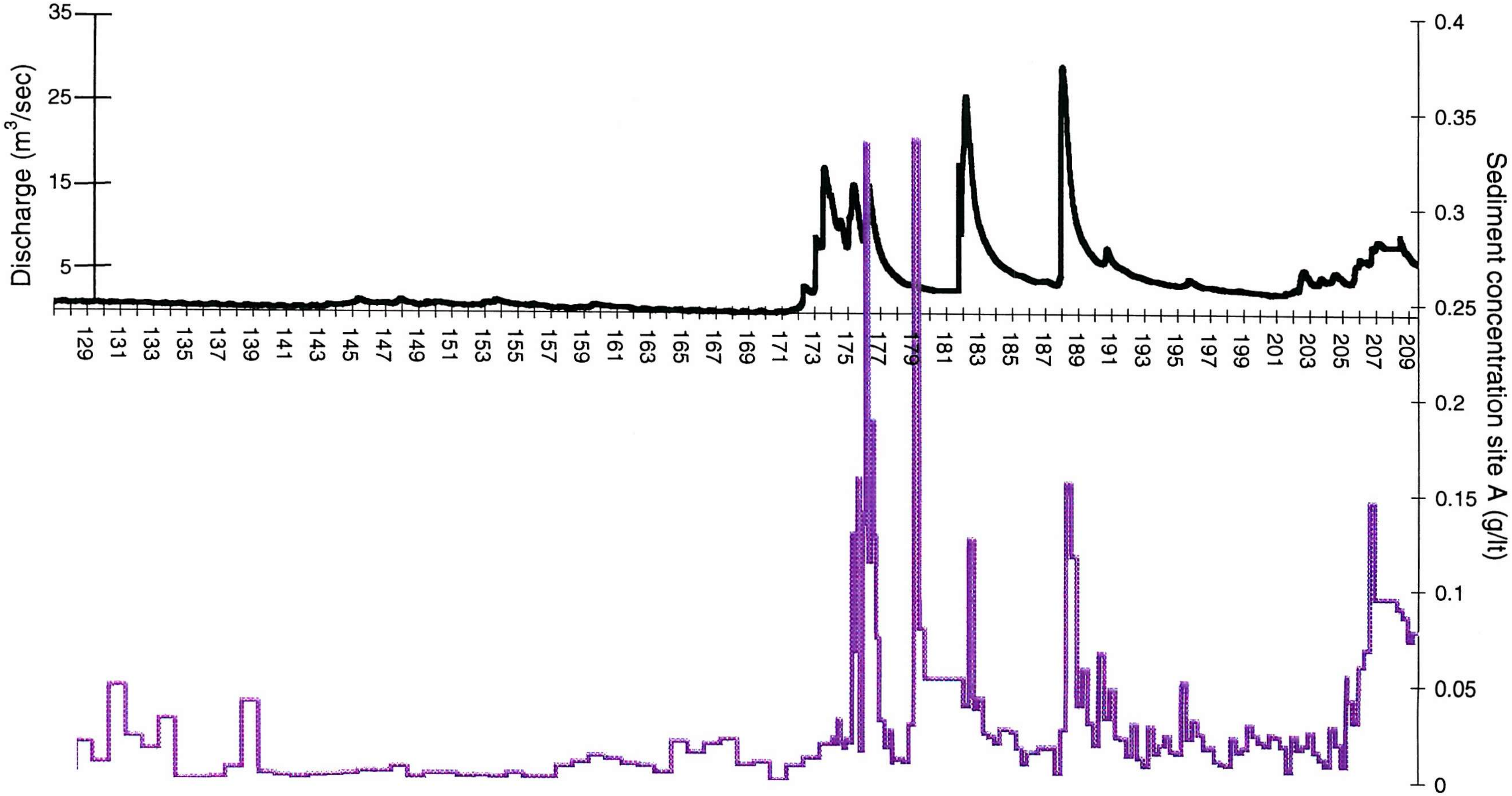


Figure 4.7: SSC/Q time series – site A

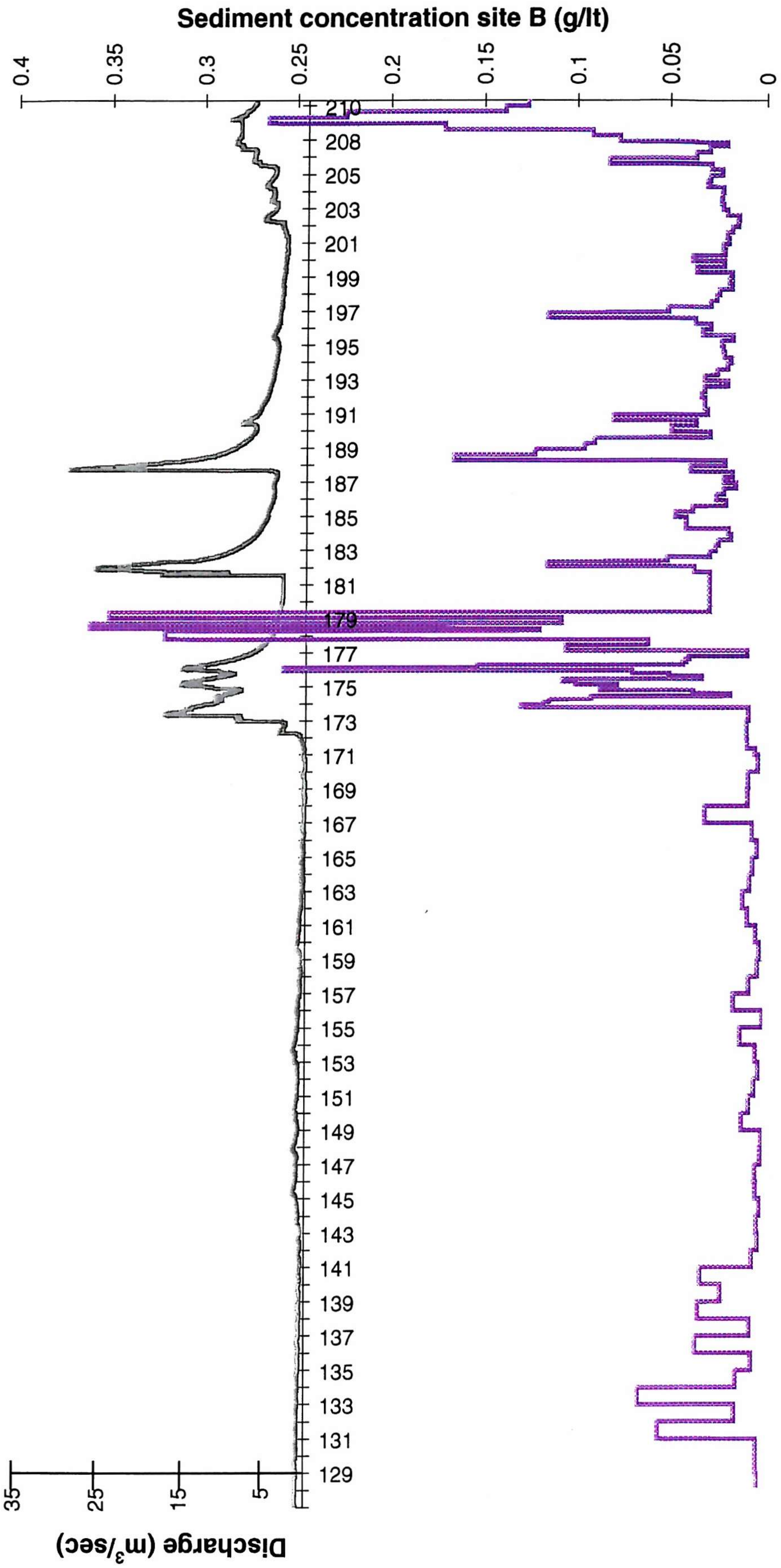


Figure 4.8: SSC/Q time series – site B

during periods of high and low Q depending on a different primary driver. Examples of this trend may be identified on 177, 178 and 179(j) and between 190 and 202(j) at site B. Further attention has been given to the specific events within the time series discussion detailed in Appendix 5.

§4.6.4 Sediment yield and budget computation

Sediment yields for site A and site B were calculated using equation 4.2. An upstream / downstream sediment budget may be expressed as the net difference between yield at site A and site B. This may be summarised as:

$$\text{Site B} \int_{127}^{209} Q(t)S(t)dt - \text{Site A} \int_{127}^{209} Q(t)S(t)dt \quad (4.3)$$

The total sediment load for the period between the 7th of May and the 28th of July 1998 was 1081.6 tonnes for site A and 1281.9 tonnes for site B. The net budgeted yield for the plantation reach was therefore + 200.3 tonnes, constituting a positive change in SSC load between site A and site B of 15.6%.

§4.7 Implications

Results suggest that a significant increase in the suspended sediment load of South Stann Creek took place between site A and site B. However, before meaning is assessed consideration should be given to error. An accuracy assessment detailed in Table 4.3 identified that maximum errors were between - 21.2% and +79.9% of the total sediment budget. This included an assessment of errors involved in field monitoring, discharge time series estimation and sediment load calculations. Table 4.3 presents an overview of all procedures involved in the computation of the fluvial suspended sediment budget. Whenever possible, maximum potential errors were quantified and expressed as a +/-% of the sediment budget. However for some methods insufficient calibration information was available due to general monitoring difficulties. For such cases an assessment has been made as to whether maximum resultant errors would lead to an overestimation or an underestimation of the total sediment budget. Whilst these margins are considerable, the overall meaning of the budget has not been compromised. In short, site A/site B suspended sediment yield for the monitored period was estimated to be between 157.8 and 360.3 tonnes. These figures clearly show that even within significant error margins, the suspended sediment yield of South Stann Creek increased markedly within the monitored reach.

Table 4.3: An assessment of errors for the fluvial suspended sediment budget

Method and procedure	*Description of Potential Errors/Assumptions*	*Quantification and Qualification of Errors*	*Potential error margins within the sediment budget*
A) Suspended sediment sampling 1) USDH 48 Hand-held sampling of suspended sediment	Field sampling	Negligible but likely to be an underestimation.	Negligible but likely to be an underestimation.
2) The use of a plastic bottle during flood periods when the handle on the USDH48 was not long enough	Larger suspended material such as leaf litter entering the sample bottle	Random but likely to result in an overestimation of SSC	Random but likely to result in a small overestimation of SSC at both sites
3) Suspended sediment sampling using the ISCO automatic pump sampler	Sampling Frequency: - Not continuous so may miss some of the resolution of the data Altering the frequency for large events – may miss some of the event due to insufficient sampling.	Dry Season (127(j) – 173(j) Samples taken 1/24 hrs: Site A:The representativeness of 1/24 hr samples for a monitoring period during the wet season (198(j) – 204(j)) monitored at 3/24 hrs was 33% . If this level of representativeness is assumed for site 1 dry season then a net error of +/-11.55 t is returned for the dry season load Site B: The representativeness of 1/24 hr samples for a period with a similar range of SSC during the wet season (198(j) – 204(j)) monitored at 3/24 hrs was 33% . If this level of representativeness is assumed for site B dry season then a net error of +/-10.7 t is returned for the dry season load	Maximum resultant error within the sediment budget: +/- 11.1%
		Wet Season (173(j) – 210 (j) Samples taken 3/24 hrs	Without finer resolution data relating to wet season SSC dynamics at both sites it is difficult to assess the representativeness of SSC data. However error related to insufficient sampling during the wet season is likely to result in a net underestimation of SSC at both sites.
	Representativeness of ISCO samples	Errors corrected against USDH 48 SSC calibration data	Negligible due to a strong relationship between ISCO samples and USDH calibration readings
4) Treatment of filter papers in the field	Handling errors and the effect of humidity etc	Papers gained +0.0002g in the field due to local conditions according to control filter papers. Therefore a control correction of +0.0002g was applied to the whole data set. Calculated error = 0.0001 of a gram. Site A Errors 0.002% of total SSC site 1 When extrapolated to discharge and sediment load estimation, errors are +/- 2.26 t of total sediment load @ site 1 ≈ +/- 0.20% Site B Errors 0.001% of total SSC site B When extrapolated to discharge and sediment load estimation, errors are +/- 2.22 t of total sediment load @ site B ≈ +/- 0.17%	Maximum resultant error within the sediment budget: +/– 0.02%

Table 4.3: An assessment of errors for the fluvial suspended sediment budget

Method and procedure	*Description of Potential Errors/Assumptions*	*Quantification and Qualification of Errors*	*Potential error margins within the sediment budget*
5) Handling and laboratory analysis	Weighing of sediment – over drying etc	Estimated to be within +/- 0.0001g Errors site A:+/ - 0.20% of total sediment load Errors site B:+/ - 0.17% of total sediment load	Maximum resultant error within the sediment budget: +/- 0.02%
B) Discharge estimation 1) Stage Readings Site A and Site B using a weighted tape measure	Sampling error – difficulty with estimating stage during high velocities	Maximum + 20cm error for stage readings greater than 1m where measurements were taken from the bridge using the weighted tape.	
		Maximum potential errors affecting the relationship between stage and discharge; the relationship between Site W and Site 1 stage readings and the subsequent determination of discharge for sediment load investigations.	Maximum resultant error within sediment budget of + 37% (Equivalent to + 74 tonnes)
		Site A Maximum error + 8.3 % of sediment load at site A = A maximum error of + 90 tonnes to the site A sediment load. Site B Maximum error of + 12.8 % of sediment load at site B = A maximum error of + 164 tonnes to the site B sediment load.	
2) Velocity measurements using the Braystoke current metre	Error in converting from revolutions/second to metres/second Difficulty measuring velocity in the centre of the channel during large events as the current metre did not reach the water. Therefore these readings were taken from the bank	Equation used to convert between r/sec and m/sec – accuracy assessment.	Maximum resultant error within sediment budget of +/- 1%
		Current metre readings are likely to have been an underestimation during high flows. However, there is insufficient calibration data to define values.	Negligible but likely to result in an underestimation
3) X-sectional area estimation	Measurement error – especially during high flows	Site A: A maximum error of +/- 0.5m^2 for x-sectional area estimations over a stage of 1m. Maximum resultant error within the stage/discharge relationship and subsequent calculations of sediment load at Site A by = +/- 4.14% (Equivalent to +/- 44.8 tonnes) Site B: A maximum error of +/- 0.5m^2 for x-sectional area estimations over a stage of 1m. Maximum resultant error within the stage/discharge relationship and subsequent calculations of sediment load at Site B by = +/- 2.28% (Equivalent to 29.3tonnes)	Maximum resultant error within the sediment budget +/- 7.7% (Equivalent to approximately 15.4 tonnes)

Table 4.3: An assessment of errors for the fluvial suspended sediment budget

Method and procedure	*Description of Potential Errors/Assumptions*	*Quantification and Qualification of Errors*	*Potential error margins within the sediment budget*
4) Computation of a stage/discharge relationship for site A with field data	Magnification of errors identified in b1) b2) and b3)	Maximum potential error within the sediment budget resulting from stage/discharge estimations at site A = -7.7 - + 44.7% (Additional errors associated with current metre accuracy are likely to result in an underestimation of sediment load at both sites and therefore have negligible influence on the sediment budget.)	
5) Use of stage data from an automatic logging device 2km upstream to interpolate temporal information on stage at site A	1) Fluvial Distance Calculations using an Opisometer	Accuracy of +/- 0.5km Potential resultant discharge timing errors: Site A maximum sediment load error = +/- 1.08% Site B maximum sediment load error = +/- 1.28%	Maximum error resulting from this on the fluvial sediment budget = +/-2.39 %
	2) a) Assumption that instantaneous velocity readings were representative of velocity across the river section	Likely to result in a slight overestimation of velocity across the river x-section – estimated to be a net error of ≈ - 2% Resultant errors within sediment load computations: Site A: = -10.6% Site B: = -6.9%	Subsequent maximum error within the sediment budget: = + 12.3% (Equivalent to 24.7 tonnes).
	3) Assumption that the stage/discharge relationship at site W was similar to site A and therefore that the shape of the stage relationship recorded at site W remained uniform until it reached site A (i.e. that no intersecting tributaries etc disrupted the shape and volume of discharge)	Examination of site W identified that the x-section was of a similar profile to site A (– although unfortunately this was not measured), and therefore it has been assumed that the error associated with extrapolating the stage pattern from site W to site A was negligible. The assumption that current meter readings recorded at site A were representative of velocity on the upstream reach between site A and site W may have resulted in a small overestimation of velocity due to the rivers meandering course between the two sites. However due to the relatively low gradient of this reach the net errors are assumed to have been negligible and certainly within the noise region.	Likely to result in a small net overestimation of sediment load at both sites. Subsequent errors within the sediment budget are likely to be small as such errors will have affected both sites and will have only affected major events over a timescale of minutes (within the noise region).
	3b) Assumption that current meter readings at site A were representative of velocity between site A and site B.	Associated errors may have resulted in a greater lag between SSC and discharge at site B. (Although it is likely that this has minimal effect on loading as timing errors will have been within a magnitude of minutes/hours during low discharges and of minutes during high discharges where the "order of magnitude" variation in velocity was less. Indeed, looking at the data it is possible that this is a plausible error as a greater lag between discharge and SSC would become evident.)	
C) Estimation of Sediment load 1) Averaged load for missed dates	Assumption that SSC was the average of adjacent readings	For dates illustrated in Table 4.2, 177(j) Site B was the only date where missed samples took place during a period of notable activity. For remaining dates errors are assumed to be minimal 177(j): Maximum error site B (based on the 177(j) sample 3 being of the magnitude of sample 4 = 1.5% of sediment load for the field season site B.	Maximum error within the sediment budget = + 9.4% (assuming that a major flux of SSC took place during the missed sample) Equivalent to 19 tonnes of sediment.
2) Multiplication of 500ml samples by 2 to compare site B sediment weights with 1000ml samples from site A			Negligible

Table 4.3: An assessment of errors for the fluvial suspended sediment budget

Method and procedure	*Description of Potential Errors/Assumptions*	*Quantification and Qualification of Errors*	*Potential error margins within the sediment budget*
3) Extrapolation of point SSC measurements to calculate total SSC load	Depth	Unfortunately depth integration was not carried out due to logistical restrictions. ISCO samples were taken from the centre of flow and are therefore when extrapolated to represent the total x-section are likely to result in an overestimation of sediment load.	Small overestimation of sediment load at both sites Θ unlikely to have a significant affect on the sediment budget.
	Width	Negligible impact on sediment load as width integration was carried out for high, medium and low flows at both sites	Negligible
D) Computation of Sediment budget 1) Assumption that discharge was the same at site A as site B 2) 2) Magnification of errors defined above	Errors associated with ignoring over-bank and drainage inputs of water to the river between site A and site B.	Inputs from plantation drainage channels over the field season were the only drainage input between site A and site B. May have been more of a lag between SSC and discharge at site B (Although it is likely that this did not have much effect on load as timing errors are only likely to have been on a small scale (i.e. mins/hours) and velocity at high discharges is likely to have been less variable and less affected by in-stream features (excluding over-bank flow) Indeed, looking at the data it is possible that this error is likely as the expected –lag between discharge and SSC would become evident.	Likely to result in the underestimation of the sediment budget as if anything discharge increased at site 2 and therefore sediment load would have been greater.
			Definable Errors **-21.2% (Equivalent to 42.5 tonnes)** **+79.9% (Equivalent to 160.1 tonnes)**

If yield at site B is assumed to be representative of suspended sediment delivered from the basin to the coastal zone, the budget has identified that a significant proportion of this material was derived from a reach adjacent to a banana plantation unit. On a catchment scale, it is unlikely that a 16% increase in sediment yield would take place within a downstream reach draining only approximately 2% of the basin, unless significant activity was taking place within the river or its delivery system (Walling 1984, Walling 1988). However, suspended material may be derived from numerous sources, ranging from in-stream erosion and re-suspension to processes operating on, or within, the banks and river floodplain (Grimshaw & Lewin 1980). Overall trends in upstream/downstream sediment dynamics suggested that a number of such processes were interacting to control the delivery process. In particular, SSC mobilisation associated with temporary bank stabilisation during high stage, bank armouring and local agro-hydrological interactions, were suggested as possible drivers of change. A more detailed discussion of interactive components has been provided in Chapter 6.

The feasibility of banana plantation agriculture as a driver may be crudely assessed through calculating the rate of plantation soil erosion that would have produced the same quantity of sediment as the budgeted load. The rate of soil erosion for the plantation unit was therefore calculated to be 1.6 tonnes/hectare/year, assuming that the field season rate represented an annual constant. This figure is well within erosion rates reported for similar humid tropical environments (e.g., Kirby & Morgan 1980, Heyman & Kjerfve 1999).

The sediment budget may therefore be understood as an integral component of a conceptual framework linking interactions between the plantation, the river and the coastal zone. Further calibration will facilitate understanding of the extent to which in-stream sediment yield represents processes operating within the plantation unit. Through budgeting fluvial sediment load upstream and downstream of a key reach, the shape of driver and delivery interactions with the peripheral environment may be identified. This provides a platform for the subsequent identification and calibration of system components.

The concept of the fluvial system as an "indicator" of erosional processes has already been well reported in the literature (e.g., Olive *et al.,* 1988). However, with respect to understanding the role of the plantation system as a driver of sediment delivery to the coastal zone, a fluvial sediment budget has been identified as an important source of base line information for subsequent research. These estimated sediment yields represent a significant but not extreme challenge to catchment managers, and further consideration has been given to identifying appropriate response options in Chapter 7.

Chapter 5

Characterising sediment dynamics within the Stann Creek coastal zone: a feasibility assessment for monitoring the delivery system

§5.1 Introduction

Initial aims outlined in Chapter 1 emphasised the need to link agro-hydrological and fluvial sediment delivery with coastal sediment dynamics, to facilitate understanding of the continuum of sediment from the land to the ocean. Significant gaps in time and space between drainage basin and coastal ocean processes necessitate the monitoring of change at the river mouth, where land and ocean meet. However, this is not a simple process. Interactions between land, ocean and atmosphere within the coastal zone distort the nature of sediment delivery, making the identification of cause and effect difficult. Furthermore, monitoring the dynamics of a sediment plume emitted from the river mouth is a task that is scientifically and logistically challenging. This chapter considers the importance of monitoring and understanding suspended sediment dynamics at the river mouth for LOICZ research in Belize. Methods previously used to monitor dimensions of this process have been discussed with respect to their potential application to Belize.

§5.2 Why is it important to monitor suspended sediment dynamics within the Belizean coastal zone?

There is growing evidence that anthropogenically derived sediments may reach and interact with coral reef communities (i.e. Abelson, *et al.*, (1999), Cavanagh, *et al.*, (1999)). The existence, and subsequent spatial and temporal dynamics of riverine sediment plumes are now understood to be important components of this process (CCAD, 1997). Whilst it is widely recognised that coral reef deterioration may be driven by a wide range of factors (Rogers, 1989), it is clear that material delivered from point riverine sources has the potential to interact with and drive system change (§2.2.3).

Chapters 3 and 4 have identified the agro-hydrological and fluvial dimensions of sediment delivery within Belize, however, it is important both in terms of the science and the management that processes are understood within the framework of coastal zone sediment dynamics. The LOICZ framework highlights the importance of monitoring drivers of land-ocean sediment movement for understanding interactions and change within fragile marine systems (IGBP, 1995). In environmental management terms it is important to monitor and understand the relative contribution of different sources of marine sedimentation and their dynamics over time. With respect to industrial management it is important to show and quantify the "continuum" of sediment movement from the farm to the coastal zone so options for future monitoring and management may be considered appropriately. Attention has been given in the following sections to understanding how sediment plume dynamics in Belize may be effectively monitored over space and time, with a view towards linking processes operating in the fluvial system with coastal sediment dynamics.

§5.2.1 Sediment plume dynamics

The temporal and spatial dynamics of a sediment plume will be a function of interactions between fluvial, climatic and coastal systems. To understand the relative importance of the fluvial system it is important to outline the processes that may drive and shape plume behaviour over time and space.

Sediment plumes are pulsing events that occur as a result of a continuum of energy, material and frequency (Hensel, *et al.,* 1998). Three key factors affect the temporal and spatial scale of these: River velocity, buoyancy and friction between material and the sea bed.

The extent of plume intrusion into the coastal zone will be related to the velocity of a river, the quantity and characteristics of material transported and the temporal distribution pattern (Wolanski, *et al.*, 1999). Material transported by the river will affect the buoyancy of the emanating plume and will determine whether the plume is hyperpycnal (negatively buoyant) or hypopycnal (positively buoyant), (Wright, *et al.,* 1990). A general rule of thumb for fluvial sediment plumes is that the greater the sediment load, the greater the tendency for the plume to be hyperpycnal (Hensel, *et al.,* 1998). For example, a clear water plume will be naturally hypopycnal when emitted into coastal water (Liu, *et al.,* 1999). However this relationship between buoyancy and material will also be a function of the characteristics of suspended sediment transported as well as its quantity. Friction between material and the seabed will also govern the behaviour of a fluvial sediment plume in time and space, where particularly for hypopycnal plumes transport rates will be particularly affected (Liu, *et al.,* 1999). Because the dynamics of sediment plume behaviour in time and space are a function of all of these components, the reality is that they are characterised by the overall effect of all three.

In addition to being a partial control over pulsing events, suspended sediment can also affect the pathway of sediment plumes (Liu, *et al.*, 1999). A complexed interplay between river load and discharge, tidal phase and wind-field will govern the direction of plume intrusion into the coastal zone.

Within shallow coastal lagoon systems fluvial discharge and sediment inputs tend to be a dominant control over plume dynamics, where tidal range, wind strength and ocean currents are greatly reduced compared to less sheltered areas (Oliverira & Kjerfve, 1993). The multidimensional nature of sediment plumes and their response to a complexed network of drivers has served to restrict effective monitoring and the understanding of processes involved (Liu, *et al.,* 1999).

§5.2.2 Sediment plume interaction with coral reef systems

Whilst this research does not seek to detail interactions between coastal sediment dynamics and sedimentation within coral reef systems, it is valuable to highlight why fluvial sediment delivery in plumes to the Belizean marine environment is important. The wider context of this issue has been overviewed in §2.5. Fluvial sediment plumes have already been identified as delivery mechanisms, where dynamics may be affected by a range of environmental drivers at the interface between the river and the coastal zone (§5.2.1). However, sediment plumes may also interact with change in the coastal zone. Therefore, to define their importance, plumes may be considered in three ways:

- Firstly they may be understood as a simple "*source*" of suspended sediment to the system. Material may subsequently be transferred, deposited and re-suspended within the coastal zone and comprise an input to the coastal sediment budget (e.g. Milliman, *et al.*, 1999).

- Secondly plumes may be seen as a "*delivery mechanism*" of material to the reef system where sediment is transferred from the drainage basin to the reef through the dynamics of the plume (e.g. Abelson, *et al.*, 1999). This process may be distinguished from "sourcing" as instead of the plume being defined as a simple system "input" the temporal and spatial characteristics of the plume are understood to shape the nature of the delivery process (Liu, *et al.*, 1999).

- Thirdly they may be seen as mechanisms that are *interactive components* of change in the near-shore and off-shore zones. Within the near-shore environment, sediments from the plume may become trapped in mangrove systems or be deposited on patch reefs as a direct effect of plume dynamics (e.g Yamamoto & Chiba, (1994), Wright & Nitrouer, (1995)). In the off-shore zone, sediments from the "source" plume may settle on coral reef and sea grass beds and contribute or respond to processes that change the nature of the system (Wolanski, *et al.*, 1984).

Fluvial sediment plumes are an important "source" of material to the Belizean coastal zone (GESAMP, 1994). However, it is now important to understand their role as delivery mechanisms and interactive components of the coastal sediment system over time and space. Whilst significant research is still required to quantify the total load of sediment delivered from fluvial sources to the coastal system in Belize (WRISCS, 1999) it is clear that once this material is in the coastal zone it has the potential to interact with the reef system (Hughes, 1980). An increase in the quantity of sediment delivered to the coastal zone may change the system through increasing sediment in the water column and increasing sediment fall-out and settling deposits on the coral reef (Wright, 1989). Resultant effects are likely to be unfavourable physiological conditions for coral growth and a net decline in productivity (Rogers, 1990). However there are many factors that will determine the nature of effect that sediment delivered in fluvial plumes will have on the Belizean coastal zone and reef system. This research does not attempt to define these. Rather, it is concerned with understanding the processes that control fluvial plume dynamics so that their importance in altering the land-ocean sediment flux in Belize may be assessed.

§5.3 The development of techniques for monitoring and understanding coastal sediment delivery and plume dynamics

Interactions across the land – ocean interface have only been conceptualised within a unified framework (LOICZ) over the last 10-15 years (§2.4). Prior to this, processes operating within the drainage basin were rarely linked to those taking place within the coastal zone and *vice versa* (GESAMP, 1990). This section explores the development of monitoring techniques and discusses their relative advantages and disadvantages for understanding coastal sediment delivery and plume dynamics.

§5.3.1 Sediment Yield

Within Earth system science, sediment yield (i.e. basin output in tonnes per set period) is now considered as an important indicator of global and continental erosion (Walling & Webb, 1996). Whilst it is accepted that sediment yield is not necessarily an accurate reflection of the total amount of material eroded within the drainage basin (§2.2.3) it allows us to compare and contrast coastal sediment delivery from drainage basins and promotes interdisciplinary links between hydrology, agricultural engineering, fluvial and coastal geomorphology and environmental management.

Sediment yield offers a useful perspective on the availability and timing of coastal sediment delivery. This information may be estimated from a calibrated record of discharge and fluvial suspended sediment concentration at a point close to the mouth (Waling & Webb, 1996b). The temporal coverage depends on the information required from the data but sediment yield investigations usually illustrate trends over seasonal or annual scales, although historical data has been increasingly used to identify changes over longer time frames.

Sediment yield information is important for understanding the characteristics of sediment dispersal at the river mouth. The characteristics of the emanating surface or subsurface (hyperpycnal) plume will be an integrated function of suspended matter, discharge, tidal phase and wind field, (Liu, *et al.*, 1999).

Within the tropics it is particularly important to monitor SSC dynamics close to the river mouth during peak flow events, when large quantities of river-borne material tend to be delivered in a "flashy" manner to the coastal zone. However, good records of SSC and discharge are seldom available for sites close to the basin outlet (Mulder & Syvitski, 1995), especially within tropical regions, where monitoring programmes have been restricted by logistical problems (e.g. §4.4.9). Fluvial sediment yield to the coastal zone has subsequently been predicted for environments with insufficient data, using climate and local drainage basin characteristics as key variables in a simulation model (Mulder & Syvitski, 1996). However, even using this technique, a number of problems have been experienced. For example, obtaining information relating to model input variables has often been difficult, especially in environments with little historical data. To overcome such difficulties a generalised technique for estimating SSC during periods of peak activity has been developed, enabling improved understanding of the dynamic response of ungauged rivers. This involved the use of a rating curve based on averaged SSC and discharge and has been discussed in more detail by Mulder and Syvitski, (1995) and Syvitski (1999).

However, for rivers where records of SSC and discharge are available for a site close to the river mouth, sediment yield may be calculated to provide a good indicator of suspended sediment delivery to the coastal zone from the fluvial system. Sediment yield may subsequently be integrated with coastal – ocean sediment transport and deposition data to budget interactions between system components and identify alternative sediment sources.

§5.3.2 *In-situ* measurements

Whilst sediment yield information is an important indicator of delivery from drainage basin systems to the coastal zone, when used exclusively the technique provides little "real" information about dynamics at the land-ocean interface and the behaviour of suspended sediment after it has been discharged into the coastal zone. These *"in-situ"* data are, however, particularly important, because it facilitates accuracy assessment of less laborious and expensive methodologies for estimating and modelling future patterns of change.

In-situ sampling procedures for estimating suspended particular matter (SPM)[†††] dynamics at the river mouth can provide good spatial and temporal data, particularly if monitoring equipments are compatible with environmental conditions. Three standard procedures have been used successfully in a range of different environments to monitor SSC and SPM dynamics at the land-ocean interface:

- Secchi disc measurements

  The measurement of secchi disc depth is simple proximate method for estimating the suspended sediment concentration of water within the coastal zone. The method involves lowering a disc into the water column and recording the depth at which it disappears and then raising the same disc and recording the depth at which it re-appears; secchi disc depth is the mean of these two readings (Schellenberger, 1987). Secchi disc depth is dependent on the optical properties of water, hence assuming for the estimation of SSC, that high concentrations of suspended sediment will "cloud" visibility and return a low secchi disc value. However, because secchi disc measurements are optical they will also reflect the concentrations of additional water constituents such as chlorophyll and will be affected by the absorption and scattering of light within the water column (Mulhearn, 1995). Ideally to achieve an "accurate" definition of SPM within the water column these parameters would require definition. Despite the "roughness" of the technique the simplicity of secchi disc measurement has promoted its continued use throughout optical water quality research, (e.g. Duntley, (1963), Brezonik, (1978), Lorenzen,

[†††] Whilst SSC has been used to describe suspended sediment per volume within the fluvial environment, SPM has been used to describe this and other suspended matter within the coastal zone.

(1980) and Mulhearn, (1995)). Indeed, determining the optical properties of the water column is an important pre-requisite to further detailed sampling of SPM within the coastal zone. The measurement of secchi disc depth is a useful tool for reducing sampling time and the cost of subsequent measurements, through identifying important areas of interest or uncertainty.

- Turbidity measurements

  The measurement of turbidity within the water column is another technique that estimates SPM indirectly using optical data. Logging devices attached to a turbidimeter record the attenuation of a light beam passing between sensors within the water column (§4.3.1). These devices may be suspended between a solid base on the sea-floor and a surface buoy to monitor continuously if required, or sample continuously or at intervals from a vessel moving through the study area. This technique demands careful calibration with "real" SPM data, and along with secchi disc data, should in no way replace that obtained from the analysis of SPM samples, but can provide valuable information about patterns and characteristics of SPM within the coastal zone.

- Sampling "real" SPM data

  SPM is obtained using a range of different water samplers (Mudroch & MacKnight, 1994). However, the principle of collecting SPM at discrete depths and locations within the water column to determine gradients in particle concentration has been widely accepted as "standard" within marine particulate investigations (e.g. Smetacek, *et al.*, 1978). SPM is most commonly measured using instantaneous water samplers that obtain single or multiple point data from the water column. These samplers collect and retain water and SPM from pre-determined points within the water column from a fixed platform suspended between a weight on the sea-floor and a surface buoy. A particular advantage of this technique over optical procedures is that it retains the SPM facilitating further analysis of particle size, organic matter composition, trace elements, etc. Specific procedures have been discussed in addition to alternative techniques in Mudroch and MacKnight (1994).

The implementation of sampling procedures described above for coastal SPM investigations will be determined by local environmental conditions at the time of desired monitoring. This poses a significant challenge for monitoring fluvial sediment discharge dynamics at the river mouth. It is particularly important that coastal dynamics associated with peak flow events are monitored (§5.3.1). However, peak flow events, especially within the tropics, tend to be related to regional storm activity (Arenas, 1983b) and thus, peak flow will take place during rough sea states when sampling would be especially difficult.

However, if local conditions are favourable and error margins defined, these procedures can provide valuable data for understanding the behaviour of SPM at the river-mouth. They allow us to monitor features such as the "turbidity maximum". The turbidity maximum is related to river discharge and SSC, where variation is sometimes reflected in the oscillation of an area of maximum turbidity that is higher than concentrations recorded within the fluvial system (Dyer, 1994). It is of particular importance as it contains a high proportion of fluvial sediment and shapes the nature of delivery to the coastal zone (Wellershaus, 1981). These techniques also facilitate the monitoring of sediment plume dynamics at the river mouth. However, the spatial and temporal information extracted from this data will vary significantly. For example, using secchi disc measurements to monitor the extension of a turbid sediment plume into the coastal zone, data will normally be obtained along a transect and geo-referenced with co-ordinates obtained using a Geographic Positioning System (G.P.S). This information will usually be discontinuous unless a vessel is deployed permanently within the coastal zone and the field team record measurements continuously. In contrast, a fixed SPM sampler with a continuous cycle of water collection may obtain data over longer periods, although if only positioned in one location the spatial dimension of sediment plume dynamics will be in-sufficiently covered. In addition there will be difficulties in obtaining simultaneous data over a wide spatial area, which is important for the analysis of SPM dynamics (Sabins, 1996).

The relative advantages and disadvantages of spatial and temporal data coverage for each technique suggest that ideally an integrated approach would be used for monitoring sediment plume dynamics within the coastal zone. To understand plume characteristics (§5.2.2) calibrated spatial data needs to be collected simultaneously over regular intervals. The integration of optical secchi disc data with SPM depth integrated samples for fixed locations may achieve this in part, although consideration needs to be given to calibration of optical data and the position of sampling apparatus. However it is clear that logistics are a considerable limitation to the regular monitoring of sediment plume dynamics within the coastal zone, especially within tropical climates where storm activity drives the catchment sediment system. Logistics and cost will subsequently be an important consideration for any monitoring programme striving to achieve this. All *in-situ* techniques described above interfere in some way with the variable being monitored. Ideally a remote technique is required that collects calibrated temporal and spatial information simultaneously whilst keeping logistics and cost to a minimum. The following section discusses how remotely observing the colour of the ocean may provide a potential solution.

§5.3.3 The remote sensing of ocean colour

Ocean colour is determined by the optical properties of sea water, suspended particulate matter and organic elements (Groom & Lavender, 1998). Ocean colour may be used to detect SPM within the coastal zone through observing the scattering, absorption and attenuation of light throughout the visible part of the electromagnetic spectrum.

The electromagnetic spectrum, illustrated in Figure 5.1 may be divided into a number of wavelength bands, of which the visible region is only a small part:

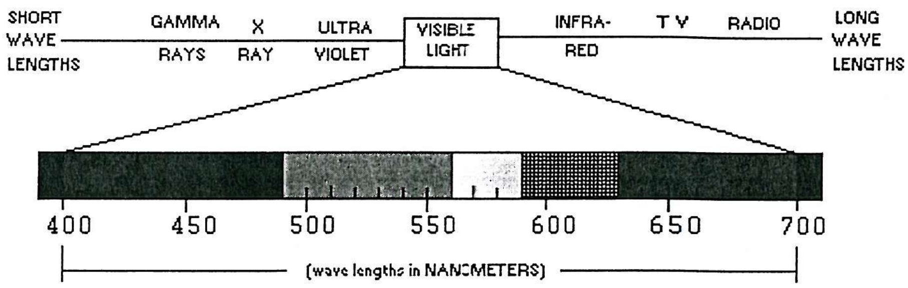


Figure 5.1: The electromagnetic spectrum

Electromagnetic sensors may be used to detect the "spectral reflectance" of properties within the water column. Detected spectral reflectance will be a function of various fractions of energy incident on the element, further to absorption, reflection and/or transmission. This relationship may be summarised by Equation 5.1:

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda) \qquad (5.1)$$

Where, E_I expresses incident energy, E_R expresses reflected energy, E_A expresses adsorbed energy and E_T expresses transmitted energy. Energy components are a function of wavelength (λ).

The proportion of energy, reflected, absorbed and transmitted will vary greatly between different features being monitored. Furthermore variations exist across wavelengths so a characteristic may be distinguishable in one band but not in another. It is the *difference* between responses that allows discrimination between features.

Variations in the visible part of the electromagnetic spectrum will facilitate the identification of colour and subsequently within the ocean properties such as SPM, chlorophyll, and organic matter may be identified by a spectral response pattern. The spectrum of response patterns for the ocean is referred to as "ocean colour". Visible wavelengths are the only part of the electromagnetic spectrum that can detail information from beneath the sub-millimetre skin of the ocean to a depth of several metres (Robinson, 1985), hence facilitating the identification of features such as sub-surface SPM dynamics.

Whilst the colour of low-productivity open-ocean areas will be blue, this colour changes in shallow marine environments with increased concentrations of suspended sediment and phytoplankton. Phytoplankton are microscopic algae, which are often found throughout coastal waters. These algae adsorb sunlight for photosynthesis using chlorophyll and subsequently the level of reflectance in the blue and red parts of the spectrum decrease with this process and the level of reflected light in the green part of the spectrum increases. Concentrations of SPM and organic matter within the coastal zone originating from re-suspended particles or river plumes will also affect the "colour" of coastal water within the visible part of the electromagnetic spectrum. However, the extent of variation throughout bands will be greater than that of chlorophyll due to the different particle sizes and compositions of SPM.

The ability to detect variations such as these throughout bands will depend in part on the characteristics and capabilities of the electromagnetic sensor. In the past, attempts have been made to observe ocean colour from ships, however this has not been particularly successful as simultaneous data over space and time has been difficult to obtain (Robinson, 1985). Over recent years, electromagnetic sensors for detecting ocean colour have been deployed on aircraft and satellites, promoting the collection of data "remotely" over large areas. Advances in the "remote sensing" of ocean colour have promoted the development of scientific techniques for quantifying spatial and temporal variations in water column constituents such as SPM.

§5.3.4 Estimating suspended particulate matter (SPM) concentrations from ocean colour data: some considerations

The section above has discussed the need for SPM dynamics to be monitored over time and space and the difficulties experienced in attaining this data using exclusively *in-situ* measurements. The remote sensing of ocean colour has therefore been identified as a potential tool for understanding SPM dynamics within the coastal zone. However a relationship is required between the spectral response of SPM and measured *in-situ* SPM concentrations.

For estimating SPM concentrations from spectral data, SPM may be identified and measured by its optical properties between the bandwidths of 400 and 700 nanometres (nm). SPM is located between broad wavelengths because of the diverse range of origins, particle sizes and colour exhibited in its distribution. Indeed it has been reported to be the most diverse of all ocean colour contributors (Robinson, 1985).

However, in addition to the concentration of SPM, chlorophyll and organic material in coastal water will alter ocean colour within these bandwidths from blue to green to light brown (Rast & Bezy, 1999). To distinguish between these, coastal waters have been divided into two categories: Case 1: where optical properties are governed by phytoplankton; and Case 2: where non-chlorophyll-related sediments are present, instead of or in addition to phytoplankton (Robinson, 1985, Rast & Bezy, 1999). Figure 5.2 illustrates the reflectance spectra for Case 2 waters where suspended sediment is the dominant constituent:

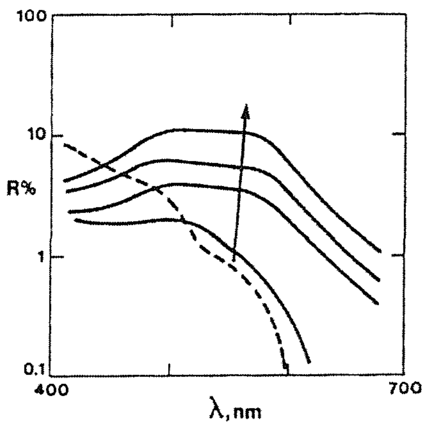


Figure 5.2: Typical reflectance spectra for suspended sediment dominated Case 2 waters (Robinson, 1985)

The arrow in Figure 5.2 indicates the way the spectrum changes with increased sediment load and the dashed line shows the clear water spectrum. Reflectance ratios can be seen here to increase with SPM concentrations in all wavelengths, although it is the increase is smaller in shorter wavelengths.

A number of studies have reported strong correlations between *in-situ* SPM concentrations and remotely sensed spectral reflectance ($L_{(\lambda)}$) (Holyer, 1978, Fischer, 1985, Gradie & Lunn, 1995). However difficulties have been experienced with deriving SPM concentrations from $L_{(\lambda)}$ (Curran & Novo, 1988). A poor regression relationship between SPM and $L_{(\lambda)}$ created a number of problems in the development of a universal algorithm for SPM determination from $L_{(\lambda)}$ (Curran, 1987).

To achieve a quantitative determination of SPM, retrieval variables have been used to perform empirical correlation with $L_{(\lambda)}$. These variables are usually inserted into a logarithmic expression such as Equation 5.2 (Tassan, 1988):

$$\log(Ch, s) = A + B.\log(X) \qquad (5.2)$$

Where, *Ch* denotes chlorophyll-a, *s* denotes suspended sediment, *X* is the retrieval variable, and *A* and *B* are determined from *in-situ* measurements. In some cases these variables have included waveband ratios to suppress problems such as atmospheric effects (Amos & Topliss, 1985).

However retrieval variables have needed to be highly sensitive to the retrieved parameter (SPM concentration) and largely insensitive to other optical properties such as chlorophyll and organic matter. Methods for achieving this have been developed using multispectral techniques (i.e. Ritchie & Cooper, 1988) to discriminate between different adsorbing agents by using wave band combinations instead of wave band ratios. However where SPM concentrations taken from *in-situ* measurements have been regressed against the retrieval variable, a wide spread of values have been returned (Lavender, 1996). This was in part due to the great spatial variability of SPM data and in part due to atmospheric scattering (Curran & Novo, 1988). Atmospheric scattering has been found to be a particular problem for the remote sensing of SPM because of the low reflectance of water surfaces and because blue/green wavelengths ideal for the remote sensing of SPM are particularly affected by atmospheric scattering.

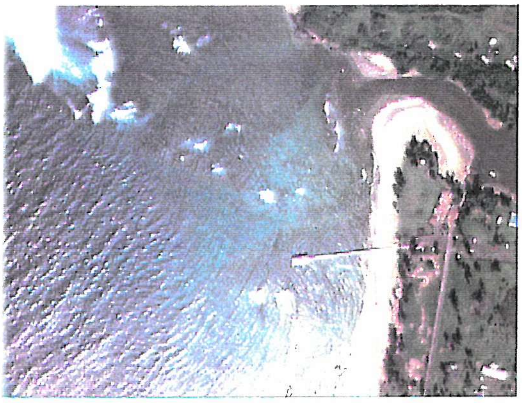
A further problem with this regression technique is that it assumes that *in-situ* SPM measurements are "truth", i.e. that they contain no error and instead that all error is in the reflectance recorded by the sensor $L_{(\lambda)}$ (Whitlock, *et al.*, 1981). However the high variance of SPM data in space and time indicates that such statistical techniques should not be applied unless used under controlled environmental conditions (Lavender, 1996), and subsequently the development of an algorithm using such techniques would be site - sensor and season-specific. This would mean that any attempts to apply such an algorithm to identify SPM dynamics within a coastal zone such as that of Belize would either produce significant errors or require such considerable accuracy assessment that the initial advantages of "remotely sensing" SPM concentrations would be outweighed by logistics and expense.

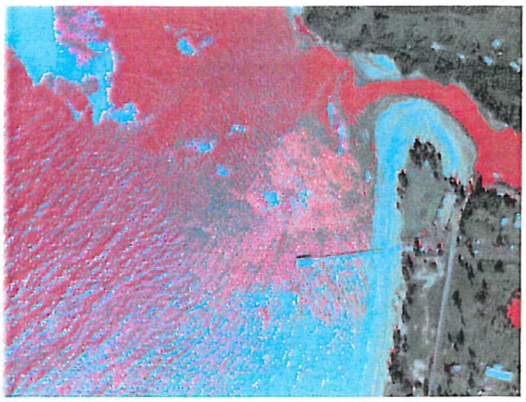
In light of such problems, Lavender (1996) developed a universal algorithm for SPM concentration estimation from $L_{(\lambda)}$ using the near infrared part of the electromagnetic spectrum, where $L_{(\lambda)}$ was determined by particle size instead of the magnitudes of reflectance and spectral response of SPM within the visible part of the spectrum. Further discussions relating to SPM concentration estimation using $L_{(\lambda)}$ and a comprehensive review of algorithm development for this procedure may be found in Liedtke, *et al.*, (1995).

Algorithms to determine SPM concentration from $L_{(\lambda)}$ have developed in conjunction with technological advances in ocean colour remote sensing instruments. The following sections discuss how airborne and satellite remote sensors have facilitated the monitoring of SPM dynamics at the river mouth, further to considering present limitations and future developments in the remote observation of suspended sediment delivery to the coastal zone.

§5.3.5 Aerial photography

Aerial photography has become a useful tool for remotely monitoring SPM dynamics at the river mouth and their subsequent dispersal and deposition within the coastal zone (Lillesand & Kiefer, 1994b). The main advantage of using aerial photography over *in-situ* techniques is that a wider spatial area may be covered systematically without interfering with SPM directly. Aerial photographs can provide high-resolution multispectral information about coastal sediment dynamics, for example Gradie and Lunn (1995), used 1-metre spatial resolution multispectral imagery to monitor the spatial extension of a sediment plume associated with high discharge events for Hanalei River into Hanalei Bay, Hawaii (Figures 5.3 & 5.4):





Figures 5.3 & 5.4: The Hanalei Bay sediment plume, illustrated as a "near normal" colour image and as a classified "false colour composite" image (Gradie & Lunn, 1995).

This research illustrated that even within tropical environments it is possible to map the spatial extension of a fluvial sediment plume into the coastal zone, especially using classification techniques to distinguish SPM from other optical features.

Aerial photography may be used to quantify SPM concentrations from $L_{(\lambda)}$ using algorithms such as those discussed in the above section. Although the spectral response of SPM may be detected between 400 and 700nm (Figure 5.2), it is clear that between 510 and 620nm there are a greater range of reflectance spectra as suspended sediment concentrations increase. Subsequently the majority of attempts to quantify SPM concentrations from $L_{(\lambda)}$ will concentrate on the spectral characteristics of SPM between these wavebands as the breadth of change is greater. Multispectral data may sometimes be used to achieve this, involving the simultaneous collection of data in several spectral bands using a multispectral camera. Through analysing these signals in conjunction with each other greater and more accurate information can be obtained about the SPM for quantitative studies, with discrimination from other features such as chlorophyll and organic matter. To assess the accuracy of this technique *in-situ* data of SPM concentrations are recorded at the same or a similar time (less favourably known as ground/sea truthing), to ensure a realistic assessment of accuracy (Rimmer, *et al.*, 1987).

However some problems have been experienced with using aerial photography for monitoring sediment plumes, particularly in tropical environments. Limitations, such as the extent of cloud cover (Ibrahim & Yosuh, 1992) and sun glint (Jupp, *et al.*, 1985) will affect the quality of the image. The use of infrared film, favoured for sediment plume analysis in temperate environments, is affected by heat, and subsequently presents a number of problems for such quantitative analysis in tropical environments (Eastman Kodak Company, 1981).

Aerial photography has advantages and disadvantages for monitoring the temporal characteristics of sediment plume behaviour and SPM dynamics within the coastal zone. Primarily it is advantageous because once the sensing platform has been set up, the aircraft may be flown over the area of interest at a specific time, providing high resolution information at short intervals during consecutive passes. However the physical logistics of the flight will be dependent on local conditions where adverse weather may hamper attempts, especially during storm activity, when it is particularly important to monitor plume behaviour (§5.2.2). Aerial photography is also an expensive method for monitoring SPM dynamics, where especially within tropical environments *in-situ* methods for obtaining data may be favoured following cost-benefit analysis. Because it is not always possible to control the timing of the fight (i.e. to correlate with high discharge fluvial events) aerial photography may be of greater use for monitoring "continuous" features within the coastal zone opposed to episodic sediment plumes.

Prior to the middle to late 1990's this procedure was often favoured over SPM observation from space as satellite sensors were less well suited to marine environments (Lillesand & Kiefer, 1994). This was due to their fixed broad spectral channels and a lack of bands in the blue/green region, required for bathymetry and quantification of low SPM concentrations (Robinson, 1985). Sensors such as Landsat, System Probatorie d'Observation de la Terre (SPOT) and the Advanced Very High Resolution Radiometer (AVHRR), have been used in a number of coastal SPM studies (e.g. Froidefond, *et al.*, (1991), Braga & Setzer, (1993), Mulhearn, (1995)) although, limitations have often been reported to significantly compromise benefits (Green, *et al.*, 1996).

However, during the late 1990's rapid developments in ocean colour remote sensing have promoted a movement away from the exclusive use of *in-situ* sampling techniques and aerial photography towards the observation of processes from space.

§5.3.6 Satellite Remote sensing

Satellite remote sensing has become a standard technique for the detection of material transported in suspension in coastal waters (Hinton, 1991). Through measuring the upwelling light at various wavelengths within the visible and infrared parts of the spectrum, the concentration of suspended sediment can be estimated from satellite imagery providing the accuracy is assessed using *in-situ* data. Imagery from sensors such as the AVHRR, **Sea**-viewing **W**ide **F**ield of view **S**ensor (SeaWiFS), Landsat Thematic **M**apper (TM), **M**ultispectral **S**canner **S**ystem (MSS), SPOT and the **ME**dium **R**esolution **I**maging **S**pectrometer (MERIS) should be able to detect sediment plumes (Froidefond, 1991). In comparison to sampling procedures carried out locally (i.e. ship-borne) that provide relatively accurate concentration data but usually poor spatial coverage, remote sensing is a tool that provides comprehensive spatial and temporal information about the nature of sediment plumes. This section discusses the development of this technique and its potential value for monitoring coastal SPM dynamics.

> ***""Oceanography from a satellite"- the words themselves sound incongruous and to a generation of scientists accustomed to Nansen bottles and reversing thermometers, the idea may seem absurd..."***
>
> (Ewing, 1964)

In Robinson's book "Satellite Oceanography" (1985), this quote from Gifford Ewing was used to exemplify the pace of development from initial considerations about the oceanographic potential of man's new presence in space in 1964 to "the beginnings of a new branch of marine science" (Robinson, 1985, (pp17)). Since "Satellite Oceanography" first illustrated the fundamental ideas and techniques of ocean colour it's development has advanced at an incredibly rapid pace.

Ocean colour remote sensing began with the launch of the Coastal Zone Colour Scanner (CZCS) in 1978 (Sabins, 1996). The CZCS was a "proof of concept" mission, which carried a visible wavelength scanner designed to observe ocean colour. The scanner captured data with a spatial resolution of better than 1km and produced simultaneous images of the colour and temperature of the world's oceans until June 1986. The narrow bands (20nm) were designed to facilitate mapping of suspended sediment reflectance spectra, particularly within coastal waters (Lillesand & Kiefer, 1994c). The CZCS proved the concept of observing coastal SPM distributions from space (e.g. Hochman, *et al.*, (1994), Barale & Larkin, (1995)) and subsequently was followed by a large number of ocean colour missions attempting to monitor this and other oceanographic features.

Satellite remote sensing has advanced capabilities for monitoring SPM dynamics from *in*-situ, airborne and theoretical techniques in a number of ways:

- The temporal dimension

The temporal component of coastal SPM dynamics intrinsically related to environmental forcing functions. Through improving the temporal resolution of data collected during suspended sediment movement, processes may be identified and distinguished more easily, especially within high-energy environments where sediment transport is takes place during episodic events (e.g. Stumpf & Goldschmidt, 1992). Unlike *in-situ* and airborne techniques high-resolution temporal data may be acquired over sustained periods. For example, the SeaWiFS sensor (1997-2002) has been obtaining data within a 48-hour return period, for every kilometre of the global ocean surface (ESA, ESRIN, undated, NASA, 2000).

- The spatial dimension

Whilst *in-situ* monitoring techniques provide relatively accurate concentration data the spatial detail relating to sediment movement is usually poor. Aerial photography offers some improvement, where simultaneous multispectral data may be obtained for specified periods (§5.3.5). However even with aerial photography, spatial information will only be obtained at the local scale. Satellite remote sensing facilitates simultaneous coverage of wide spatial areas, and can provide a high-resolution time series of information at the global scale (e.g. NASA, 2000). At this level data sets may be assimilated and inserted into a wider framework to promote understanding within broader system change (e.g. LOICZ, 1995 (§2.4.1)).

- The spectral dimension

The increasingly defined spectral capabilities of satellite ocean colour remote sensors have promoted the isolation of SPM from other optical water constituents such as chlorophyll and organic matter (Hinton, 1991). Whilst these advances have also taken place within airborne remote sensing, the coupling of simultaneous spectral, temporal and spatial information using satellite imagery has been advantageous for SPM monitoring within the coastal zone.

- Logistics

§5.3.2 identified a number of logistical constraints associated with monitoring *in-situ* SPM dynamics. Whilst it is recognised that accuracy assessment of satellite data using *in-situ* sea data is important within regional studies (Robinson, 1985), the logistical advantages of employing a "remote" technique as a tool for continuous monitoring are clear. In addition the unprecedented launch of numerous satellite ocean colour remote sensors over recent years (Rast & Bezy, 1999), has promoted the availability of relatively inexpensive data to the scientific user. Whilst the cost of data is greater at the commercial scale, competition between agencies has considerably reduced this.

Satellite remote sensing has improved analysis and understanding of coastal SPM dynamics in a number of ways:

- Data assimilation

The quantity of coastal – ocean data obtained from satellite remote sensing, far outweighs that available from any other technique (Robinson, 1985). However whilst it is recognised that considerable accuracy assessment is required to establish local, regional and global algorithms, the increasing amount of available SPM data, facilitates understanding of coastal zone processes within environments where there is little information. Despite limitations related to accuracy and the relatively short historical data set, global data sets enable coastal zones to be compared against one another at different phases of development (Kam, *et al.*, 1992). Whilst the accuracy of the technique requires considerable sharpening, especially at the regional scale, the shape of the global data set will illustrate trends in space and time and highlight areas where attention needs to be focused (IGBP, 1999).

- Vertical and horizontal SPM dynamics

A major criticism of satellite remote sensing of the oceans has been that unlike *in-situ* techniques it fails to obtain information from beneath the water surface, and hence provide little information about sub-surface dynamics. However, visible and infrared remote sensors can obtain information about characteristics up to 30 metres below the "skin" of the ocean (Robinson, 1985). This part of the coastal ocean is well understood to be of great importance in terms of sediment and water constituent dynamics and marine life (Brink, 1987). Radiometric satellite imagery such as SPOT HRV Data has been used to detail sediment plume behaviour vertically as well as horizontally, and therefore enable a vertical as well as horizontal evaluation of the sedimentary flux (Froidefond, *et al.*, 1990). Horizontal fluxes of plume extension into the coastal zone are also anticipated to be better understood as the spatial resolution of sensors improve with commercialisation and techniques for merging and sharpening existing data sets are refined (Rast & Bezy, 1999).

Although the visible part of the electromagnetic spectrum has been identified in §5.3.3 as the most appropriate region within which to monitor and quantify SPM dynamics, alternative bands have been used successfully to monitor the spatial dimensions of this process from satellites. Thermal infrared imagery such AVHRR has been used to monitor freshwater plumes from large rivers to the coastal zone in regions where the ocean is a significantly different temperature to the land (e.g. Abbott, 1984). However, the quantification of SPM concentrations from this imagery has been rather more challenging, where its value has been more in detailing spatial patterns in plume dynamics (Sabins, 1996). The roughness of the coastal ocean surface may be identified using radar data. This surface will change as waves are created at the interface between different fluid densities, i.e. between freshwater and saltwater and has been used to identify the spatial extensions of plumes where visible data has not been available, due to limitations such as cloud cover (e.g. Gaddis & Mouginis-Mark, 1985).

Table 5.1 presents a comprehensive review of all ocean colour missions and their characteristics, from the initial launch of the CZCS on Nimbus 7 to the MODIS-PM sensor, due for launch on EOS-PM1 in December 2000.

However despite the large number of sensors and the wealth of ocean colour information increasingly available to the researcher, albeit at cost, the characteristics of the chosen sensor(s) must be suited to the system under investigation (Sabins, 1996). The spatial, temporal and spectral resolution of data will affect the appropriateness and accuracy of information derived and will determine the extent to which sediment dynamics within the coastal zone are understood (Barale & Larkin, 1995).

The selection of an appropriate sensor will be strongly influenced by local environmental factors; existing knowledge about regional SPM dynamics and those of similar systems; and the level of information required for present/future research and management. Further consideration has been given in the following section to sensor design and the importance of spatial, temporal and spectral resolutions for monitoring suspended sediment within the Belizean coastal zone.

§5.4 A feasibility study for Belize

Techniques for monitoring SPM dynamics at the interface between the fluvial and coastal environments have been outlined in the section above. Selecting the most appropriate methodology for linking South Stann Creek to the Belizean coastal zone requires a feasibility study considering scientific effectiveness, data availability, logistics and future research. Figure 5.5 illustrates the conceptual framework for linking these components. At the outset of this

Table 5.1: Past, present and future satellite ocean-colour sensors (1987-2000), (Groom & Lavender, 1998)

Sensor	*CZCS*	*MOS / WiFS*	*OCTS*	*POLDER*	*SeaWiFS*	*OCM*	*MODIS-AM*	*OCI*	*OSMI*	*MERIS*	*GLI*	*POLDER-2*	*MODIS-PM*
Platform	Nimbus-7	IRS P3	ADEOS-1	ADEOS-1	Orb View – 2	IRS-P4	EOS-AM1	ROCSAT	KOMPSAT	Envisat	ADEOS-2	ADEOS-2	EOS-PM1
Agency	NASA	DLR	NASDA	CNES	OCS/NASA	ISRO	NASA	Taiwan	KARI	ESA	NASDA	CNES	NASA
Country	USA	Germany/India	Japan	France	USA	India	USA	Taiwan	Korea	Europe	Japan	France	USA
Operation Start	Oct. 1978	Mar. 1996	Aug. 1996	Aug. 1996	Sept. 1997	Nov. 1998	1999	Feb. 1999	Jul. 1999	Mar. 2001	Jun. 2000	Jun. 2000	Dec. 2000
Operation End	Jun. 1986	Mar. 2001	Jun. 1997	Jun. 1997	Sep. 2002	Nov. 2003	Jun. 2003	Apr. 2003	Jul. 2002	Feb. 2004	Jun. 2005	Jun. 2005	Dec. 2005
Orbital Inclination	99.3	98.7	98.6	98.6	98.2	98.3	98.2	35	98.13	98.5	98.6	98.6	98.2
Equatorial Crossing (h) GMT.	12:00	10:30	10:41	10:41	12:00	12:00	10:30	09:00/15:00	10:50	10:00	10:30	10:30	13:30
Altitude (km)	955	817	804.6	804.6	705	720	705	600	685	800	803	803	705
Spatial Res. At Nadir(km)	0.825	0.18	0.7	6x7	1.1	0.36	1	0.8	0.85	1.2/0.3	1/0.25	6x7	1
Swath (km)	1566	200	1400	2400	2800	1420	2330	704	800	1150	1600	2400	2330
No. of Bands	6	18	12	9	8	8	36	6	6	15	36	9	26
Spectral Coverage (nm)	433-12500	408-1600	402-12500	443-910	402-885	402-885	405-14385	400-12500	400-900	390-1040	375-12500	443-910	405-14385
Tilt (degrees)	±20	No	±20	Variable	±20	±20	No	No	No	No	±20	Variable	No

research project it was assumed that techniques would be available to permit a reasonably calibrated estimation of SPM dynamics. Subsequent changes in availability, specifically through major extensions of the launch period of new satellite systems, requires subsequent revisions of approach.

The following sub-sections discuss the feasibility of using the SPM monitoring techniques reviewed in §5.3 for understanding interactions across this interface.

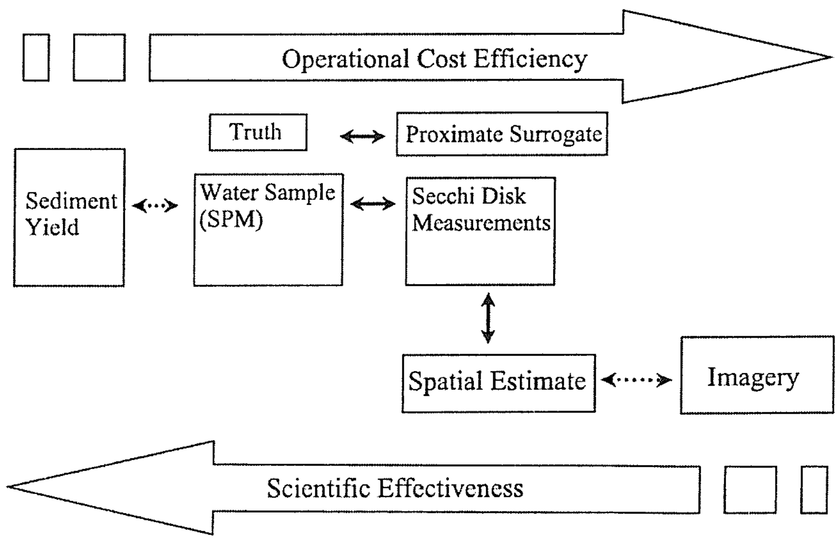


Figure 5.5: A conceptual framework for linking sediment yield from South Stann Creek to the Belizean Coastal Zone

§5.4.1 Sediment Yield

Whilst sediment yield information does not detail the dynamics of SPM within the coastal zone it provides a good indicator of material delivered from the river system and hence quantifies the relative contribution of the fluvial environment to coastal SPM processes. Within Belize, the majority of river catchments have very little data relating to SSC and sediment yield (GESAMP, 1994). However, SSC and discharge data have been collected within this study for a down-stream site on South Stann Creek (§4.5). This information may be used to provide an indication of SSC delivered to the coastal zone during the field season period.

An increased interest in water quality monitoring within Belize over the past 2 years (WRIScS, 1999) will no doubt see a rise in the number of programmes set up within drainage basins for monitoring fluvial discharge to the coastal zone.

§5.4.2 *In-situ*

A limited set of secchi disc data are available for South Stann Creek (WRIScS, 1999). However, these measurements can not be related to coastal SPM concentrations at the present time, as a site-specific algorithm has not been established and SPM concentration data are not available for the field season (WRIScS, 1999b). Difficulties experienced with algorithm development for secchi disc measurements have been discussed in Schellenberger and Stellmacher (1987) and Mulhearn (1995).

Despite quantitative limitations, the secchi disc data provide an optical-spatial indicator of SPM within the coastal zone associated with South Stann Creek and may be of some value for understanding dynamics at the river mouth.

§5.4.3 Aerial photography

To detail SPM dynamics at the mouth of South Stann Creek over a range of discharge conditions a large number of aerial photographs were required. During February 1999, a feasibility study was carried out as part of the "LightHawk" project in Belize to ascertain the potential for the continued monitoring of SPM dynamics at the mouth of South Stann Creek. Figure 5.6 shows three examples of infrared photographs taken over South Stann Creek during a "LightHawk" flight. A number of problems were highlighted during this study: Firstly, infrared film (ideal for observing SPM from the air) was unsuitable for use in the tropics and required continual "cooling" to prevent photographs from being damaged (this involved attaching icepacks to the camera during field work, and storing the film in a fridge at all other times!). Secondly, during periods of adverse weather when SPM dynamics were expected to be particularly interesting, flying was not possible. Thirdly, although the "LightHawk" flight was free as part of a conservation initiative (http://www.lighthawk.org/), the continued monitoring of coastal processes using aerial photography would be extremely expensive and therefore unrealistic for the present level of monitoring unless further funding could be arranged.

§5.4.4 Satellite remote sensing

Satellite remote sensing has been identified in §5.3.4 as a useful technique for monitoring and understanding coastal SPM dynamics. Understanding interactions across the land-ocean interface in Belize are hampered by a host of logistical problems and subsequently a "remote" technique such as satellite remote sensing, appears to be of significant potential value. This section evaluates sensors for use in Belize and identifies their relative advantages and disadvantages with respect to linking fluvial processes to coastal SPM dynamics during the 1998

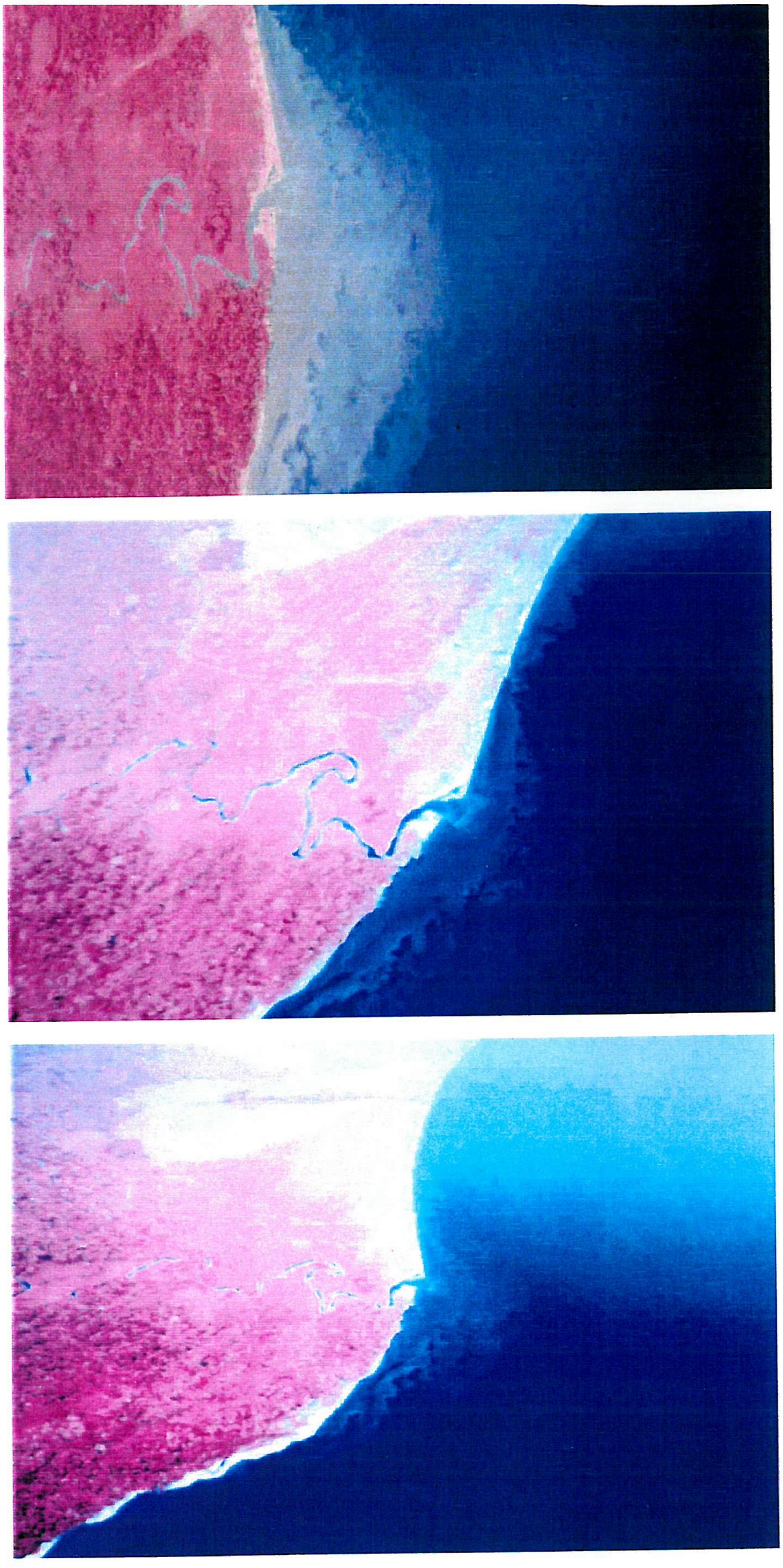


Figure 5.6: Infrared aerial photograph sequence of South Stann Creek (02/1999).

field season period. Particular consideration has been given to the availability of data, as this has been a major consideration for the feasibility study.

Sensor and data availability

Table 5.1 illustrates past, present and future ocean colour remote sensors. However for remotely sensing sediment plumes ocean colour data may be combined with data from other sensors to create a "tailored" product (e.g. Huh, *et al.*, 1996). This technique known as "merging" has been applied in cases where a singular sensor does not have all the capabilities required to monitor the object (i.e. spatial, temporal or spectral resolutions) (Sabins, 1996). The following overview of sensors and data availability subsequently includes sensors that are not exclusively designed to obtain "ocean colour" information, such as Landsat TM.

Table 5.2 provides an overview of the sensors available for monitoring SPM dynamics in Belize during the 1998 field season:

- **Landsat TM and ETM+**

The Landsat TM carried on Landsat 4 and 5, and the Enhanced Thematic Mapper Plus (ETM+) carried on Landsat 7 were deployed to acquire and in the case of Landsat 7, to "periodically refresh" a global archive of daytime, generally cloud-free images of land and coastal areas (The Earth Observer, 1997). The spatial characteristics of Landsat TM and ETM+ are ideal for monitoring coastal sediment dynamics in Belize. Firstly, the spatial resolution of 30 metres is excellent for source identification and should detail dynamics throughout the year, unlike sensors with larger spatial resolutions where differentiation between low SPM values and clear coastal water has been difficult (Cracknell, 1999 & Cracknell, 1999b). Secondly, a quarter-scene digital Landsat TM or ETM+ image would cover 92 x 85 km of the Belizean coastal zone, which would encompass a reasonable area for the level of analysis required. The spectral bands of the Landsat instruments cover the visible and infrared parts of the spectrum required for the distinction of SPM. In particular bands, 525-605nm and 630-690nm would be ideal. However, unfortunately the Landsat 16-day return period is not sufficiently frequent for a detailed temporal analysis of sediment plume behaviour, i.e. it would be difficult to understand the relationship between plume extension into the coastal zone and fluvial SSC delivery, unless the temporal resolution was sharpened significantly. If the temporal resolution of Landsat TM and ETM+ imagery could be sharpened then it would provide a valuable means by which SPM could be monitored in the Belizean coastal zone.

Table 5.2: Availability of satellite imagery considered for the Belizean coastal zone.

Sensor	*Data availability period*	*Spatial Resolution*	*Temporal Resolution (return period)*	*Spectral Resolution (Bandwidths nm)*	
Landsat TM	*Landsat 4: 1982- Present Day,*	*30m*	*16 days*	525-605 630-690	
	Landsat 5:1984-Present Day	*30m*	*16 days*	525-605 630-690	
Landsat ETM+	*Landsat 7:1998 – Present Day*	*30m*	*16 days*	525-605 630-690	
IRS-P3 WiFS	*1996-Present day*	*188 m*	*5 days*	620 - 680	
SeaWiFS	*1997-2002*	*Global Area Coverage:4km* *Local Area Coverage:1km*	*2 days*	500 - 520 545 - 565	
MERIS	*Due for launch in June 2001. For more information:* http://envisat.estec.esa.nl/	*Full Resolution: 300m*	*3 days*	***Band centre*** 510 nm 560 nm 620 nm	***Band width*** 10 10 10

However, the cost of Landsat TM imagery is considerable (for example, two sequential quarter scene Landsat TM images would cost approximately £1330 or $4000BZ (Belize Dollars) (Nigel Press Associates, 1999).

- **IRS-P3 WiFS**

The Indian Remote Sensing Satellite (IRS-P3) was launched during 1996 and carries the Modular Opto-electronic Scanner (MOS) and the Wide Field Sensor (WiFS) (Table 5.1). The MOS and WiFS sensors have been designed to monitor coastal water quality constituents and are highly compatible with a range of ocean colour instruments (Interface, 1996). The 188m spatial resolution of IRS-P3 WiFS data are notably coarser than Landsat TM although they are still sufficiently high for distinguishing the mouth of South Stann Creek from other coastal input points within the vicinity (Figure 2.6). The spectral characteristics of IRS-P3 are ideal for identifying coastal SPM, in addition to being compatible with instruments such as SeaWiFS (Interface, 1996). However, unfortunately, as with Landsat TM and ETM+ the temporal resolution of IRS-P3 WiFS is not quite high enough for linking coastal SPM dynamics with fluvial sediment delivery. Although a return frequency of 5 days is high in terms of earth observation, sediment plume dynamics, especially within the tropics will require monitoring more frequently to identify interactions between the river and the coastal zone and to capture episodic events (§5.2.2). Opportunities for merging IRS-P3 data with SeaWiFS and other compatible high temporal resolution imagery should therefore be explored. IRS-P3 data are significantly cheaper than Landsat TM and ETM+, and costs approximately £570 / $1710BZ for a 774km x 774km scene (Nigel Press Associates, 1999).

- **SeaWiFS**

The SeaWiFS sensor was launched as part of NASA's Mission to Planet Earth (MTPE) on Orbview-2 in 1997. The sensor was designed to obtain quantitative data of the global ocean (NASA, 2000). Subsequently the spectral characteristics of SeaWiFS are ideal for monitoring SPM dynamics where bandwidths 500 – 520nm and 545 – 565nm can differentiate sediment from other water constituents in coastal seas. The 48-hour temporal resolution of SeaWiFS imagery is also advantageous for monitoring sediment within the coastal zone. Whilst a return period of 48 hours will not provide the same level of data as continuous *in-situ* sampling techniques (§5.4.2), it is sharp enough to distinguish fluvial influences on coastal sediment dynamics from other sources within the coastal zone (§5.2.2).

Local Area Coverage (LAC) SeaWiFS data covers a spatial resolution of 1km, which is available to "Authorised Users" within the scientific community. For monitoring coastal sediment dynamics in Belize a spatial resolution of 1km is too coarse. Such a resolution would fail to distinguish between sediment sources and identify SPM concentration variations at a local scale. However through merging SeaWiFS imagery with sharper compatible spatial resolution data it is possible to achieve a product that fulfils all the monitoring requirements for coastal SPM dynamics (Rast & Bezy, 1999).

- **Merging SeaWiFS with compatible imagery**

The sections above have outlined the monitoring capabilities of sensors that recorded imagery of Belize during the 1998 field season that may be value for understanding SPM dynamics at the mouth of South Stann Creek. Subsequently Landsat TM data and IRS-P3 data were considered as potential sharpeners for SeaWiFS data to achieve a high temporal, spectral and spatial resolution product (§5.4.4). Figure 5.7 illustrates a typical LAC SeaWiFS image of Belize taken during the field season that would be used in this merging process:

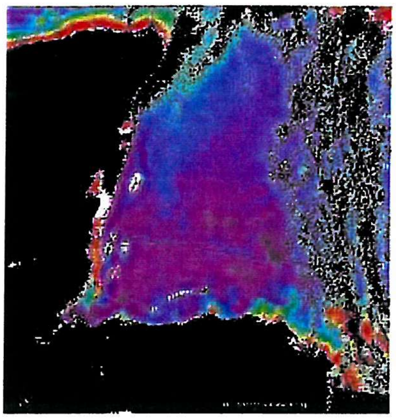


Figure 5.7: A typical LAC SeaWiFS image for Belize (Plymouth Marine Laboratory/NASA, 1988)

A number of reports have identified the potential value of MERIS and SeaWiFS merged imagery for monitoring the dynamics of SPM within coastal zones (e.g. Cracknell, 1999).
For this research, merged SeaWiFS and MERIS imagery of the coastal zone during the field season period could have provided excellent information about this process in Belize. Subsequently a "Principal Investigatorship" was applied for and awarded to the project by the European Space Agency, pending the launch of MERIS in 1999. Unfortunately the launch date for MERIS was postponed until 2001 (ESA, 2000) and therefore, whilst recognising the potential value of a merged MERIS/SeaWiFS for LOICZ research in Belize in the future (§5.6), it could not be used for this study.

Case 1: Data availability for merging SeaWiFS with Landsat TM / ETM+

A data search for Landsat TM and ETM + data for the field season period found that every available image for the field season had high cloud cover (i.e. between 30 and 100%) (Nigel Press Associates, 1999). It was subsequently clear that Landsat data acquired during the field season was un-acceptable for any quantitative or qualitative analysis of SPM within the Belizean coastal zone during the field season period. However, if cloud free data were available Landsat TM or ETM+ data would be of particular value to this study.

Case 2: Data availability for merging SeaWiFS with IRS-P3 WiFS

Figure 5.8 illustrates three images from the archive of IRS imagery available for Belize during 1998. The highlighted area illustrates the location of South Stann Creek and the associated coastal zone. Again, as with the Landsat imagery, cloud cover presented the main problem. Unfortunately image "B" was taken in the north of Belize, however it illustrates the quality expected from a "good" image, i.e. cloud free with no shadow. Due to the climate of the southern coastal plains it is common for the north of Belize and the reef system to have clear skies, whilst the Stann Creek District is cloudy. The coastal plains in this district represent a"convergence zone" between moist south-easterly winds moving in from the coast and the uplifting associated with the Maya Mountains (§2.7).

Therefore it is not entirely unexpected that the remaining three images for the field season were found to be unsuitable for SPM analysis. Image "A" was taken after the end of the field season and whilst the Placencia Peninsular - just south of South Stann Creek is distinguishable (west of the cross hairs), cloud shadow distorts the quality of the image for quantitative SPM analysis. In addition, because this image was recorded outside of the field season its value for linking a continuum of sediment from the land to the ocean was subsequently limited. Image "C" illustrates a "typical" quick look view for the field season, where cloud cover dominates the coastal strip. Similar problems to those experienced here have been reported for the Coral Sea, Australia, where the analysis of sediment plume dynamics was restricted by a lack of cloud-free satellite images (Wolanski, *et al.*, 1984).

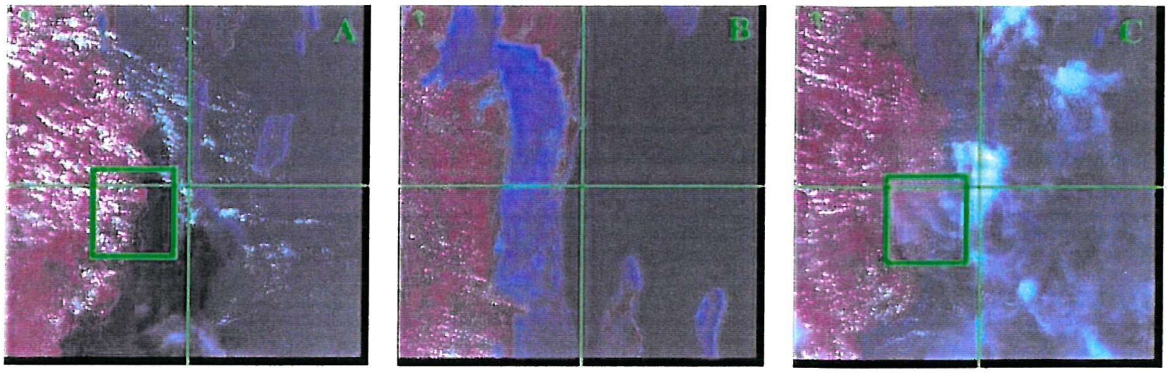


Figure 5.8: IRS 1-C Images of Belize (Plymouth Marine Laboratory, 1988)

Clearly the presence of cloud on satellite imagery of Belize presents a significant problem for SPM analysis from remotely sensed data during the rainy season. Sediment dynamics within the fluvial and coastal environments must be linked during periods of heavy rainfall, as this is when a significant portion of annual catchment suspended sediment yield is delivered to the coastal zone (GESAMP, (1994), Heyman & Kjerfve, (1999)). Additional investigations relating to the practicalities of using this technique also revealed that a number of IRS – P3 images would be required for interspectral and interspatial merging with the SeaWiFS imagery. This would not only be expensive, but given the poor quality of imagery obtained for 1998 it would be highly unlikely that in any future ocean colour analysis using visible or infrared bands that cloud free imagery would be available.

Therefore whilst the scientific basis for using satellite remote sensing for monitoring sediment dynamics within the Belizean coastal zone is strong, the practicalities of attempting to achieve this for a typical year (1998) are challenging at this stage. Further consideration is given to the potential use of satellite remote sensing techniques for coastal SPM analysis in Belize, in §5.8. Nevertheless, it is felt that this in-depth review of feasibility is a useful research output in its own right.

§5.5 An alternative framework for linking fluvial sediment load to SPM within the Belizean coastal zone

It has been established that there are a number of practical difficulties with using satellite remote sensing techniques to link sediment delivery from South Stann Creek to dynamics within the Belizean coastal zone. The advantages of this technique for providing high temporal and spatial resolution data about coastal SPM dynamics usually outweigh the disadvantages associated with inaccuracies in algorithm development and calibration (accuracy assessment with *in-situ* data). However, where these advantages are diminished by the problems described above the innovative value of the technique is compromised. It is subsequently preferable to use less innovative but more robust methods to understand the link between the land and the ocean in Belize at the present time.

Sediment yield information may be derived from downstream SSC and discharge for South Stann Creek. This provides a continuous record of SSC delivered to the coastal zone. However it does not provide any information about spatial dynamics within the coastal zone. Secchi disc information on the other hand, provides good spatial information (although only a proximate surrogate for coastal SPM) about the optical spatial patterns at the river mouth and within the near-shore coastal zone (§5.3.2). The following sections discuss the development of a framework for integrating fluvial sediment yield with coastal secchi disc data. Building on the trade off model detailed in Figure 5.5 the framework offers a cost effective compromise between operational and scientific requirements to provide information on the relative spatial and temporal, fluvial and coastal dimensions of the process.

§5.5.1 Methodology

Table 5.3 summarises the 1998 secchi-data, available for the Stann Creek coastal zone. Data were collected as part of a volunteer development initiative supporting the marine component of the WRIScS project (Raleigh International, WRIScS[‡‡‡]).

[‡‡‡] Addresses and contact information for contact organisations have been provided in Appendix 3

Table 5.3: Summary of secchi measurements

Date	*Date (j)*	*Number of observations*	*Minimum Secchi Transparency (m)*	*Maximum Secchi Transparency (m)*	*Max x*	*Min x*	*Max y*	*Min y*
24 Mar 98	83	41	4.5	12	-88.320	-88.168	16.877	16.543
15 April 98	105	38	3	17	-88.317	-88.147	16.877	16.539
29 April 98	119	38	3.5	16.3	-88.318	-88.147	16.877	16.540
4 May 98	124	38	6.5	21.0	-88.317	-88.146	16.877	16.056
30 June 98	181	33	3.7	14.2	-88.317	-88.167	16.873	16.540
18 Aug 98	230	25	4	15.5	-88.318	-88.183	16.791	16.540
9 Sept 98	252	33	9.0	19.5	-88.318	-88.168	16.873	16.540
15 Sept 98	258	37	5.25	18.5	-88.319	-88.169	16.877	16.543

Suspended sediment load for South Stann Creek was derived for the field season period from SSC and discharge recorded at site B. SSC (kg/m^3) was multiplied by discharge (m^3/sec) to determine sediment load (kg/m^3/sec). Subsequently, it was assumed that inputs to the fluvial system between site B and the basin outlet were minimal and that sediment load remained the same until discharged to the sea at the basin outlet. Timing was derived from the same methodology outlined in Chapter 5 where an Opisiometer (§5.3.2) was used to determine the fluvial distance between site B and the river mouth (7.3 km) and velocities recorded at site B were assumed to remain constant until water was discharged into the coastal zone. Figure 5.9 illustrates the temporal pattern of sediment load discharged to the coastal zone from South Stann Creek during the field season.

However, the field season time series failed to encompass the entirety of dates for which secchi data were sampled. Therefore due to the limited availability of secchi data and the importance of integrating the two data sets the following procedure was adopted to extend the data set:

An extended time series of stage data for site W (§4.5.3) was obtained for the period between 212(j) and 258(j). This was converted to discharge using the stage-discharge relationship illustrated in Figure 4.9. Mean suspended sediment loads calculated for each day of the field season were plotted against mean discharge for the same dates. Results for the downstream site,

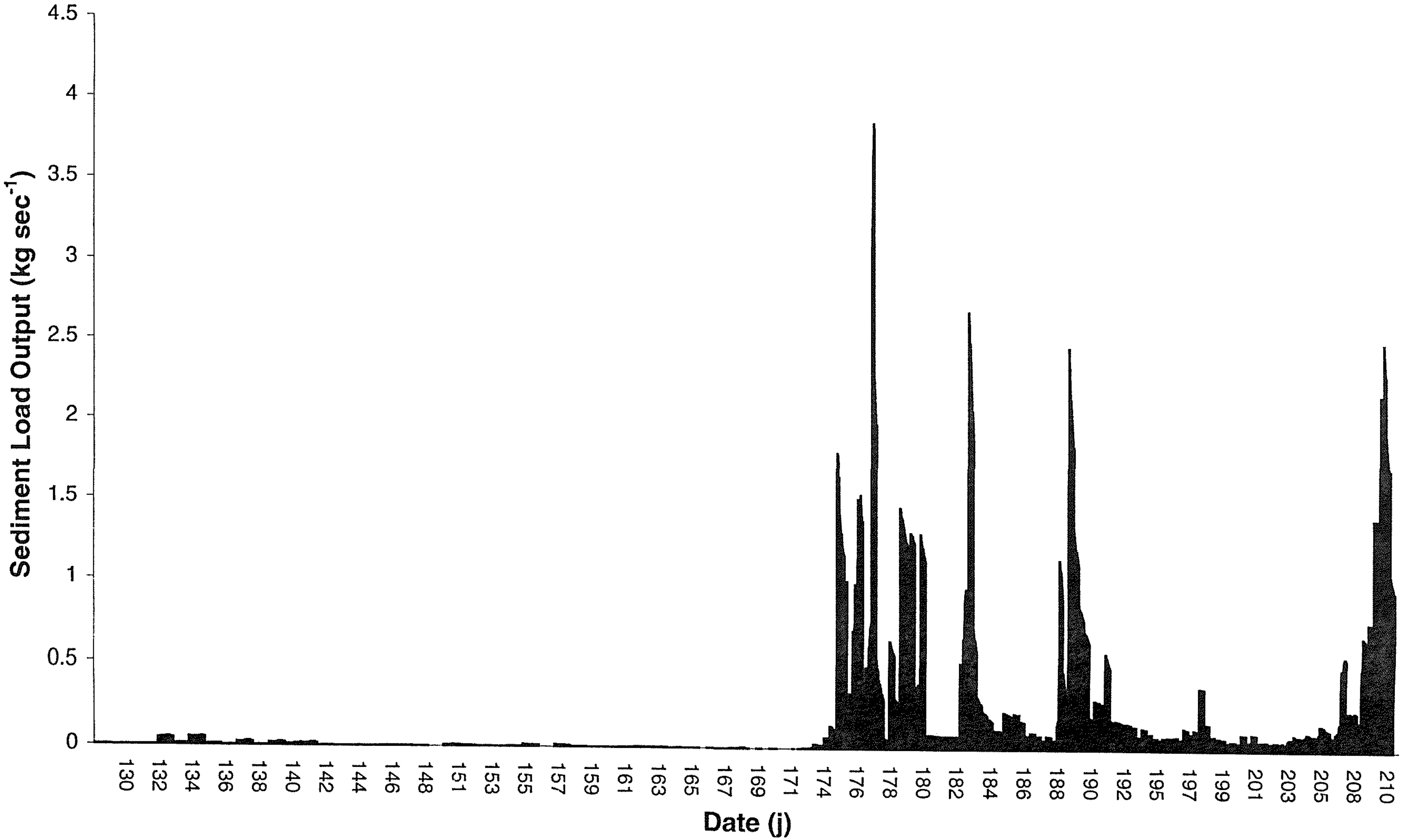


Figure 5.9: Time series of sediment load output from South Stann Creek to the coastal zone during the field season period

site B have been presented below where a power relationship provides the best fit for this data with an R^2 value of 0.83:

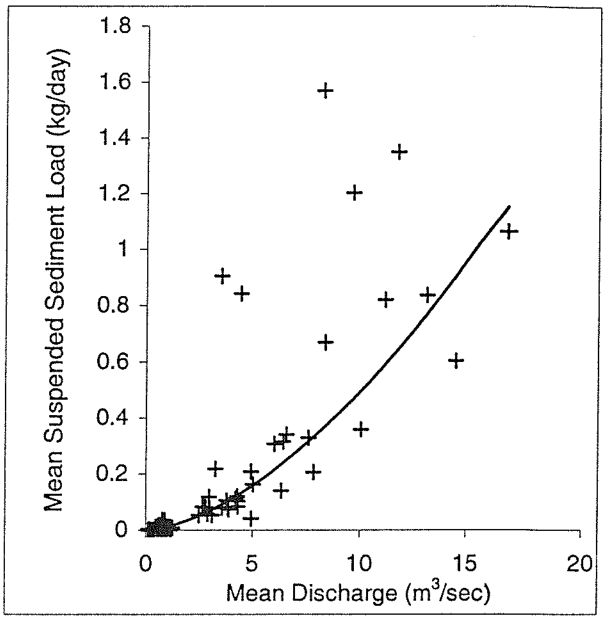


Figure 5.10: Relationship between mean daily discharge and mean daily suspended sediment load for Site B, South Stann Creek (May-July 1998)

This relationship was subsequently applied to discharge data from the 7th of May (127j) to the 15th of September 1998 (258j) to derive the simulated time series illustrated in Figure 5.11. Calculated sediment loads for the downstream site have been included to contextualise the data.

Spatial estimates generated for secchi measurements

To produce spatial estimates, transects of secchi transparency (z_d, m) were re-formatted and imported into "GRASS" GIS (Shapiro and Waupotitsch, 1993). Within GRASS the secchi depth measurements were interpolated using an inverse distance-weighting algorithm. Estimates at un-sampled locations were produced by interpolating the nearest 10 sampled locations to derive a continuous surface from each data set. A digitised mask of the coastal plains and the four important river networks within the Stann Creek District were overlaid on the interpolated surfaces.

§5.5.2 Secchi disc results

Interpolated results have been presented in Figures 5.12 a-h for the coastal zone associated with South Stann Creek. The points from which interpolated surfaces were calculated have been highlighted in blue and referred to as #1-*n* from the southern to the northern part of the Stann Creek coastal zone.

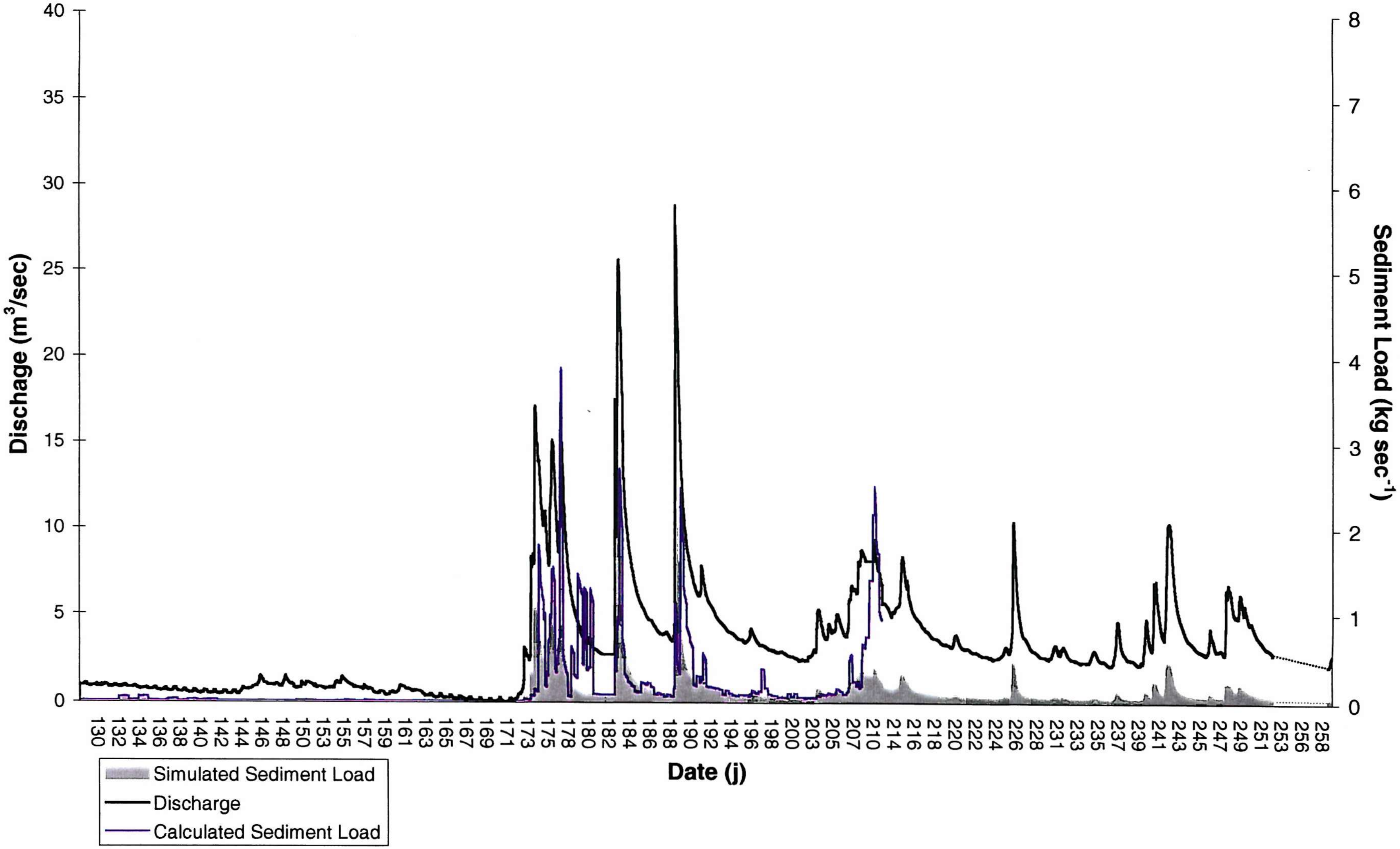


Figure 5.11: Calculated and simulated downstream suspended sediment load and discharge time series for South Stann Creek (7th May – 15th September 1998)

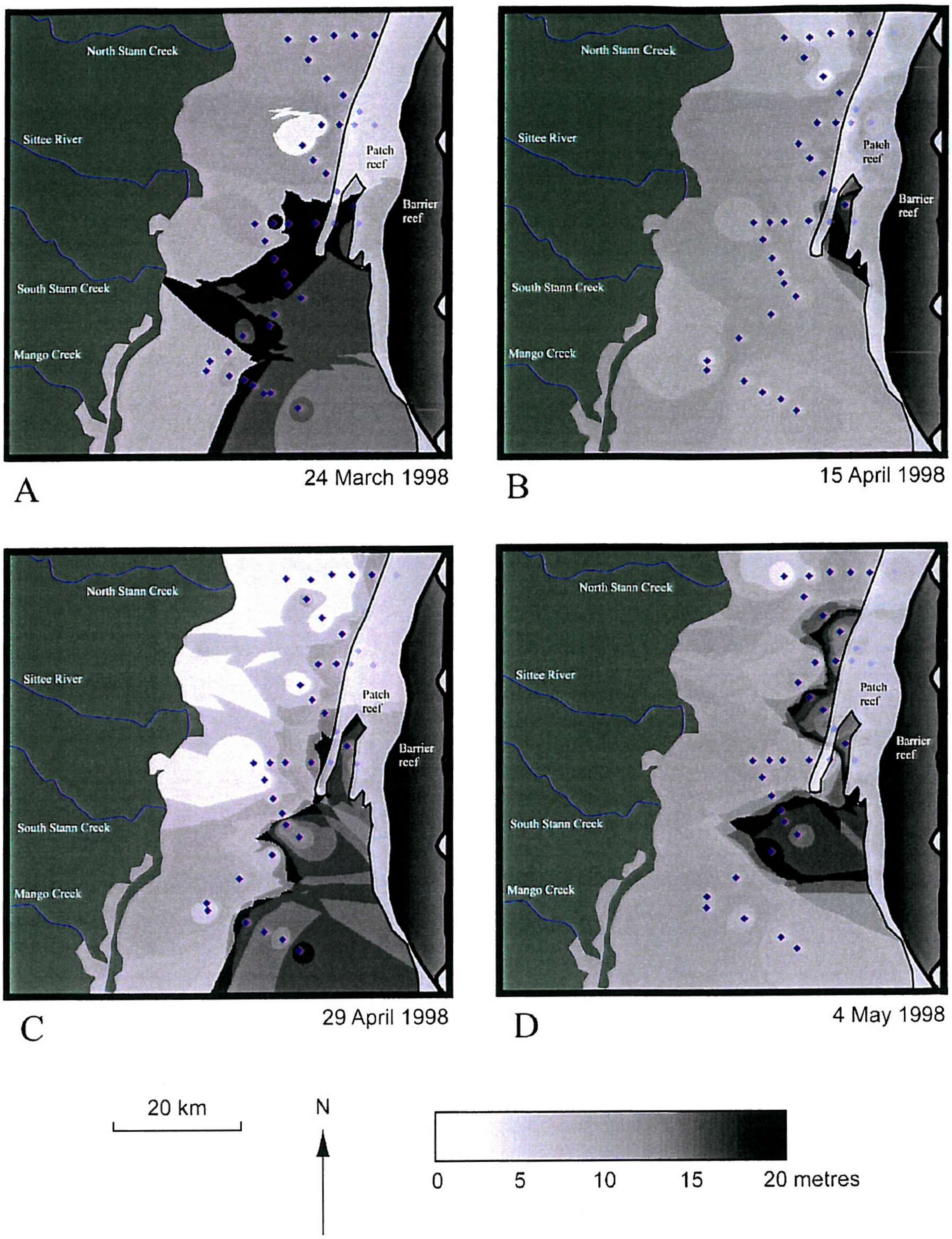


Figure 5.12 (a-d): Interpolated secchi surfaces for the Stann Creek lagoonal system

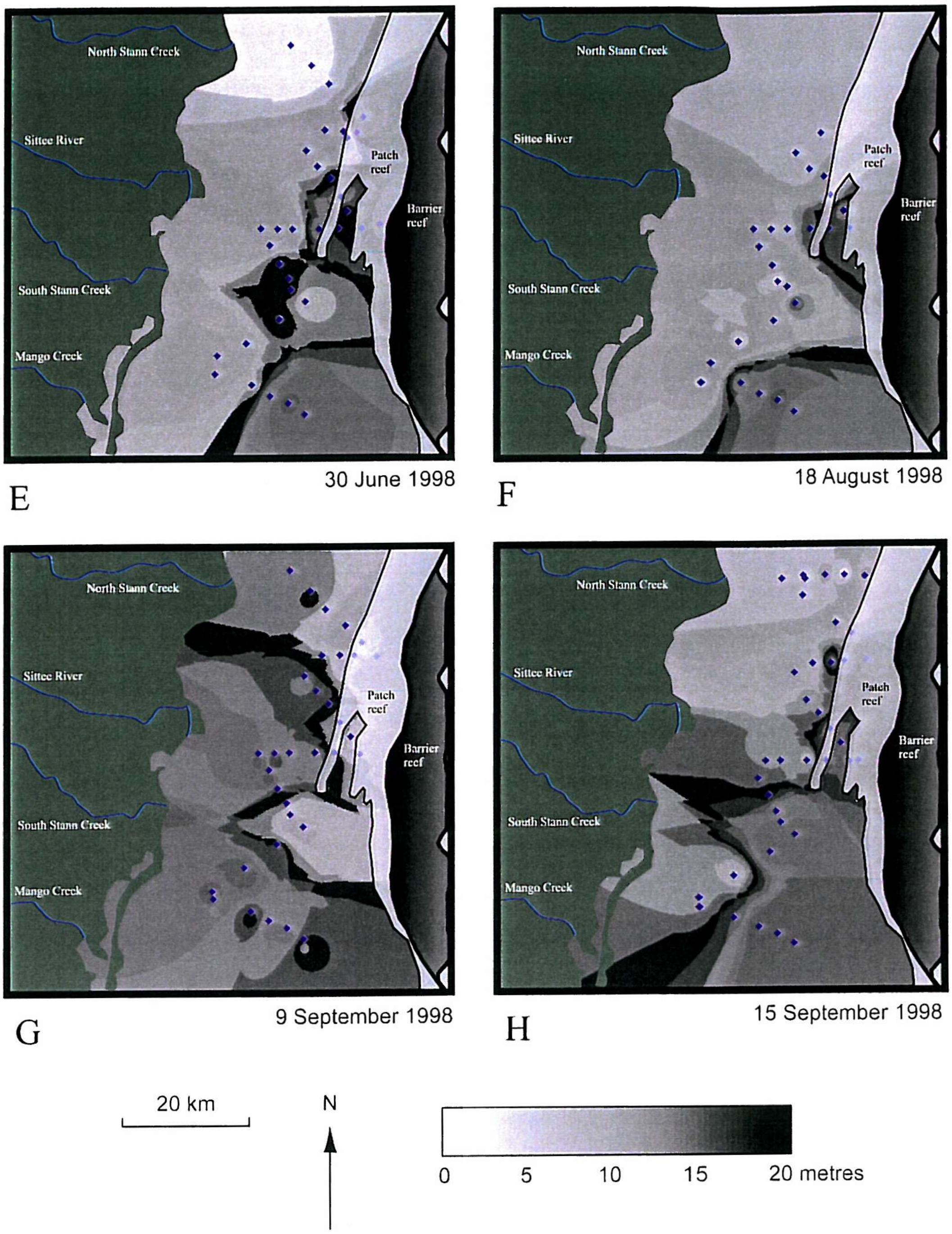


Figure 5.12 (e-h): Interpolated secchi surfaces for the Stann Creek lagoonal system

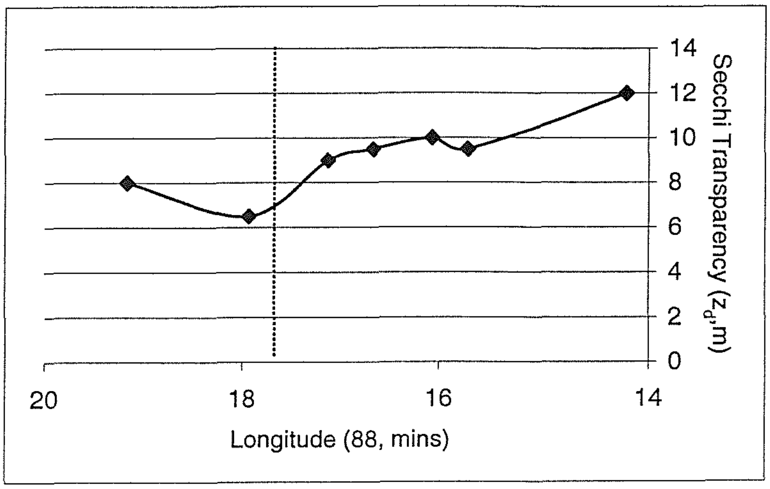
Table 5.4 details available information about hydrological system drivers whilst Table 5.5 presents a review of spatial patterns identified within the interpolated secchi surfaces.

Table 5.4: Information relating to local conditions during the recording of secchi depths

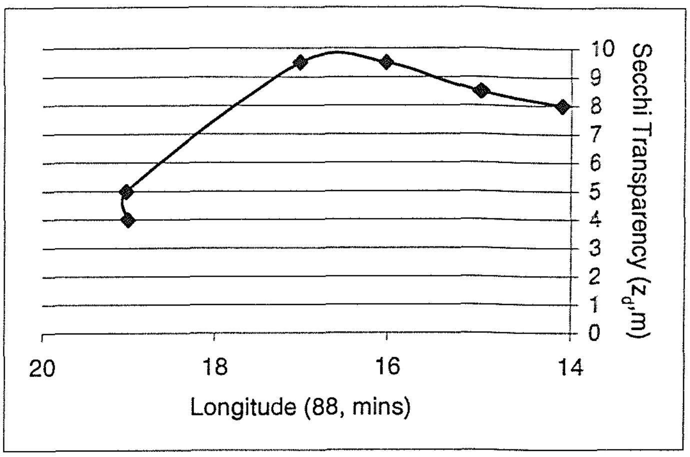
Interpolated surface	*Supporting information*
A **24th of March 1998** **(83(j))**	Mid dry season Fluvial discharge reported to be at annual minimum for South Stann Creek (Pers.Comm., National Meteorological Service, Belize, (1998) & Pers.Comm., B.G.A., Belize, (1998))
B **15th of April 1998** **(105(j))**	Mid dry season: however, a sequence of inland thunderstorms took place within the southern districts of Belize 3 days prior to the monitoring period (National Meteorological Service, Belize (1998a))
C **29th of April** **(119(j))**	Following a period of light rainfall activity (approximately 3mm) within the South Stann Creek catchment (National Meteorological Service, Belize (1998a)) Rainfall totals were markedly higher within the North Stann Creek and Sittee River Catchments (between 20 and 30 mm) during the days preceding the monitoring period (National Meteorological Service, Belize (1998a)).
D **4th of May 1998** **(124(j))**	Secchi readings were taken during a particularly dry period across Belize where there had been no rainfall activity within the any of the catchments and precipitation levels were below normal for the time of year (National Meteorological Service, Belize (1998b)).
E **30th of June 1998** **(181(j))**	Significant rainfall had fallen over all three catchments in the week prior to the sampling of these data especially between the 19th and 26th of June (170-177(j)) although little rainfall activity had taken place either on the 29th or 30th of June. Average discharge of South Stann Creek: 2.8m^3/sec
F **18th of August 1998** **(236(j))**	Secchi readings taken following a period of significant rainfall in the Stann Creek District (Pers.Comm., B.G.A., Belize, (1998)) Average discharge of South Stann Creek: 2.4 m^3/sec
G **9th of September 1998** **(252(j))**	Secchi readings taken during light rainfall activity in the South Stann Creek catchment but little rainfall activity had taken place within the North Stann Creek or Sittee River catchments. Average discharge of South Stann Creek: 3.0 m^3/sec
H **15th of September 1998** **(258(j))**	Secchi readings taken during a period of significant rainfall activity in the North Stann Creek catchment but during light rains in the South Stann Creek and Sittee River catchments. Average discharge of South Stann Creek: 2.2 m^3/sec

* There was no information available on discharge for North Stann Creek and Sittee River during the field monitoring period– although rating curves are presently being derived (WRIScS & Hydrological Monitoring Service, Belize (Appendix 3).

Table 5.5: Spatial transparency patterns identified through examining surface interpolations

Interpolated surface	*Observed Patterns*
A (83(j))	Points 4-7 illustrate low secchi depths of 6.5 metres in the area to the south of South Stann Creek (area 1). Between points 3 and 4 and between point 7 and the river mouth an area of distinctly clearer water may be identified. The transgression from clearer to less transparent water may be seen by the dotted line in Plot a below.  Plot a: 24th of March – Secchi transgression (Points 1-7) The interpolated surface generates an area of comparatively high transparency around the mouth of South Stann Creek. This was generated as a result of points 10, 11 and 12 where transparencies were recorded to be between 9 and 10 metres. However the model interpolated the surface from these points to the river mouth because due to their proximity to the estuary they were given greater weighting. Whilst this pattern is somewhat misleading it is clear that secchi depths in the coastal zone south of South Stann Creek were higher than those to the east and north-east in the middle of the coastal lagoon system. Within the rest of the coastal system it is clear that there are two other distinct areas of low secchi depths (areas 2 and 3). These again, appear to be associated with the water just south of two river mouths, Sittee River and North Stann Creek. Whilst this research is not concerned with these catchments, it is interesting to compare secchi behaviour at the mouths of these rivers with that at South Stann Creek. In particular an area of low secchi depth is evident just south of North Stann Creek in area 3, with secchi values of 4.5 metres. However, it should again be noted that the area to the east of North Stann Creek – whilst appearing to be of low secchi depth is again a function of the model biasing towards values where insufficient points were available to influence weightings.
B (105(j))	Secchi depths were generally between 4 and 9 metres within approximately 25km of the three river mouths. However, interpolated secchi surfaces for the coastal zone to the east of South Stann Creek returned lower secchi depths over a greater distance. Plot b illustrates the decline in transparency associated with the north-westerly run towards the South Stann Creek estuary.

B
(105(j))

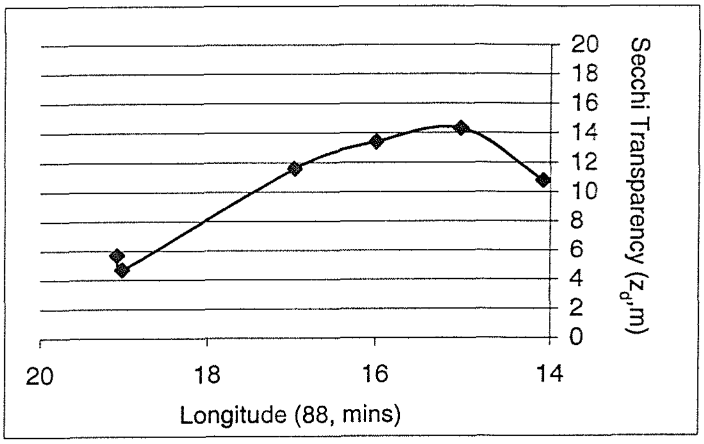


Plot b: 15th of April – Secchi transgression (Points 1-6)

Whilst surfaces to the far east of the coastal zone were again the result of inverse distance weighting due to insufficient data points, secchi disc readings taken at points 1,2 and 9 indicate that an area of lower secchi depth was present over 25km from the river mouth. In addition, particularly low secchi depths (3 metres) were recorded for areas 4 and 5 at the mouths of South Stann and North Stann Creek.

C
(119(j))

Surface C was interpolated from readings taken on the 29th of April 1998. Points 5 – 9 (area 6) indicate an area of moderate to low secchi depth in the coastal zone south of South Stann Creek. The transgression in secchi depth for this area has been illustrated in Plot c.



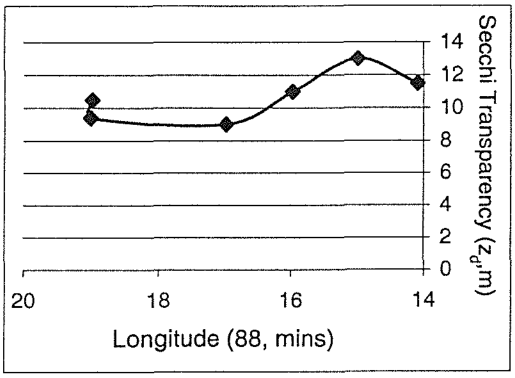
Plot c: 29th of April – Secchi transgression (Points 5-9)

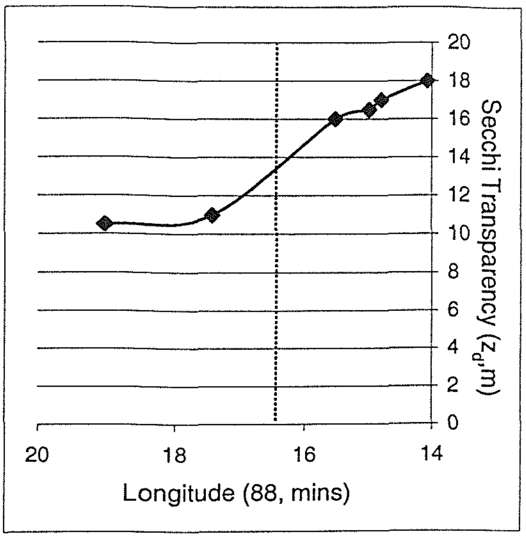
Whilst values are not as low as in interpolated surface B it is once again clear that there is a significant contrast between near shore and offshore secchi depths and that the areas in close proximity to the three river mouths return the lowest secchi values. Of particular note the areas south of Sittee River and North Stann Creek return the lowest secchi values.

D
(124(j))

Points 1-6 on the interpolated secchi surface for the 4th of May illustrate an area of relatively uniform secchi depth in the coastal zone south of South Stann Creek (Plot d). This area contrasts significantly with the interpolated secchi surface further north (Plot e).

D
(124(j))



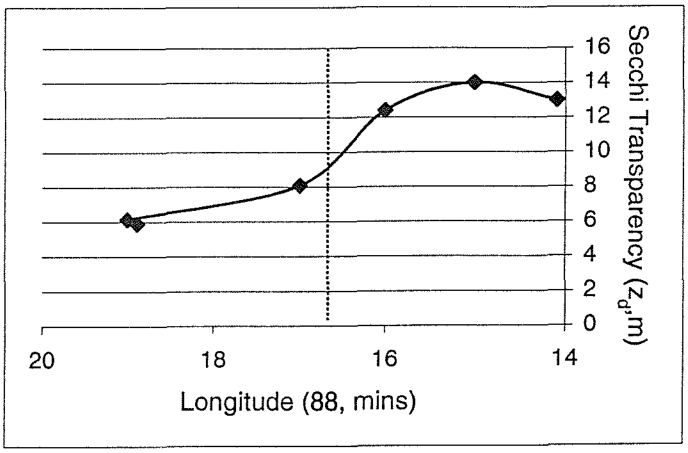


Plots d & e: 4th of May secchi transgression for points 1-6 and 6-11

It appears that transparency within the southern part of the Stann Creek coastal zone (area 7) is considerably lower than the areas directly adjacent to North Stann Creek and Sittee River which displays patterns more characteristic of those observed in the surfaces discussed above.

E
(181(j))

This interpolated surface for the 30th of June illustrates three distinctive areas of contrast (areas 8-10) between low and high secchi disc values. The transgression between the two for South Stann Creek has been illustrated in Plot f:



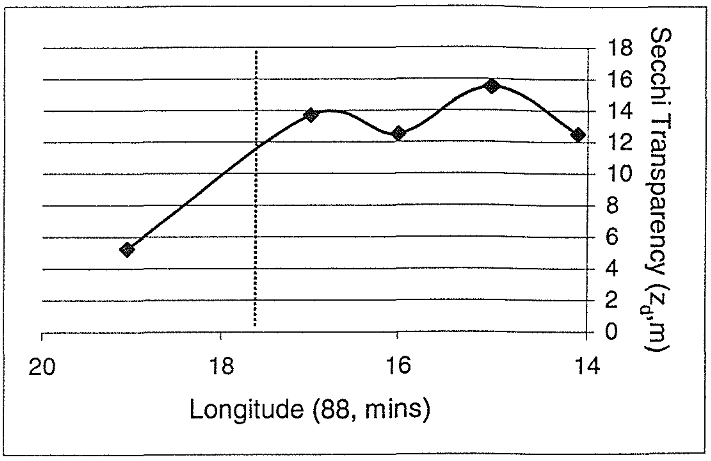
Plot f: 30th of June – Secchi transgression (Points 1-6)

F
(236(j))

Interpolation F illustrates the surface for the 18th of August. Whilst it is clear that there is an area of low secchi depth within the coastal area close to the river mouths of South Stann Creek and Sittee River it is particularly difficult to differentiate between the low secchi depths associated (although tentatively) with the rivers, unlike in the surfaces above. The large area of low secchi depth close to North Stann Creek and the large intrusion of the low secchi disc surface into the off shore zone are again a function of insufficient data points, however apart from this there is a clear distinction down the coast between areas of low secchi depth and high secchi depth. This has been illustrated for area 11 by Plot g:

F

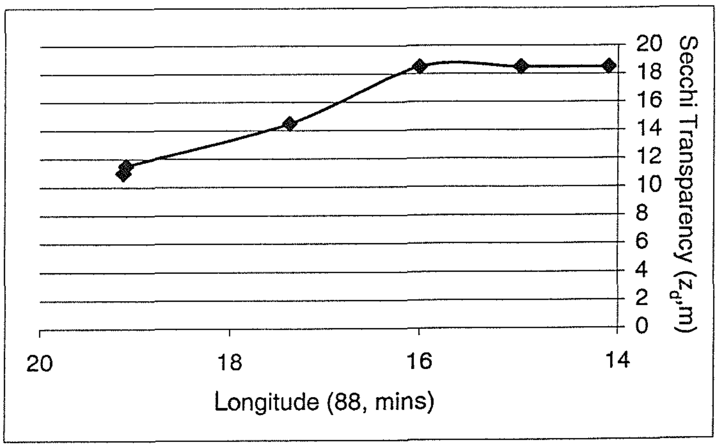
(236(j))



Plot g: 18th of August – Secchi transgression (Points 1-5)

G (252(j)) Surface G was generated from secchi data measured on the 9th of September. Observed patterns are less clear than in the interpolated surfaces discussed above, however it is again identifiable that the general area of medium to low secchi depths close to the river mouth (area 12). An area of low secchi depths is also apparent to the east of the interpolation suggesting that an off-shore processes may have been a more dominant control over water transparency than fluvial discharge.

H (258(j)) This surface was generated from secchi data measured on the 15th of September 1998. Of particular note is an area of very low secchi depth is evident south of South Stann Creek in area 13. Again a clear pattern of high secchi values is identifiable in the coastal zone close to the river mouth. A distinct margin has been generated by the model on the outside of area 13, but it is unclear as to whether this marks the eastern-most limits of the plume or whether it is simply the result of insufficient data points. Data points recorded further east though, return moderate secchi values and suggest that the high secchi depth margin identified in surfaces a, c, e and f is not present in the southern part of this surface interpolation. This has been illustrated by Plot h below:



Plot h: 15th of September – Secchi transgression (Points 1-6)

A further contrast may be observed in secchi depth interpolations for the coastal zone offshore from North Stann Creek, where values were notably lower than any of the previous dates.

§5.5.3 Data Quality

Secchi measurements are well recognised as a robust technique for monitoring the optical properties of water (e.g. Schellenberger, (1987), Mulhearn, (1995)). However, the versatility of the technique trades off against data quality and whilst it is still regularly used as a method for monitoring patterns of optical variation within marine and freshwater environments its value is generally recognised as a technique for identifying comparative change. The following section considers the factors that affect the quality of secchi disc data and explores the limitations of the technique with respect to data obtained in Belize during 1998.

Limitations of secchi disc data

As identified above, a number of factors limit the quality of secchi disc data. The principal constraints with respect to effectively monitoring coastal SPM patterns are as follows:

- Sea state (i.e. wind/tide conditions) and boat/shipping traffic
- Cloud cover and meteorological conditions (i.e. rainfall/hours of sunlight and sun zenith angle)
- Frequency and number of measurements (i.e. spatially and temporally biased)
- Quantities of chlorophyll and organic matter (yellow substance)
- Human error

Sea state is an important control over secchi depth readings and it is important that secchi depths obtained during rough conditions are not compared with those obtained during calm conditions. In addition, it is particularly difficult to read the secchi depth during rough seas or high levels of turbulence and subsequently it is generally accepted that this is not the best time for sampling as observations made are often prone to significant error. In the same way, variations in cloud cover and the zenith angle of the sun will affect water transparency and subsequently readings need to have been taken under similar conditions. However, in reality the feasibility of this is governed by logistics and it is subsequently an area where inconsistencies in the data set are common.

The frequency of measurements will also affect data quality as transects taken at different years or under different conditions are difficult to compare against each other and interpret effectively. Likewise, the annual / inter-annual distribution and quantities of chlorophyll and organic matter (yellow substance) within the water column will affect the optical properties identified by secchi interpretation and therefore careful consideration should be given to the assumption of a relationship between secchi depth and SPM concentrations.

Human error is well recognised to be the largest control over errors generated in secchi measurement and interpretation (Schellenberger, 1987). Especially with volunteer programmes the reading of secchi depth can not always be carried out by the same person and therefore operator error can be introduced into the data set in this way. Estimations suggest that errors created as a result of human variance have usually been calculated to be within +/- 0.5m of recorded secchi depth (British Columbia Ministry of Environment, Lands and Parks, 2000).

In addition, for monitoring coastal sediment plume dynamics it is important that readings were taken in the most appropriate location and that consideration be given to alternative sources of sediment and water quality constituents that may have affected the data.

Limitations of inverse distance weighting for secchi disc interpolations

Aside from the overall quality of the secchi data limitations associated with using inverse distance weighting to interpolate surfaces between data values, requires brief consideration. Insufficient sample points within the coastal zone resulted in a combination of extrapolated and interpolated surface values. Careful consideration should subsequently be given to the meaning of interpolated surfaces where few data points are available. It should also be noted that the assumption that inverse distance weighting describes the spatial distribution of secchi depth throughout the coastal zone might be inappropriate. Important areas of low/high secchi depth may be missed during surface generation as a result of insufficient sample points and therefore it should not necessarily be assumed that the surface plotted between two values represents coastal secchi depth accurately. It should again be stressed that the interpretation of interpolated surfaces should rely primarily on the comparative value of the technique rather than on the specific values assigned to the interpolated surfaces, although in-depth accuracy assessment with an independent data set would provide a measure of spatial estimate accuracy.

Understanding the relationship between secchi transparency (z_d, m) and SPM concentration dynamics

Despite the known limitations of secchi disc observations it is generally well recognised that a relationship exists between variations in coastal SPM concentrations and variations in secchi depth (Schellenberger, 1987). However, a number of factors will affect the nature and strength of this relationship over time and space. To interpret secchi data with respect to understanding patterns in coastal SPM dynamics it is therefore important to consider the possibility of water quality constituents such as chlorophyll and dissolved organic matter (D.O.M.) influencing observed transparency. In addition SPM dynamics within the wider coastal system require some consideration to identify how they may have affected observed variations in secchi depth.

Empirical relationships derived between secchi transparency, SPM, chlorophyll and D.O.M have been well reported in the literature, but, due to the site-specific nature of interactions between these constituents, derived relationships mean very little when applied elsewhere (Bulakova, *et al.*, 1994). Unfortunately there is little information available for Belize to facilitate the calibration of secchi transparencies against these constituents, and therefore it is necessary to discuss their influence on secchi transparency and potentially observed SPM within a wider context.

It is well recognised that that the delivery of phytoplankton and D.O.M to shallow tropical lagoon systems operates in association with fluvial point sources of water and suspended sediment to the marine environment (e.g. Harris, 1999). Indeed, the dynamics of the sediment and phytoplankton riverine flux are so interlinked that satellite observations of ocean colour can not rely on temporal discontinuities to distinguish their otherwise similar spectral signals (Han, *et al.,* 1994). However, despite difficulties with separating their influence temporally, providing no other significant point sources of chlorophyll and D.O.M. are operating within the coastal zone they will, in addition to fluvial sediment load, be the principal drivers of patterns of change observed by secchi transparency measurements.

The coastal lagoon system associated with the Stann Creek District (encompassed by the interpolated surfaces) has only three dominant point sources of sediment, phytoplankton and D.O.M.. These are, North Stann Creek, Sittee River and South Stann Creek. Mango Creek discharges to the coastal zone south of the Placencia Peninsular (Figure 2.5) and influences processes significantly outside the coastal region discussed here because of the predominant North – South circulation current forcing water and material in a southerly direction (GESAMP, (1994), Heyman & Kjerfve, (1999)). Due to the relative intolerance of high concentrations of phytoplankton and D.O.M. to significant water transport compared with SPM owing to dilution and disturbance disseminating concentrations (GESAMP, 1990b), it is very likely that if observed patterns of change within the Stann Creek coastal zone were related to their presence that the principal sourcing would have been the three river systems.

A principal difficulty still remains however, with differentiating between the influence of fluvial sediment load on secchi transparency and the potential influence of fluvial inputs of chlorophyll and D.O.M. In this respect little can be hypothesised without field data. The influence of agrochemicals associated with plantation agriculture have been reported to have marginal influence over algal growth due to the rapid deterioration of chemicals (Hall, 1994), but this is clearly an area where the calibration of secchi measurements is required with *in-situ* water samples.

This difficulty is accentuated further by the internal properties of the fluvial sediment plume. It is possible that the plume may have been hyperpycnal (§5.2.1) – especially during large sediment loads and subsequently not be detected during observations of secchi transparency. Chlorophyll and D.O.M. concentrations may, however, have an influence over measured optical properties during such conditions and could subsequently distort the observed pattern further. This again is an area where further calibration of the system is required.

Alternative sources of sediment with the Stann Creek coastal system also require brief consideration to develop understanding of the relationship between secchi transparency and SPM within the region.

Due to barrier reef systems providing the most effective natural protection for shorelines against wave-dominated erosion, the low-energy mangrove-dominated coastline of southern Belize has experienced very low levels of coastal retreat over the last century (Zisman, 1992). Subsequently the quantities of sediment contributed to the coastal sediment budget from shoreline erosion are considered to be minimal. The role of mangroves within the sediment delivery system is further explored in Chapter 6.

Sediments derived and transferred via alternative mechanisms within the coastal zone and delivered to the monitored area by coastal circulation currents are a much more feasible source of SPM in significant quantities within the monitored system. This, in conjunction with disturbances to bottom turbidity are key controls over secchi transparency (Bulakova, *et al.*, 1994). However, whilst exerting control over overall SPM concentrations within the coastal zone these sources are unlikely to change the patterns identified in secchi distributions and therefore should be considered as an important factor, but one that may be distinguished from consistent input delivery patterns.

§5.5.4 Integrating fluvial sediment yield with secchi disc data to understand change across the land – ocean interface

Given the rationale for a definable relationship between coastal SPM dynamics and water transparency indicated by secchi depth, it is important to construct a framework within which the two may be integrated. The temporal flux of SSC from the fluvial system requires positioning against the spatial distribution of SPM at the river mouth to promote the ultimate understanding of cause and effect relationships between the two. This would facilitate the prediction of plume dynamics within the coastal zone from a network of information on fluvial sediment yield and oceanographic (i.e. wind/current) conditions at the land-ocean interface. In this way sediment delivery drivers may be combined with sediment delivery determinants to identify the transfer of change through the system.

To achieve this level of integration, secchi data and sediment yield information would ideally be required over broad range of sampling dates and local conditions to detail the temporal and spatial fluxes associated with sediment yields and delivery determinants over the full spectrum of possible scenarios (Figure 5.13).

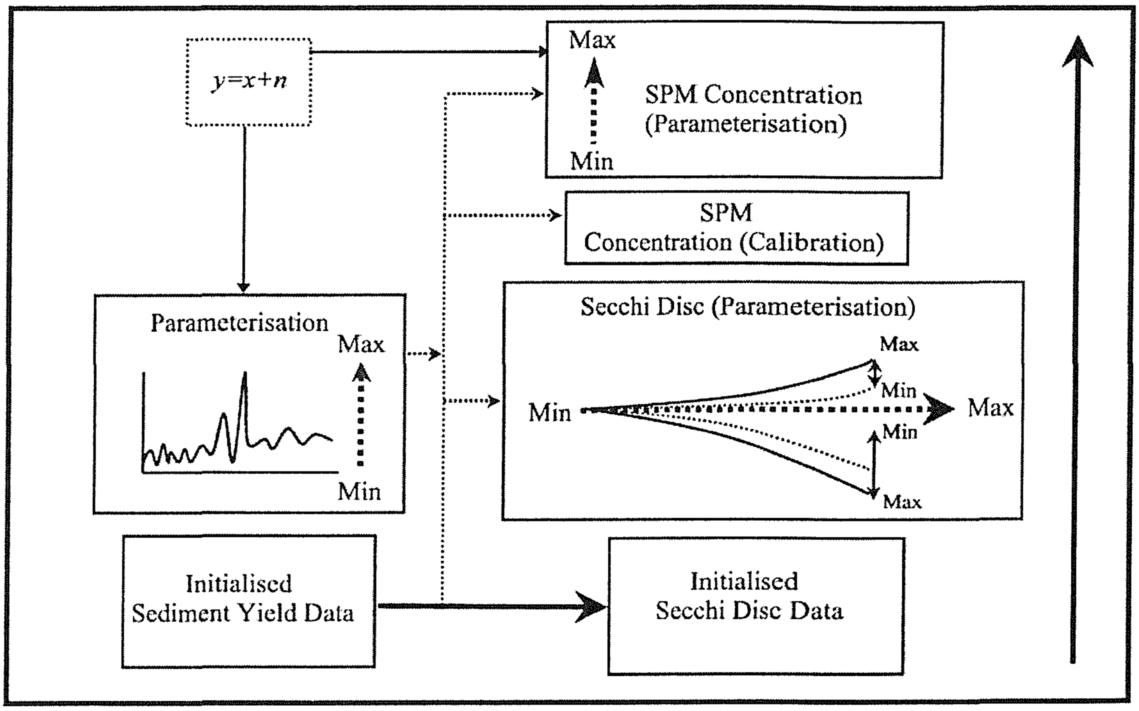


Figure 5.13: A framework for linking fluvial sediment yield with secchi disc data

Secchi surface interpolations and sediment yield data presented in the sections above provide the initial base for initialising this framework. Figures 5.14a-h illustrate the average daily sediment yield and secchi surface fluxes associated with the interactions between South Stann Creek and the coastal lagoon system. A summary of data has been provided in Table 5.6:

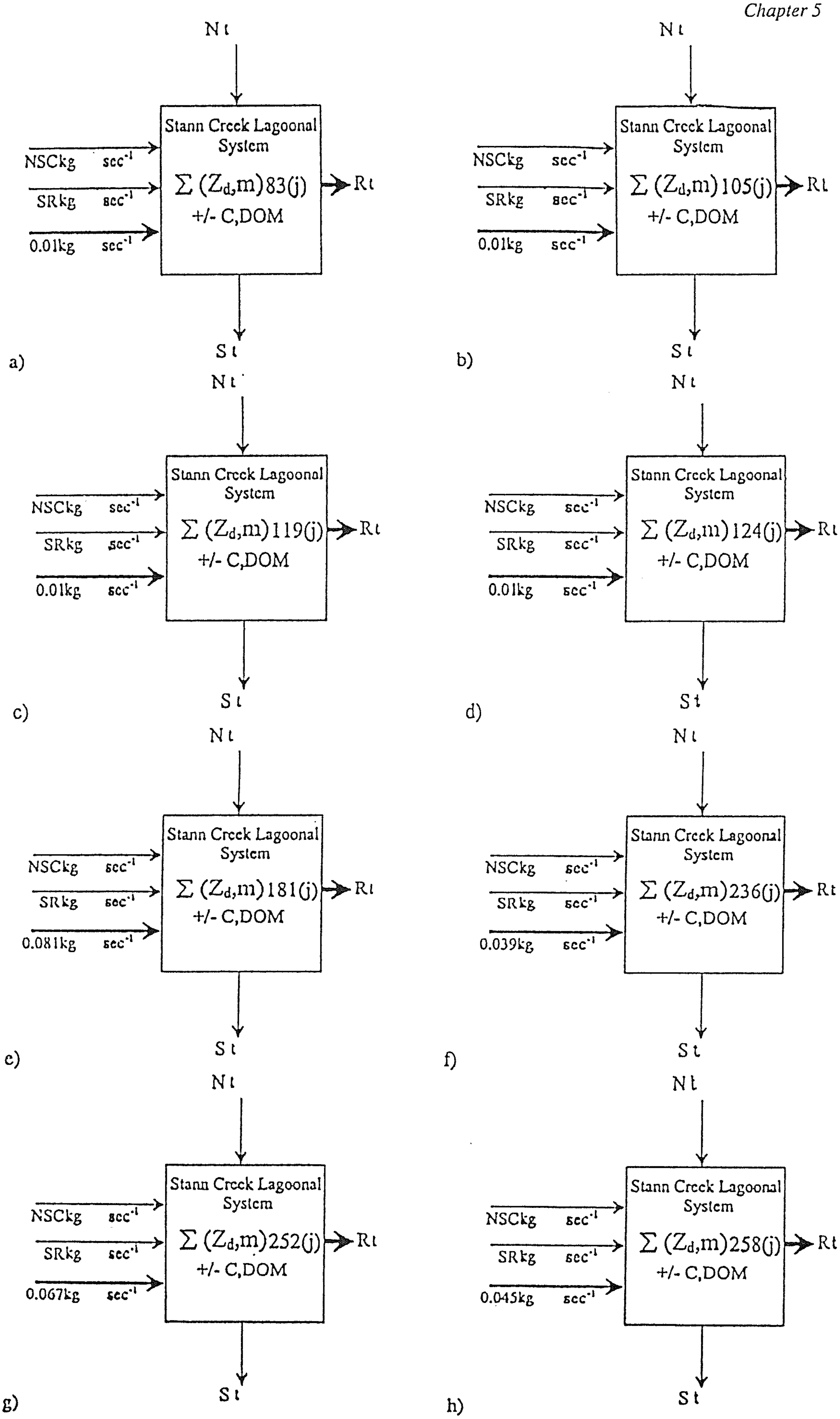


Figure 5.14 a-h: Initialised budgets detailing interactions between South Stann Creek and the Stann Creek Lagoonal System

Table 5.6: Database for budgets initialising interactions between South Stann Creek and the Stann Creek Lagoonal System.

Secchi data set	*Date (j)*	*Time*	*South Stann Creek Sediment yield kg sec-^{1}* *Average*
A	83	08:44 – 14:46	Dry season approx. 0.010
B	105	10:45 – 15:31	Dry season approx. 0.010
C	119	08:00 – 13:10	Dry season approx. 0.010
D	124	08:05 – 13:30	Dry season approx. 0.010
E	181	07:45 – 13:51	(Calculated) 0.081
F	236	09:04 – 14:29	(Simulated) 0.039
G	252	12:05 – 14:15	(Simulated) 0.067
H	258	09:15 – 15:33	(Simulated) 0.045

The budgets may be summarised where horizontal fluxes in are, North Stann Creek (NSC), Sittee River (SR) and South Stann Creek (*n*, sec $^{-1}$), and where the horizontal flux of sediment load out to the reef system is R t, m^{3} $^{-1}$. Vertical fluxes in, associated with forcing from the northern sediment system are N t, m^{3} $^{-1}$, whilst vertical fluxes out (S t, sec $^{-1}$) are a function of delivery, settling and re-suspension within the lagoonal system. Internal dynamics are expressed by the range of interpolated secchi data (Σ (Z_d, m)) as a proximate surrogate for SPM for the day on which samples were taken.

In addition to facilitating the initialisation of daily budgets for the fluvial-coastal sediment system, transects of secchi data (illustrated in <u>Table 5.5</u>) highlighted that for every date apart from 252(j) the transparency of the water decreased as readings neared the area of water just south of the river mouths. For South Stann Creek the transition from clear to less transparent water was identified to be significant from east to west on 119(j), 181(j), 236(j) and 258(j), whilst on 83(j), 105(j) and 124(j) the magnitude of difference was less pronounced.

Whilst it is difficult to identify trends within such a limited data set it is clear that the greater transitions in secchi depth were associated with periods when more activity was taking place within the hydrological and fluvial systems of the Stann Creek District. It is possible that elevated loadings of fluvial suspended sediment were delivered to the coastal zone during this period and subsequently if a linear relationship existed between secchi transparency and coastal SPM concentrations the contrast between near-shore and inner channel sediment concentrations was greater.

However, it is clear that to understand interactions across the land-ocean interface further through integrating sediment yield and secchi transparencies, significant calibration of the initialised framework would be required. Key areas for this calibration are as follows:

- Improved spatial coverage of secchi data
- Improved temporal coverage of secchi data – especially during high discharge events
- Increased duration and calibration of fluvial monitoring
- Improved integration of fluvial and coastal monitoring programmes

Without a full parameterisation of the extremes of change in time and space within the coastal environment it difficult to understand how fluvial inputs of suspended sediment may drive and interact with this process. Furthermore unless the temporal coverage of secchi measurements were increased significantly the likelihood of sampling these extremes becomes undermined. Ideally, a high-resolution fluvial monitoring programme would promote the measurement (and calibration) of coastal secchi depth during periods when significant activity was taking place within the fluvial system.

However, by increasing the temporal and spatial resolution of secchi sampling within the coastal zone the value of the original strategy for monitoring change in this way has been undermined. Indeed if a future strategy were to be considered, further calibration of the system may be most appropriately carried out using remotely sensed data given sufficient improvements in the temporal and spatial coverage of ocean colour sensors. The potential for this is considered within the following section.

§5.6 Remote Sensing as a future tool for monitoring SPM dynamics within the Belizean coastal zone?

The feasibility of using satellite remote sensing as a tool for monitoring SPM dynamics in Belize has been discussed within the context of obtaining data synchronous with the field season period (§5.4). However, rapid advances in ocean colour remote sensing and improvements in sensor design and algorithm development will be accompanied by a mass of data coming available in the next few years (Groom & Lavender, 1998). It is important to assess whether present difficulties associated with data availability would still be experienced in Belize following the launch of new and improved sensors (Table 5.1).

MERIS, due for launch in 2001, promises a great deal in terms of ocean colour remote sensing for coastal zones (ESA, 1995). Unlike previous sensors MERIS offers a product that obtains the spectral, temporal and spatial data required for monitoring sediment movement within the coastal zone. Of note, bands centred around 510, 560 and 620 nm, with average bandwidths of 10 nm (although variable between 1.25 and 30nm) will be ideal for accurately monitoring SPM concentrations and distinguishing suspended sediment from other water quality constituents

(Rast and Bezy, 1999). The 3 day temporal resolution and 300 metre spatial resolution of MERIS is good for monitoring coastal water quality and would be more than adequate for identifying and measuring most water quality constituents (Doerffer, *et al.*, 1995).

However, for monitoring plume dynamics within Belize the temporal resolution of MERIS would ideally require sharpening with more frequent data from a sensor such as SeaWiFS (§5.5.4). In addition the medium spatial resolution of MERIS would also require sharpening to facilitate the differentiation of plume sources.

Aside from instrument requirements, the fundamental problem with cloud obscuring the observation of coastal SPM cannot be avoided even with sensors tailored for coastal zone applications such as MERIS. Although the high temporal resolution of merged MERIS and SeaWiFS imagery would increase the likelihood of obtaining cloud-free imagery, the probability of capturing consecutive images would be minimal and unpredictable.

The same is the case with other current and future ocean colour sensors such as GLI, POLDER-2 and MODIS-PM that have the capabilities to provide valuable data on SPM dynamics at different scales, but are still limited for use in Belize because of cloud cover restrictions. Unfortunately radar and microwave sensors that penetrate cloud to observe the water surface cannot provide any information about variables such as concentrations of SPM and chlorophyll (Sabins, 1996).

The principal advantage of using future satellite ocean colour data for Belize is that a large amount of data will become available at a greatly reduced price in the next ten years. The cost-benefit of using this data for *observing* SPM (if available and cloud free) against *in-situ* data would significantly favour satellite imagery. However, to use the data for any quantitative estimations extensive accuracy assessments would be essential, requiring *in-situ* coastal data of a similar magnitude to that required to calibrate the system exclusively (Steven, 1986).

Therefore, in terms of the *monitoring* of SPM and obtaining reliable data on sediment plume dynamics at the river mouth, ocean colour remote sensing does not offer the most cost-effective or reliable technique for monitoring within Belize. However, given future advances in algorithm development, the spatial and temporal resolutions of sensors and the penetration of cloud, the remote observation of ocean-colour may provide the key to reducing logistical constraints in the temporal co-ordination of fluvio-coastal interaction observation.

§5.7 Overview

This chapter has identified the importance of monitoring interactions at the land - ocean interface in southern Belize where fluvial sediment delivery requires integration with coastal suspended sediment dynamics to understand the transfer of change through the system.

Satellite remote sensing has been identified as a valuable tool for achieving this. However despite considerable advances in applications of remotely sensed data to coastal monitoring over recent years, the land-ocean interface within the humid tropical environment still presents a number of practical challenges that remote observation technologies need to overcome.

This chapter subsequently explored the potential for using integrated secchi depth and sediment yield data to initialise the conceptual model offered for understanding the system. The following observations were made:

- Interpolated secchi surfaces provide a means for understanding spatial change in water transparency within the Stann Creek lagoonal system, providing the limitations of inverse distance weighting are recognised.
- Interpolated secchi surfaces require accuracy assessment for spatial and temporal extremes within the coastal zone to identify patterns of water transparency over a range of conditions.
- Interpolated secchi surfaces require calibration with coastal SPM concentrations to facilitate integration with fluvial sediment yield.
- Fluvial sediment yield provides a high temporal resolution data set detailing the quantity of sediment discharged from the basin over time.
- Integrating fluvial sediment yield with interpolated secchi surfaces requires a long time-series of data for the coastal and riverine environments.
- Integrating fluvial sediment yield with interpolated secchi surfaces requires improved spatial data within the coastal zone (i.e. spatially exhaustive secchi measurements and data collected at the river mouths).

The secchi-sediment yield framework facilitated the initialisation of temporal patterns within the delivery system and spatial patterns within the lagoonal system. However, the integration of spatial and temporal change was restricted by the availability of regular secchi data over a range of conditions. This in turn was restricted by:

a) the lack of a mechanism for increasing the temporal resolution of secchi data during high sediment yield activity

b) the logistics associated with co-ordinating regular secchi disc runs - especially during rough sea states.

Conceptual budgets were subsequently constructed to illustrate the mechanism proposed for calibrating the system based on the model offered in Figure 5.13.

To calibrate the model, the temporal and spatial resolution of coastal secchi / SPM sampling and the integration of this with fluvial yield were identified to require a high maintenance operation. Indeed, the spatial and temporal resolution of coastal data required the re-consideration of remote satellite observation techniques for future monitoring (§5.6). However, unless the need to assess the accuracy of such data with coastal measurements was removed by the development of a specific algorithm it was identified that the technique would create the need to obtain more data than it could provide. Indeed, only given the future development of a "super sensor" with excellent spectral, spatial and temporal resolutions, in addition to site-specific algorithms, could the flux of anthropogenic sediment delivery from the fluvial to the coastal environments of Belize be monitored effectively during episodic hydrological events.

It is clear that options for calibrating the continuum at the land-ocean interface have effectively completed a full circle, where despite the attractions of remote observation, the advancement of system understanding will be most appropriately focused at the sampling of high temporal and spatial resolution *in-situ* data and co-ordinating this with fluvial sediment yield predictions based on improved understanding of system drivers. This will be given further consideration in the following Chapters 6 and 7.

Chapter 6

Understanding interactions between the plantation, the river and the coastal zone within a land – ocean sediment delivery framework

§6.1 Introduction

This chapter seeks to address interactions between the system components detailed in Chapters 3, 4 and 5, for interfaces between the plantation, river and coastal zone respectively. Whilst each chapter has contributed to a characterisation of change at key stages of the model it is now important to explore inter-relationships between drivers, transfers and delivery mechanisms to provide a platform for future calibration and understanding.

In view of this, focus is directed towards temporal and spatial change within the framework where the economic and physical development of the banana industry has been considered relative to geomorphological change within the continuum. The value of the LOICZ framework as a mechanism for understanding the interaction of drivers within such change is given attention prior to exploring its value as a conceptual framework for threshold change within the Belizean barrier reef system.

Given the immediate pressures on monitoring and managing the economic and environmental systems associated with the continuum, specific consideration is given to areas where further calibration would be most appropriately focused. This has provided a basis for designing a strategy where understanding may be enhanced through monitoring the continuum and its interaction with future change.

§6.2 Interactions between the plantation and the fluvial system

In chapter 3 the plantation system was considered as a driver of suspended sediment to South Stann Creek. The design of the plantation and the nature of practices employed on it were identified as a means by which the industry has adapted to a fragile growing environment. The cost-effective production of bananas and the economic viability of the industry in Belize has become dependent on the effective management of the inter-relationships between climate, soil and water.

However, in achieving this balance, agricultural practices have modified the plantation sediment system and the extent of its interaction with local hydrology. Drainage channels were identified as a key mechanism by which this has taken place, where sediment mobilised within the plantation unit by a range of processes has been delivered in suspension to the interconnected fluvial system. A conceptualisation of this process has been outlined below in Figure 6.1:

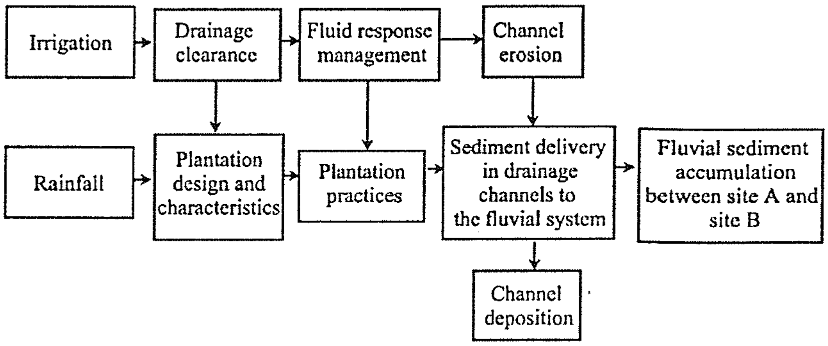


Figure 6.1: A conceptualisation of plantation sediment delivery to the fluvial system.

Through obtaining base level information about the loadings of sediment delivered to the river system in these drainage channels over the field monitoring period initial figures have been given to key processes within this framework. Information on the dimensions and location of channels within the drainage network has promoted a preliminary understanding of the spatial context within which these processes are operating.

However, to advance the model from characterisation to calibration, detailed information is required about the spatial and temporal dimensions of processes operating over short term and projected time scales. Indeed, the highly dynamic nature of the system suggests that full calibration of the conceptual framework would require significant monitoring and modelling over time and space. Further consideration is given to possible techniques for future research avenues in §6.5.5.

In Chapter 4 a fluvial suspended sediment budget was constructed from the net difference between upstream / downstream sediment load in the reach adjacent to the banana plantation unit. Figure 6.2 illustrates the framework within which the budget has been conceptualised:

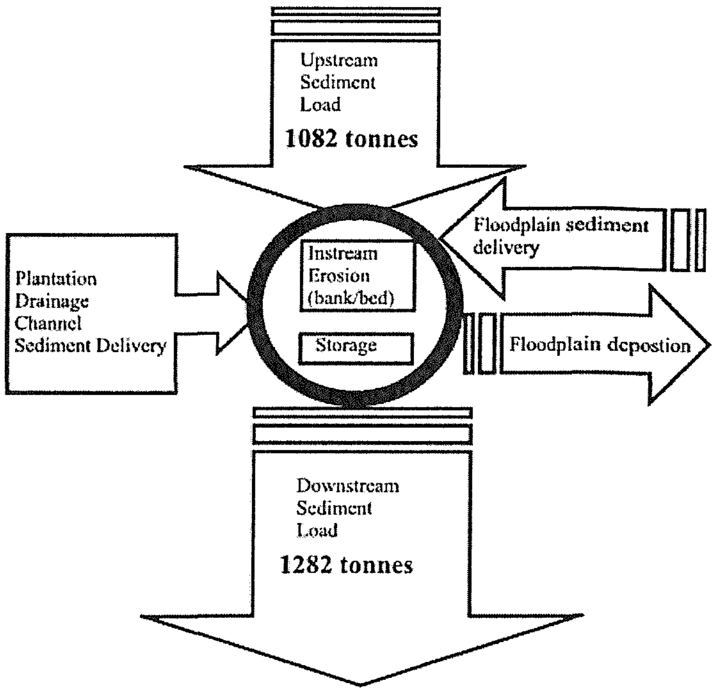


Figure 6.2 A conceptual framework for the fluvial suspended sediment budget

The budget identified within significant but definable error margins that a net gain in suspended sediment took place between the two monitoring sites of approximately 200 tonnes.

However, the budget does not provide direct quantitative information about the processes that may have contributed to sediment loadings. Indeed, it is well recognised that a wide range of processes may interact with and modify suspended sediment dynamics within a river (e.g. Grimshaw & Lewin, (1980), Olive & Reiger (1992), Yang (1996)) and subsequently the identification of cause and effect relationships from the budget would be inappropriate without supporting information.

It is therefore clear that whilst the data presented in Chapters 3 and 4 provides important initial information about the processes operating within the plantation and fluvial systems, an understanding of cause and effect scenarios will only come from the conceptualisation of this information relative to the wider delivery system.

There are two mechanisms by which this may be achieved. The first is through focusing intensive research on the plantation or the fluvial system to understand processes at the local scale. The second is through using the LOICZ conceptual framework as a base for understanding sediment delivery interactions between the plantation, the river and the coastal zone. Understanding may be constructed through the characterisation, calibration and ultimately parameterisation of the model. Figure 6.3 illustrates this further, where a) represents the first approach and b), the second:

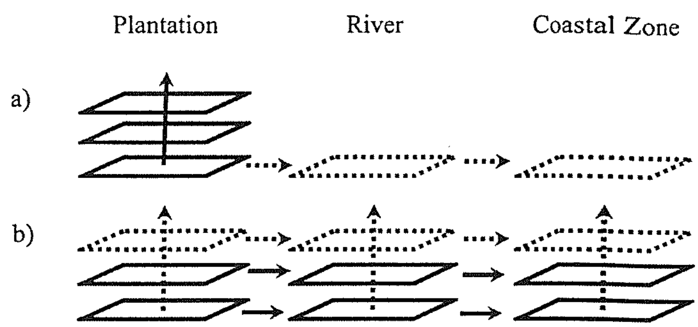


Figure 6.3 Alternative frameworks for understanding cause and effect scenarios within a sediment delivery environment

Whilst both approaches are well accepted within sediment delivery research, the second facilitates the identification of interactions between peripheral systems and provides a platform for calibration at key stages of the model. Characterised data presented in Chapters 3 and 4, constructs the second layer of the model (where layer 1 is the conceptual framework) and the third layer (parameterisation) is created from an improved understanding of cause and effect relationships over time and space based on the contextualisation of characterised data within the land – ocean sediment delivery system.

Within this framework, process interactions between the plantation and the river may be considered at a range of levels:

- Through assessing the feasibility of plantation sediment delivery contributing to the fluvial sediment budget
- Through assessing the feasibility of in-stream and non-plantation processes contributing to the fluvial sediment budget
- Through examining the sediment budget within the drainage basin context.

The following sections have subsequently explored the dimensions of a cause and effect relationship between plantation sediment delivery and the fluvial suspended sediment budget.

§6.2.1 Plantation sediment delivery to the fluvial system

Instantaneous sediment loading results indicated that a clear flux in the delivery of suspended sediment to the fluvial system took place via monitored drainage channels during the field season period (Figures 3.10 & 3.11).

It would subsequently be useful to extrapolate these data over time and space to investigate whether this tendency may have contributed to a significant increase in fluvial suspended sediment load between site A and site B. However, the nature of variability identified for the temporal distribution of drainage channel sediment loadings (Figure 3.12) and the high density and spatial variation of the channel network throughout the plantation unit (Figures 3.8 & 3.9), increases the risk of generating large errors in this process. Due to a lack of rainfall duration information, instantaneous sediment loadings may have been recorded at any point on the storm sedigraph and therefore it would be problematic to assume that they were representative of a general daily sediment delivery trend.

An alternative method for testing the feasibility of plantation sediment delivery to the fluvial sediment budget is through using rainfall intensity information to simulate potential sediment delivery scenarios. However, unfortunately there is little information relating to rainfall intensity for Belize and the majority of hydrological research uses values of mean rainfall per rainday to compare regional rainfall intensity values (e.g. Heyman & Kjevfve, 1999). Given the experimental nature of the feasibility study an acceptable alternative would be to use reported rainfall intensity values for similar humid tropical environments to test the model.

Rainfall intensities for humid tropical environments have been well reported in the literature (e.g. Hudson, 1981, Jackson, 1989, Walsh, 1996a). Hudson, (1981), identified that within the tropics 34.2% of rainfall is likely to occur at intensities of at least 25mm/hr – a threshold at which rainfall is considered to become erosive. However, intensities of 150 mm/hr are recorded regularly and occasionally intensities of up to 340mm/hr have been recorded (Jackson, 1989). Table 6.1, below illustrates rainfall intensities and associated characteristics reported in the literature for some humid tropical environments:

Table 6.1: Rainfall intensities reported in the literature for humid tropical environments

Rainfall Intensity	*Characteristics*	*Tropical Region*	*Publication*
25mm/hr	40% or tropical rain	All	Hudson, 1971/81
60mm/hr	22% of annual rainfall	Indonesia	Mohr *et al.*, 1972 (In Walsh, 1996a)
60mm/hr	22% of annual rainfall	Malay Peninsula	Dale, 1959 (In: Walsh, 1996a)
150mm/hr	Regular occurrence	All	Hudson, 1971/81
340mm/hr	Infrequent and likely to only occur for a few minutes	All	Hudson, 1971/81

To investigate the feasibility of interactions between the plantation and the river, rainfall intensities can be applied to daily rainfall totals to indicate rainfall duration periods. This information may be then used to identify whether delivery interactions are likely based on the maximum limits of any relationship, where plantation sediment delivery is simulated to account for the total fluvial sediment budget.

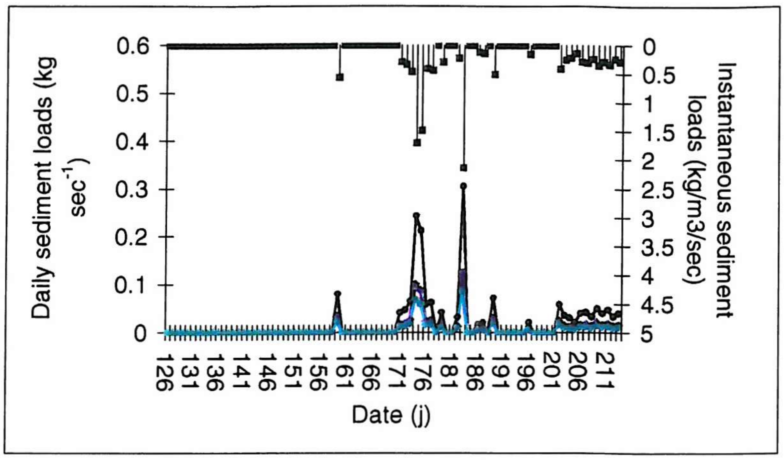
For modelling purposes rainfall intensities of 25mm/hr and 60mm/hr were used to obtain a regression relationship between daily rainfall totals and duration periods. Table 6.2 illustrates the structure of the plantation delivery network and the relative sediment loadings that would be required to comprise the total fluvial sediment budget of 200.3 tonnes.

Table 6.2: Plantation delivery characteristics and calculated sediment loadings for a direct relationship with the fluvial sediment budget.

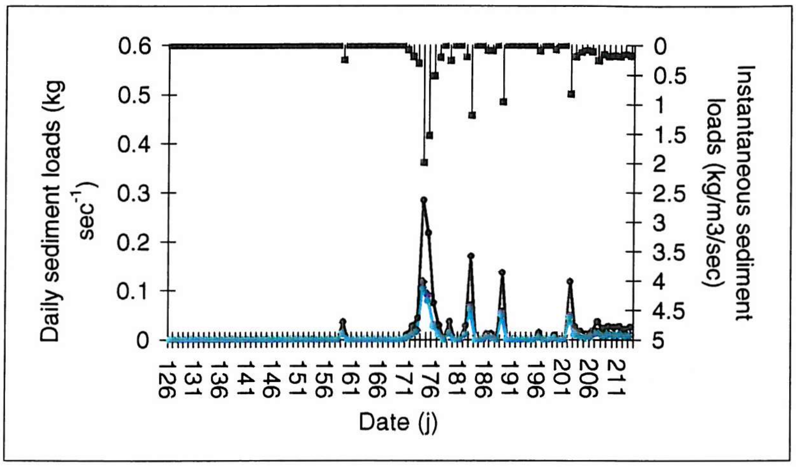
Plantation	*Channel Type*	*Calculated Seasonal Loading (kg)*	*No of Intersecting Fluvial Tributaries*	*Total Loading (kg)*	*% of budget*
8	Primary	3805.1	6	22830.4	15.6
8	Secondary	3682.6	4	14730.4	5.4
16	Primary	2830.2	6	16981.0	11.6
16*	Secondary	2739.0	11	30129.4	11.1
7	Primary	5365.8	8	42926.4	29.4
7*	Secondary	5193.0	14	72702.4	26.8
			Total sediment loading (tonnes)	200.3	100%

* Sediment loadings for plantations 16 and 7 were not monitored and were therefore derived from the relationship between primary and secondary loads on plantation 8

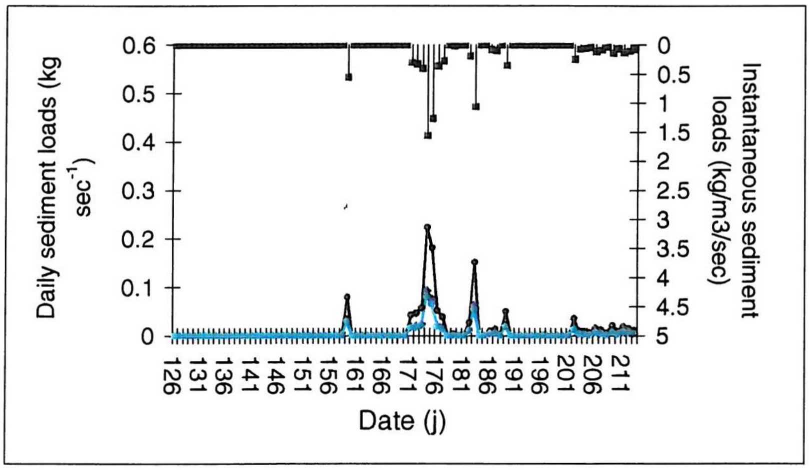
Simulated sediment loadings for rainfall intensities of 25mm/hr and 60mm/hr have been illustrated in Figure 6.4 (a-d) by dark blue and grey data points respectively and simulated rainfall duration periods have been presented in Figure 6.5 below. Sediment loads in kg sec^{-1} for each day of the field season have been presented on the first *y*-axis and instantaneous sediment loads recorded during the field season have been illustrated on the second *y*-axis.



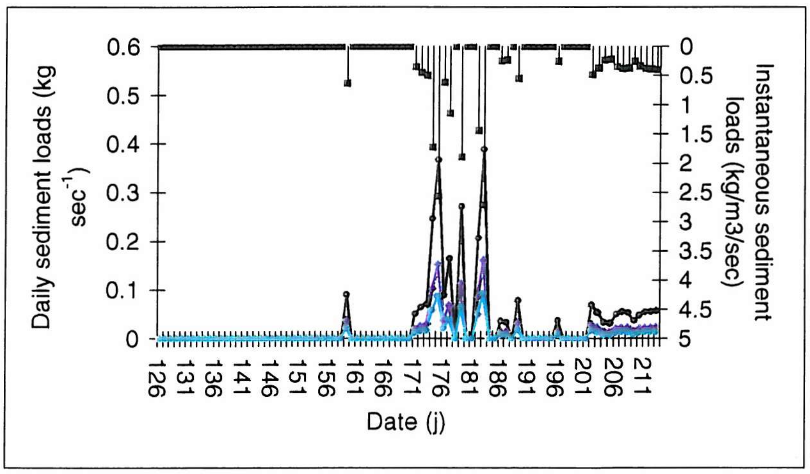
(a) Plantation 8: Primary Drains



(b) Plantation 8: Secondary Drains



(c) Plantation 16: Primary Drains



(d) Plantation 7: Primary Drains

Key:

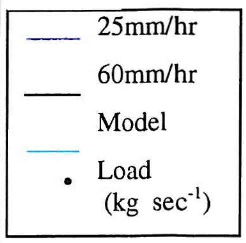


Figure 6.4 (a-d): Predicted daily sediment loads based on simulated rainfall duration scenarios

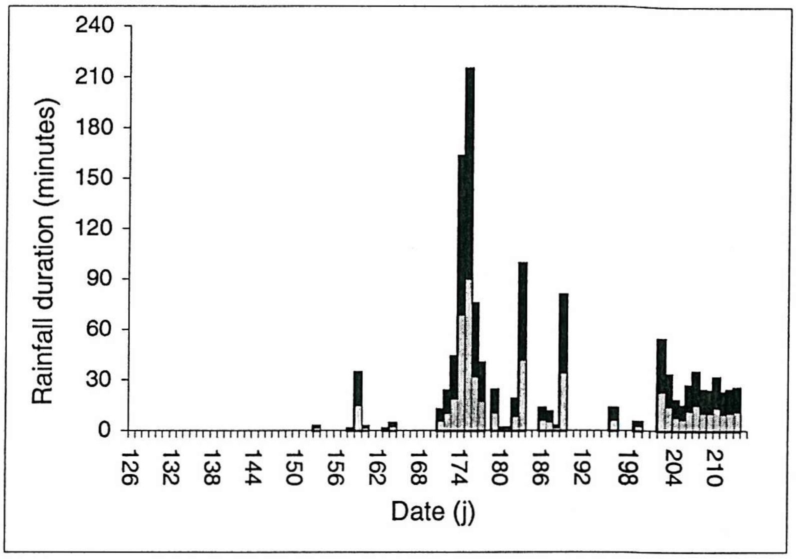


Figure 6.5: Simulated rainfall duration periods based on rainfall intensities of 25mm/hr (black) and 60mm/hr (grey)

A number of interesting patterns can be identified from this data. Firstly, daily sediment loads based on the intensity / duration simulations are within the same order of magnitude as the instantaneous sediment loads monitored for the same period in the field. At a crude level, this suggests that it would have been feasible under both rainfall intensity scenarios for the quantity of sediment identified in the fluvial sediment budget to have been derived from the plantation drainage channel network. However, further examination identifies that all simulated sediment loads are less than those recorded in the field.

Several factors may account for this.

- A high level of variability within the instantaneous sediment load data set may result in readings being unrepresentative of total daily sediment loadings.
- Sampling errors may have resulted in an overestimation of instantaneous sediment loads.
- Monitored channels may not necessarily have been representative of the sediment load of plantation drainage channels discharging to the fluvial system.
- A greater plantation sediment load may have been discharged to the fluvial system than accounted for by the sediment budget due to factors affecting in-stream deposition and storage of delivered material.
- Actual rainfall intensities may have been higher than those used in the simulation
- The assumption that rainfall intensity was uniform throughout the field monitoring period may have been inappropriate for the data set and subsequently have resulted in the underestimation of daily sediment loads

Given the high level of variability identified in Chapter 3 for three channels within the drainage network (Figure 3.11) it is quite probable that sediment loads recorded at different points on the storm sedigraph would reflect a wide range of loads. However, if plantation sediment delivered in drainage channels is assumed to be synonymous with the fluvial sediment budget it is unlikely that monitored sediment loads would be consistently higher than those predicted under different rainfall intensity-duration scenarios.

In view of this uncertainty, it is important to consider whether instantaneous sediment load data provided an accurate representation of the plantation delivery process and whether loadings simulated within the model also characterised the delivery process effectively.

An error assessment was not performed for drainage channel loading investigations due to the dynamic nature of the physical environment and the temporal constraints of the field monitoring programme. However the hand-held USDH-48 suspended sediment sampler used was calibrated for the fluvial environment and found to be an effective and accurate measure of SSC (§4.5.1).

If a reasonable degree of confidence is subsequently given to the monitoring process, discrepancies may be attributed to estimated loadings being unrepresentative of sediment discharged to the fluvial system. For example, if settling took place in the drainage channel between the monitoring location and the interfluve, or if the monitored drainage channels did not accurately represent (i.e. overestimated) the sediment load discharged from the rest of the network to the river. Alternatively settling, storage and deposition may have taken place within the fluvial system following the delivery of sediment from the plantation. This may have taken place if the delivered load was particularly dense resulting from the high SSC of drainage discharge and flocculation therefore lower settling velocity of fine - cohesive sediments (Gibbs, 1974). However, even if large quantities of sediment were deposited within the reach or held in temporary storage it is unlikely that the high discharge events recorded during the field season (Hadley, 1986) would not have re-suspended a significant proportion of this freshly deposited material.

An alternative explanation for the discrepancies between the identified and simulated loadings is that rainfall intensities used within the model did not represent intensity during the field season. If the model is run for rainfall intensities of 150mm/hr, which have been reported to occur occasionally throughout the tropical environment (Hudson, 1981) simulated daily loadings are still lower than instantaneous readings but are well within the same order of magnitude. However the rainfall duration periods calculated using intensities of 150mm/hr are considerably shorter than those observed during field research and therefore whilst recognised that resultant loadings provide the best fit for the model, they are not anticipated to be a realistic indication of model feasibility. It is therefore important that consideration is given to the assumption that a linear relationship existed between rainfall quantity and rainfall duration before the feasibility of the model is discussed. This has been investigated through applying a regression relationship between rainfall quantity and duration to the data set. Figure 6.6 illustrates the relationship identified between the two variables for a similar humid tropical environment where rainfall totals were within the same range as those recorded for Belize (Oguntoyinbo & Akintola, 1983).

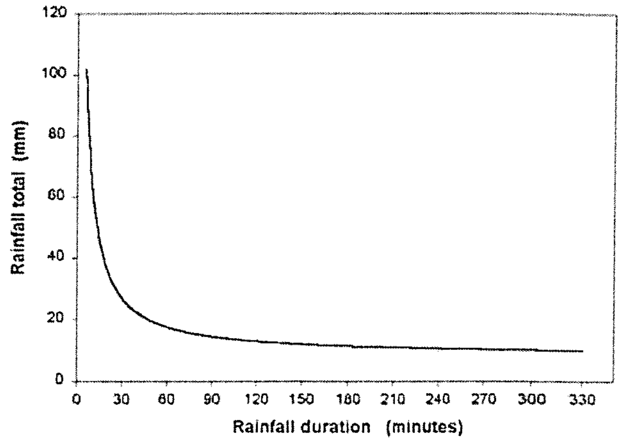


Figure 6.6: Regression relationship between rainfall totals and rainfall duration (Adapted from Oguntoyinbo & Akintola, 1983(pp70))

The inverse regression line may be summarised by the following equation:

$$x = 8.06 + (a/y) \tag{6.1}$$

Where x = daily rainfall duration and y = daily rainfall totals (mm) and a is a constant (a=562.6).

Whilst the model represents the relationship between the two variables more accurately than through linear regression, when applied to the data set it has the potential to generate large errors in sediment loadings for low rainfall days (i.e. less than 1mm). Low rainfall values recorded for the tropics are equally likely to have been the result of a short but heavy shower or a long continuous period of drizzle and subsequently the potential for error in duration estimations from low rainfall totals is considerable (Hudson, 1981). Therefore, prior to applying the regression relationship to the model, low rainfall days (less than 1mm) were removed from the data set to avoid distortion. The resultant rainfall duration periods have been illustrated in Figure 6.7.

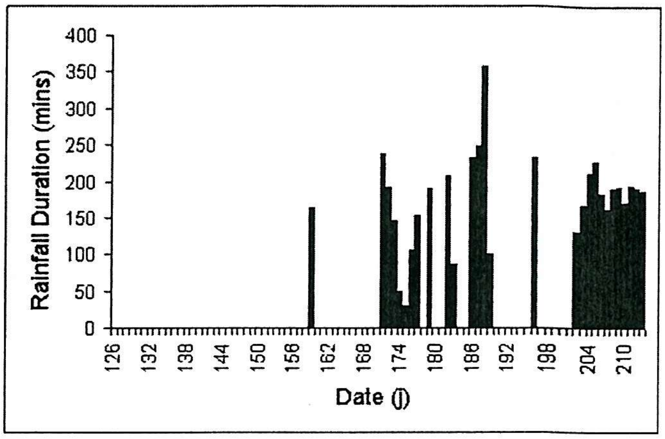


Figure 6.7 Rainfall duration periods calculated using an inverse regression relationship for a similar environment

The simulated sediment load data sets have been illustrated in Figure 4.6 (a-d) by the pale blue points.

Predicted loads were within the same order of magnitude as those simulated under the linear intensity – duration relationships and reinforced the feasibility of plantation sediment delivery accounting for the fluvial sediment budget. Again, simulated loads were lower than instantaneous readings. It is suggested that either monitored channels were not explicitly representative of plantation drainage channel discharge to the fluvial system or that a greater plantation sediment load was delivered than was accounted for in the sediment budget due to in-stream processes such as deposition and storage.

An alternative method for identifying the feasibility of banana plantation agriculture as a driver is through calculating the rate of plantation soil erosion that would have taken place to produce the same quantity of sediment as the budgeted load. The rate of soil erosion for the plantation unit was calculated to be 1.6 tonnes/hectare/year, assuming that the field season rate represented an annual constant. When expressed relative to catchment erosion, calculated from recorded basin sediment yield over basin area, this rate is approximately ten-fold the basin average of 0.17 tonnes/hectare/year. The calculated rate of soil erosion for the plantation unit is well within erosion rates reported for similar agricultural environments within the tropics (e.g., Kirby & Morgan (1980), Lal, (1983), Lal, (1990), Heyman & Kjerfve (1999)).

§6.2.2 A catchment perspective

Through examining plantation sediment discharge to the fluvial system under different delivery scenarios the feasibility of the plantation as a driver has been assessed. However, to understand delivery scenarios within a fluvial context the process needs to be addressed at the catchment level so that fluvial drivers may be given appropriate weighting within the sediment delivery framework.

The position and representativeness of the plantation unit relative to basin size may be seen in Appendix 6. At the catchment scale, it is unlikely that a 16% increase in sediment yield would take place within a downstream reach draining only approximately 2% of the basin (300 sq km), unless significant activity was taking place within the river or its delivery system (Walling (1984), Walling (1988)). However, suspended material may be derived from numerous sources, ranging from in-stream erosion and re-suspension to processes operating on, or within, the banks and river floodplain (Grimshaw & Lewin, 1980). This section will subsequently consider the sediment budget from a geomorphological perspective where the interaction of plantation drivers will be considered relative to alternative sediment sources within the fluvial system.

Sediment delivery drivers within the monitored reach:

- Floodplain and bank erosion processes

The opposite bank to the banana plantation unit was predominantly dense un-disturbed tropical broadleaf forest at the time of field research (Plate 6.1). Soils associated with this vegetation cover have been reported to be "moderately erodible" but at risk from significant erosion once disturbed (Hartshorn, *et al.*, (1984), Heyman & Kjerfve, (1999)). Erosional processes operating within this system were likely to be minimal due to the low-gradient of the land surface and the dense multilayer natural canopy protecting the soil from rain-splash and other processes associated with a high energy system (Lal, 1990). The banks on this side of the reach were generally of low slope angle and vegetated with coarse grasses and shrubs (Field Notes, 1998). The sediment delivery system was subsequently anticipated to be largely ineffective on this bank due to the lack of intersecting fluvial tributaries and the dense vegetation coverage. Reported sediment transport rates for tropical forested catchments vary considerably, but studies carried out in Malaysia and Indonesia where rainfall characteristics are similar to those identified for Belize, identified rates of between 0.2 and 0.6 tonnes/hectare/year (Sim & Hock, (1986), Lal, (1990)).

In contrast, erosional processes operating within the plantation unit on the south bank were likely to have been significant. Erosion rates for tropical banana plantation areas have been reported to be as high as 92.5 tonnes/hectare/year on some slopes in Taiwan and between 0.7 and 22.0 tonnes/hectare/year within plantations experiencing normal management practice (Liau & Wu, 1987). Unlike the broadleaf forest, banana plantations provide little protection from rain-splash erosion and management practices such as the construction of drainage networks are likely to

Plate 6.1: Drainage channel erosion scars following a period of heavy rainfall activity

Plate 6.2: An area of plantation 7 washed away during large storms in November 1997

accelerate the mobilisation of material and its delivery to the fluvial system. The use of the river floodplain for plantation development is well understood to increase the risk of flooding and erosion events within the farm area, having occasionally disastrous consequences (Pers. comm., Fyffes, Ltd. & B.G.A., 1998). However, the economic incentives of utilising this fertile land for production have tended to outweigh the risks associated with fluvial intrusion and erosion (Pers. comm., B.G.A., 1998).

Field observations during the dry season period in Belize identified that significant scaring had taken place within the plantation unit from past high discharge events (Plate 6.1). In addition, the partial incision of the river into the plantation unit during storms in November 1995 resulted in the deposition of fluvial sediments in drainage channels as river water cut through the plantation drainage network. It is anticipated that such material was remobilised during the early part of the 1996 rainy season and re-delivered to the fluvial system, hence illustrating the role of the banana plantation unit as a temporary store as well as a sediment source. The south bank of South Stann Creek was identified in places to have interacted significantly with the banana plantation unit during past high discharge events. During these events locals reported that the river at peak discharge flooded into the plantation unit and cut through drainage channels as a more efficient course (Plate 6.2). However during the field season period, discharge did not reach these extremes and the river flowed along its regular channel. The river bank on this side of the channel was moderately vegetated with coarse grasses and occasional shrubs, although in parts significant bank erosion appeared to have taken place and banana plants grew directly on the river terrace. It is likely that these exposed banks would have been a source of sediment within the monitored reach, however no major changes were observed to bank form in accessible areas during the field season period.

To perform further calibration of the characterised model research investigations would need to focus significant attention on this interface, especially during episodic high discharge events where the magnitude and scale of process interactions is likely to be considerable. Plantation – river interactions at this interface serve to emphasise the contrast between the north and south banks of the monitored reach and illustrate the scale of natural versus accelerated processes operating within the system.

- In-stream activity:

In addition to the potential for suspended material to be derived from the floodplain and river-banks, it is important to consider the potential for in-stream processes within the monitored reach to drive the budgeted increase in suspended sediment load.

Processes that are likely to have contributed to this are in-stream erosion and the re-suspension of material in storage. Within a geomorphological framework, erosional processes within a downstream reach of a catchment are usually identified to contribute only a small percentage of suspended material to basin sediment yield (Walling, 1988). Indeed, it is well recognised that rivers tend to deposit a significant proportion of their load in downstream reaches prior to their discharge to the sea (Walling, 1993). Within this context, for in-stream processes to predominantly drive a 16% increase in sediment yield the nature of activity within the budgeted reach would need to have been considerable. Given the size of the budgeted reach (only 2% of the catchment) processes such as the corrasion of submerged banks, erosion of the channel bed and the removal of material held in storage would need to have taken place at a rate disproportional to the rest of the downstream section for in-stream processes to have driven such a significant change in sediment yield. However, the profile and characteristics of the monitored reach were not significantly different from those identified upstream as far as monitoring site W (Adjacent to the meteorological station: Figure 3.6) and downstream as far as the estuary.

In-stream processes are however, likely to have interacted with the sediment flux between site A and site B and whilst not anticipated to have been a significant driver of change, still require consideration. This may be investigated through examining temporal patterns in sediment dynamics between the two monitoring sties and the plantation to identify whether significant events were concurrent with discharge and fluvial events or whether climatic and agricultural drivers were a more dominant force of change. Consideration has been given to these in §6.2.3.

§6.2.3 System dynamics

Consideration was given to suspended sediment and discharge dynamics in Chapter 4, however it is now important to consider the extent to which the flux of sediment between site A and site B may have been driven by interactions between the plantation and the river.

Figure 6.8 illustrates some interesting features of sediment load upstream and downstream of the plantation unit during the field season. Sections A-E are periods during which drainage channels were discharging suspended material to the fluvial system. Features of note have been summarised in Table 6.3.

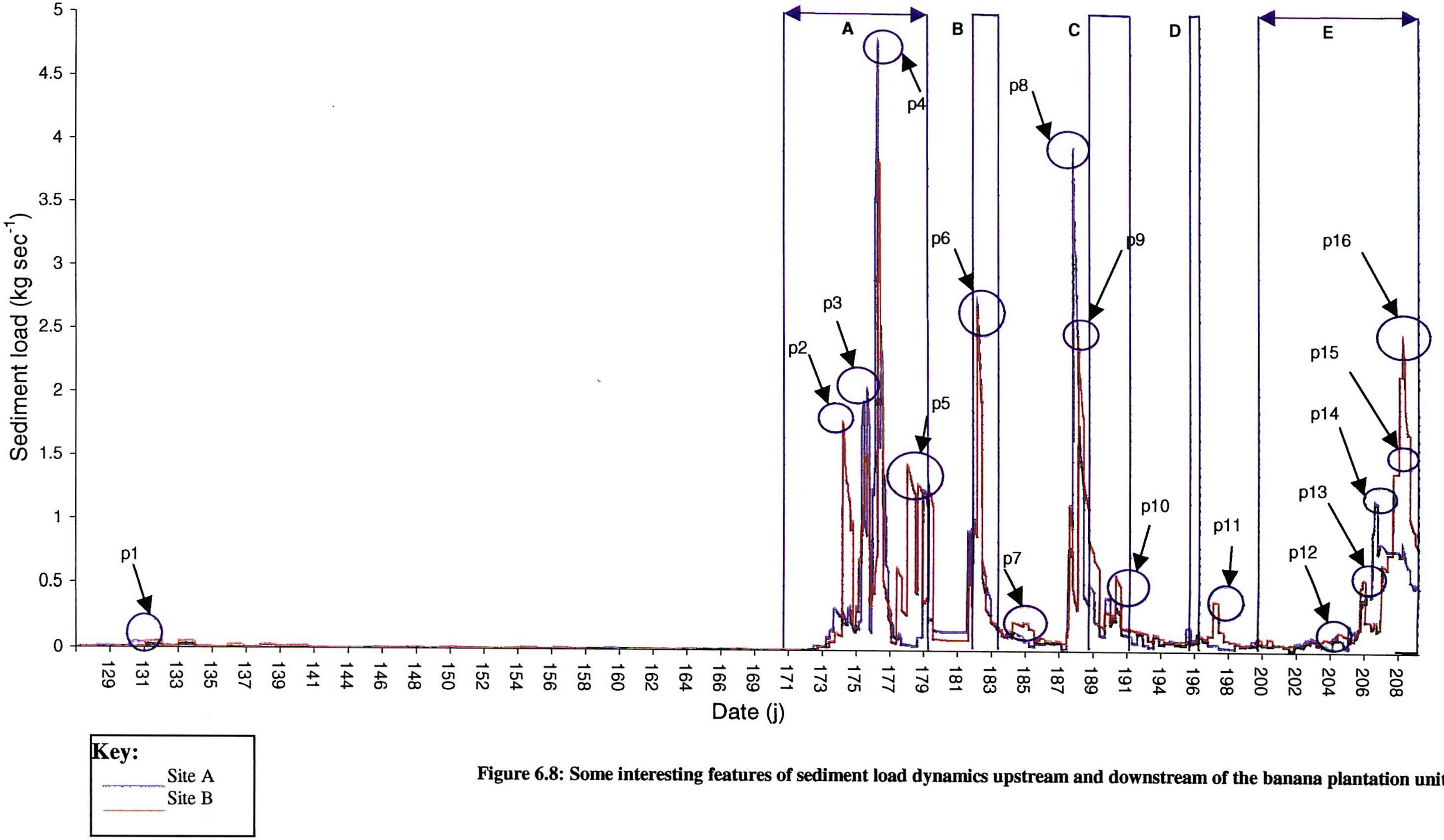


Figure 6.8: Some interesting features of sediment load dynamics upstream and downstream of the banana plantation unit

Table 6.3: Interesting features of sediment load dynamics upstream and downstream of the plantation unit

Feature	*Dates (j)*	*Observations*
p1	130-132	A series of peaks indicative of a trend of high sediment concentrations between 129 and 141(j) during a period of low discharge and little climatic activity.
p2	174-175	A significant peak in sediment load at site B despite little activity at site A
p3	175-176	A flux in sediment load through the system with load being greater at site A
p4	176	A second flux in sediment load through the system with load at site A exceeding site B in the first instance with a series of smaller peaks at site B in the second instance.
p5	178-180	A period of high sediment load at site B whilst sediment load a site A is comparably low
p6	182	A period of high sediment loads at sites A and B with a small decline in sediment load as the flux moves downstream
p7	184-186	A period of low activity where sediment load at site B exceeds load at site A
p8	188	A high sediment load peak at site A followed by a sequence of lower sediment load peaks at site B
p9	188	A lower sediment load peak at site B than the seemingly related peak at site A preceding it (see above)
p10	191	A period of low activity where sediment load at site B exceeds load at site A
p11	197	A period of low activity where sediment load at site B exceeds load at site A
p12	204-205	A period of moderate plantation activity but low discharge where sediment load at site B exceeds load at site A
p13	206-207	A small peak in sediment load at site B preceded by a lower peak at site A
p14	207	A moderate peak at site A associated with a period of increased discharge followed by a decline in sediment load at site B
p15	208	A significant peak at site B associated with notable discharge and climatic activity with a decline in sediment load at site A
p16	208	A second peak of significant load at site B associated with notable discharge and climatic activity despite relatively low loadings at site A

It is clear from Figure 6.8 that sediment loading dynamics are principally focused on four peaks during the field monitoring period, namely, p4, p6, p8 and p16. The general flux of sediment between site A and site B appears to distort at a number of stages where processes such as deposition and storage of material recorded at site A have been identified to take place within the reach during different phases. Other periods are characterised by the accumulation of sediment between the two sites, taking place during some instances in accordance with discharge dynamics and during others in a less distinguishable pattern that may be related to delivery or re-suspension mechanisms.

During the dry season sediment load dynamics were minimal, apart from the period between 129 and 141(j) during which there was a period of minor activity at sites A and B (p1). However at this time river discharge was low and there was no rainfall indicating that there was little energy within the system to promote the movement of the identified flux or the delivery of mobilised sediment to the fluvial system. A number of factors may explain this feature and have been considered in §4.5.4. However, it is also possible that this trend may have been related to sampling problems associated with initial set up of the monitoring programme and thus it is reassuring that it only accounts for a very small proportion of sediment load at both sites. Interactions between the plantation and the river at this stage were predominantly related to irrigation activity (Figure 3.12) where river water was siphoned into pump houses that fed the irrigation network.

During period A, river discharge increased significantly and considerable rainfall fell in a number of storms over the plantation area. Suspended sediment delivery from the farm to the river was identified in drainage channels and this period was considered by the banana industry to be the beginning of the rainy season and practices were modified accordingly (Pers. comm., B.G.A., 1998). The first noticeable period of activity within the fluvial system was peak p2 between 174 and 175(j) where sediment load at site B exceeded that at site A significantly. Velocity and discharge dynamics indicate that this peak was most likely to have been associated with the same flux of water as the earlier peak on 174(j) at site A. This suggests that between site A and site B a significant input or re-suspension of sediment took place on 174(j). Further examination of suspended sediment delivery dynamics within the plantation unit (Figure 3.9 & Figure 3.10) identified that on 174(j) considerable activity was taking place within the plantation drainage system. Alternative sources of suspended sediment within the fluvial system may also have accounted for this pattern, especially given the coincidence of this peak with discharge activity.

On 175 and 176(j) the reverse of this trend is apparent where sediment load at site A exceeds that of site B during two sediment fluxes (p3 and p4) that coincide with respective peaks in discharge. These fluxes suggest that sediment is either being lost from the channel or entrained within the channel between sites A and B. A number of factors may explain this. Firstly that during periods of increased discharge some over-bank flow may have taken place within the reach especially in areas where bank collapse and disturbance to the channel profile had occurred previously and river terraces had formed (§6.2.2). The associated reduction in velocity that would have followed such over-bank activity may have resulted in widespread deposition during periods of increased discharge (Ashbridge, 1995). An alternative explanation may be the entrainment of sediment in exposed tree roots within the channel although this is less likely to take place during periods of increased discharge. Sampling error should also be considered as a possibility.

The area identified by section p5 illustrates a period during which there was a significant increase in sediment load between site A and site B. This activity on 177 and 179(j) also corresponds with two peaks in discharge. During this period rainfall was taking place within the plantation area and suspended sediment was being delivered to the fluvial system. Activity at site B was contrasted with very little activity at site A until the end of 179(j) whereupon a peak in sediment load was identified. The peak at site A was not however related to a similar discharge pattern and a number of factors may explain its timing. Firstly that plantation expansion activity upstream of site A was disturbing the sediment dynamics of the river at this stage and resulted in the re-mobilisation of fluvial or plantation sediments. Secondly, that bank armouring (discussed in §4.5.4) was preventing previously weakened banks from collapsing until discharge levels dropped and banks failed. Thirdly, that during this period of rainfall within the lower part of the Stann Creek Catchment that alternative sediment delivery or bank collapse mechanisms took place upstream of site A.

Unlike section p5, section p6 identifies a peak that took place in association with an increase in discharge. Sediment load at site B was marginally higher than that at site A but there was little difference between the two. Sediment delivery was identified during rainfall activity on the plantations although the rainfall totals on 182(j) and the preceding three days were low suggesting that the level of interaction between the plantation and the river may have been less.

Between 185(j) and 187(j) there was a small increase in sediment load (p7) between sites A and B. Again this may be accounted for by bank armouring within the reach on the falling discharge limb, as there was no drainage on the plantation during this time. However between 188 and 189(j) the rising discharge limb was accompanied by an increased sediment load at sites A and B with site A exceeding that site B (p9). Again this may have been potentially related to over-bank activity within the reach and the deposition of sediment on the floodplain due to a decrease in velocity and therefore the carrying capacity of the water body. As discharge levels fell, rainfall activity took place within the plantation unit and sediment delivery to the fluvial system was identified. The maintenance of high sediment loads at site B may be accounted for by this.

Peak p10 took place during a minor increase in discharge on 191(j) and was characterised by a higher sediment load at site B than at site A. This, along with peak "p11" may have been a function of in-stream activity between the two sites such as the re-mobilisation of sediment within the channel or it may have been the result of armouring, given that it took place on the falling discharge limb.

Between 204(j) and the end of the field season a continued period of rainfall and subsequently drainage activity took place on the plantation unit. This was accompanied by a notable but disturbed relationship between upstream / downstream sediment load within the reach. Peak p12 illustrates the beginning of this trend where sediment load at site B exceeds that of A until peak p13. However on 207(j) with an increase in discharge, the pattern was reversed and sediment load at site A was notably higher than that at site B. This was identified to be slightly anomalous when compared with previously detected patterns due there apparently being little influence of plantation sediment delivery activity on the load at site B. Indeed, although over-bank activity may have explained earlier losses between the two sites it is not anticipated that this was a predominant factor due to the comparably low discharges recorded at this stage. Apart from sampling error being a possibility, this pattern was difficult to explain.

On 208(j) peaks p15 and p16 appeared to be more in accordance with the trends identified for periods of drainage channel activity and precipitation on the plantation unit. The sediment load at site B exceeded that at site A considerably and it is anticipated that this was related to plantation opposed to fluvial drivers due to the level of discharge activity remaining relatively constant. If these peaks are assumed to be related to process interactions between the plantation unit and the fluvial system they illustrate that no hysteresis in sediment mobilisation and delivery had taken place, hence suggesting that the supply of sediment exceeded the capacity of the climatic system to remove it. This balance between climatic drivers and sediment supply would be expected for a sustainable plantation environment, apart from in extreme conditions.

The repetition of a link between plantation sediment delivery and fluvial sediment accumulation in the patterns observed above strengthens the feasibility of a cause and effect relationship between the two. It should however be noted, that a wide range of factors may account for such changes in sediment mobilisation and delivery dynamics (Grimshaw & Lewin, 1980) and therefore, whilst an analysis of sediment load dynamics is useful for characterising the system, further calibration and more detailed sampling procedures would be required for interactions between the two systems to be explored further.

§6.3 Interactions between the plantation and sediment dynamics within the near-shore coastal zone

A characterised framework for conceptualising interactions between the plantation and the fluvial system has been constructed. The plantation unit has been identified to interact significantly with catchment sediment delivery to the fluvial system, although the extent and boundaries of this process require further definition over time and space. However, it is now important to position agro-hydrological processes within the wider LOICZ framework to understand interactions between the plantation and the fluvial suspended sediment flux from the estuary to the Belizean coastal zone.

§6.3.1 Interactions in time and space between plantation and coastal sediment dynamics

Ideally to identify temporal and spatial patterns in the sediment flux from the plantation to the coastal zone, spatial estimates of coastal SPM would be generated over a high-resolution time series for integration with agro-hydrological drivers. However, Chapter 5 explored the possibilities for achieving this using remotely sensed data and identified that whilst the theory suggested an optimal solution for monitoring, a number of limitations restrict its effective utilisation for LOICZ research in Belize at the present time. It was identified that the most effective technique for identifying spatial and temporal patterns in coastal SPM dynamics was integrating a calculated and simulated time series of fluvial suspended sediment yield with interpolated secchi transparency (as a surrogate for SPM) for within the Stann Creek lagoonal system. Logistical constraints, however, restricted the monitoring of secchi transparency during periods when large sediment loads were discharged from the river system to the coastal zone and as a result the identification of sinuosity between the two systems was limited to the temporal integration of plantation – river processes with the time series of catchment sediment delivery to the coastal system.

§6.3.2 Interactions between the plantation system and catchment sediment yield to the coastal zone

In §6.2 the plantation system was identified to interact with and initiate change throughout the monitored reach of the fluvial system. However, it is now important to consider how agro-hydrological interactions may have influenced the temporal and spatial dynamics of yield discharged from the basin. Whilst interactions with monitored yield at downstream site B have been considered in §6.2, processes have not been discussed within the context of plantation interactions with basin yield. Indeed, although sediment yield at downstream site B has been used as the basis for catchment yield prediction (§5.5.1) the potential for subsequent interactions becomes magnified when change is transferred from within the fluvial system to that at the interface between the fluvial system and the coastal zone.

In particular it is interesting to consider how plantation interactions modified the temporal dynamics of the fluvial suspended sediment flux to the coastal zone. A number of periods have been identified within §6.2.3 where changes to sediment load have taken place in association with either discharge or local forcing functions. Different drivers of sediment delivery from the fluvial system to the basin outlet will affect the timing and behaviour of the emanating coastal sediment flux from the basin (Milliman & Meade, 1983).

Fluxes of sediment delivery driven predominantly by hydrological forcing on the plantation unit (§6.2.3) have been identified and listed in Table 6.4 below:

Table 6.4: A summary of isolated suspended sediment fluxes associated with agro-hydrological forcing

Date	*Characteristics*	*% Of plantation input to basin yield*	*Approximate duration (hrs)*
174-175(j)	Significant increase in fluvial sediment load between sites A and B. Rainfall and drainage channel activity within the lower part of the catchment and the plantation unit. Low – moderate discharge (8-13 m^3/sec)	4.1	35:15
177-179(j)	Significant increase in fluvial sediment load between sites A and B Rainfall and drainage channel activity within the lower part of the catchment and the plantation unit. Low – moderate discharge (8-13 m^3/sec).	8.6	38:30
186-187 (j)	Rainfall and drainage channel activity within the lower part of the catchment and the plantation unit. Low – moderate discharge	0.3	48:00
189-190(j)	Significant increase in fluvial sediment load between sites A and B. Rainfall and drainage channel activity within the lower part of the catchment and the plantation unit. Low - moderate discharge (7-15 m^3/sec)	3.1	48:00
204-209(j)	Significant increase in fluvial sediment load between sites A and B. Rainfall and drainage channel activity within the lower part of the catchment and the plantation unit. Low - moderate discharge (3-8 m^3/sec)	19.7	144:00

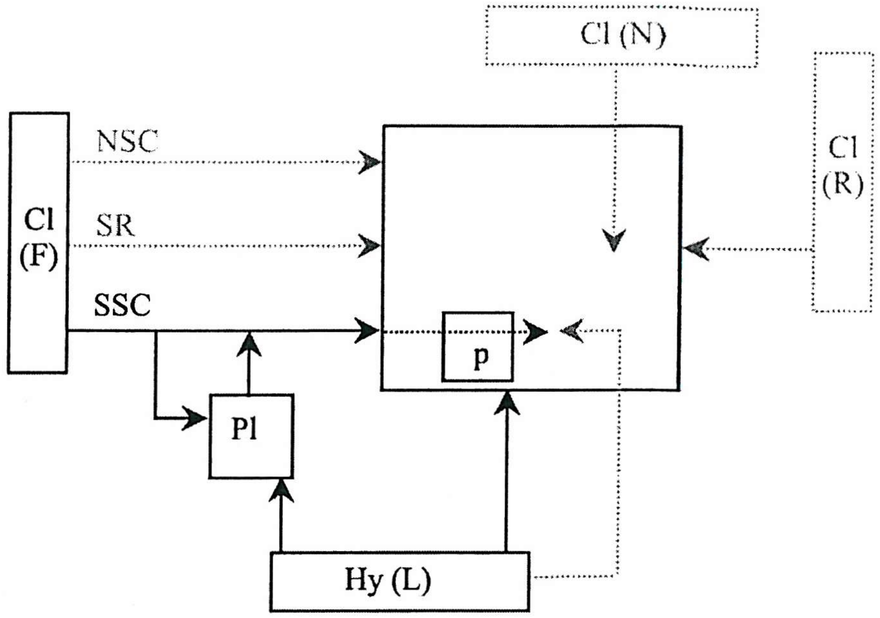
These periods illustrate fluxes when the role of hydrological forcing was particularly clear due to the interplay of rainfall, discharge and sediment delivery on specific dates. However they serve to illustrate that system change as a result of interaction between local hydrology and the plantation system was not restricted to the monitored reach, but altered the temporal pattern of conveyance of fluvial material to the coastal zone.

It should also be considered that the position of the plantation network within the fluvial system is likely to have had a profound influence over the inter-relationships between agro-hydrological drivers and sediment yield from the basin outlet, as the closer the proximity of the plantation to the river and its estuary, the greater the risk of agro-hydrological events within the lower reaches of the catchment distorting the fluvial sediment flux. However, such inter-relationships are location specific, where factors such as slope angle and soil type present important controls over process interactions.

Local hydrological drivers are clearly influenced by interactions between processes operating within plantation system and catchment sediment yield. However, the value of information attained from analysing plantation interactions with basin yield was limited by the need to understand subsequent changes to the delivery process within the coastal zone. Initial understanding has been enhanced by conceptualising material conveyance within the comparatively unilateral nature of the fluvial delivery system, however, there is a persistent need to progress further towards identifying how temporal fluxes initiated on the plantation are translated into and become incorporated within spatial pulsing events at the river mouth and coastal sediment system dynamics.

§6.3.3 A preliminary framework for interactions between the plantation system and the coastal – ocean sediment flux

The multidirectional nature of processes at the land – ocean interface serve to distort the spatial and temporal dynamics of fluvial sediment fluxes (IGBP, 1994). Thus, whilst the components of the delivery pattern may be understood within the drainage basin system, forcing from other dimensions render the isolation of specific anthropogenic influences on the coastal zone challenging. Difficulties with the spatial and temporal monitoring of sediment fluxes within the near-shore coastal zone of Belize coupled with the importance of discriminating change driven by plantation interactions necessitate the construction of a preliminary framework within which processes may be conceptualised (Figure 6.9).



Where, "Cl" = Climatic forcing via "F", the fluvial environment, "N", the northern coastal system and "R", the outer reef system. "Hy (L)" signifies local hydrological forcing within the plantation (Pl) and near-shore coastal zone. The characteristics of the emanating plume are represented by "p". "SSC" represents the river system South Stann Creek and SR and NSC represent Sittee River and North Stann Creek, respectively. Fluxes in grey have been included to contextulise the model and have been discussed further in §6.4.1.

Figure 6.9: A model for understanding agro-hydrological forcing within the land-ocean driver framework

This framework offers a basis for improved understanding in two key areas. Firstly, sediment yield monitored at site B may contain errors with respect to the flux of sediment ultimately discharged from the basin. Despite the close proximity of site B to the basin outlet it is possible that bio-geomorphological interactions between mangroves and the fluvial sediment flux (Zisman, 1992) may have taken place within the remaining portion of the reach and subsequent understanding derived from the sediment yield time series about plantation – coastal zone interactions will be devoid of this dimension. Secondly, it is important because there is a need to understand how agro-hydrological and fluvial systems and their respective drivers are interlinked with the coastal sediment flux so that ultimately effective monitoring and modelling of process change through the system may be achieved.

In particular Figure 6.9 illustrates how climatic drivers operating within the plantation system may alter agro-hydrological forcing from the land to the ocean. However, at the same time it is also clear that the same drivers may interact with conditions within the coastal system. Table 6.5 illustrates the potential for change within the land-ocean continuum for different terrestrial and oceanographic forcing scenarios.

Table 6.5: A consideration of agro-hydrological / coastal interactions for different forcing scenarios

Terrestrial Forcing Potential			*Emanating Plume dynamics*			*Oceanographic Forcing Potential*	
	Discharge 1)	*SSC* 2)	*Velocity potential* 3)	*Temporal* 4)	*Spatial* 5)	*Local system* 6)	*Northern lagoon & Reef systems* 7)
a) Fluvial events	High	High	High	Driven by fluvial system?	A function of 1-7	A function of local climatic drivers	Ocean currents and variations in SPM will alter the dynamics of a4) & a5)
b) Agro-hydrological forcing (Local system)	A function of a)	High	A function of a)	Driven by local hydrological events?	A function of 1-7	Disturbed/ Rough	Ocean currents and variations in SPM will alter the dynamics of b4) & b5)
c) Fluvial & agro-hydrological interactions	High	High	High	Interactions between a) and b).	A function of 1-7	Disturbed/ Rough	Ocean currents and variations in SPM will alter the dynamics of c4) & c5)

The conveyance of change from the plantation to the coastal zone will subsequently be affected by interactions between regional and local conditions and forcing from terrestrial and oceanographic systems. Interrelationships between these components will facilitate the discrimination of interactions at specific times between the agro-hydrological system and the coastal dimension of the fluvial sediment flux. However, the translation of change in space from the fluvial to the coastal system will be controlled by a multitude of drivers, hence rendering the identification of plantation drivers more challenging in this respect.

It is clear that significant calibration of the system will be required to understand the dynamics of interaction between sediment delivery from the plantation and sediment dynamics within the coastal zone. In particular, periods of significant agro-hydrological interaction need to be investigated against the capability of the coastal system to transport delivered sediments. The calibration of this preliminary framework will again rely on the monitoring of spatial and temporal fluxes within the coastal system, where estimates of water transparency will require conversion to quantitative data on coastal SPM dynamics, before plantation interactions with the coastal-ocean sediment flux can be effectively understood.

§6.4 A "LOICZ" sediment delivery continuum?

Chapter 2 discussed the importance of conceptualising processes through the LOICZ framework to promote integration of anthropogenic, geomorphological and biogeomorphological systems. Studies of process interactions between system components have characterised a land-ocean sediment delivery continuum, however it is now important to identify the specific mechanisms that drive the continuum and how these are likely to interact given future spatial and temporal change.

§6.4.1 The role of drivers

System drivers have been divided between climatic, agro-hydrological and agro-economic forces that interrelate to mechanise the continuum of sediment from the plantation to the coastal zone. Whilst the overall system is driven by climatic forcing (Figure 6.10) at the local scale it is driven by agro-hydrological and agro-economic forcing (Figure 6.11).

Climatic forcing may be understood to control interactions between precipitation, hydrology and geomorphology within the catchment over time and subsequently promote the mobilisation of material from a local driver (banana plantation agriculture) via the fluvial and estuarine systems to the coastal zone. The length of time associated with the different transfer processes within this continuum will increase as it moves through the system from the plantation to the river to the coastal zone.

At the same time, the agronomic and agro-hydrological systems may be conceptualised as local drivers that interact fluidly to sustain a profitable growing environment. Whilst climatic forcing is well recognised to be the dominant control over the land-ocean sediment flux – especially within the tropics, the extent to which this forcing takes place within the plantation environment is dependent on the interrelationships between components detailed in Figure 6.11.

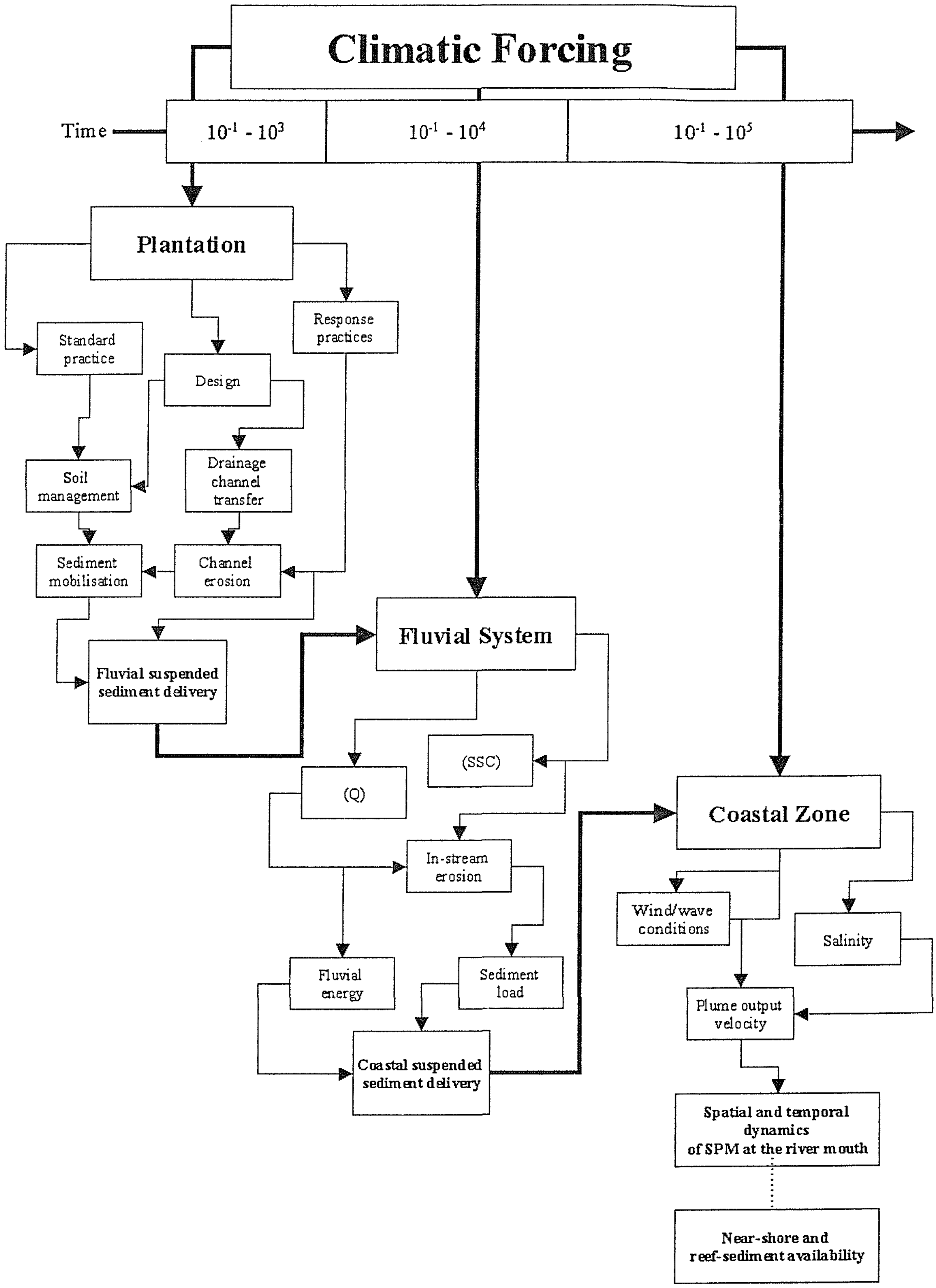


Figure 6.10: Interactions between the plantation and the coastal zone following climatic forcing

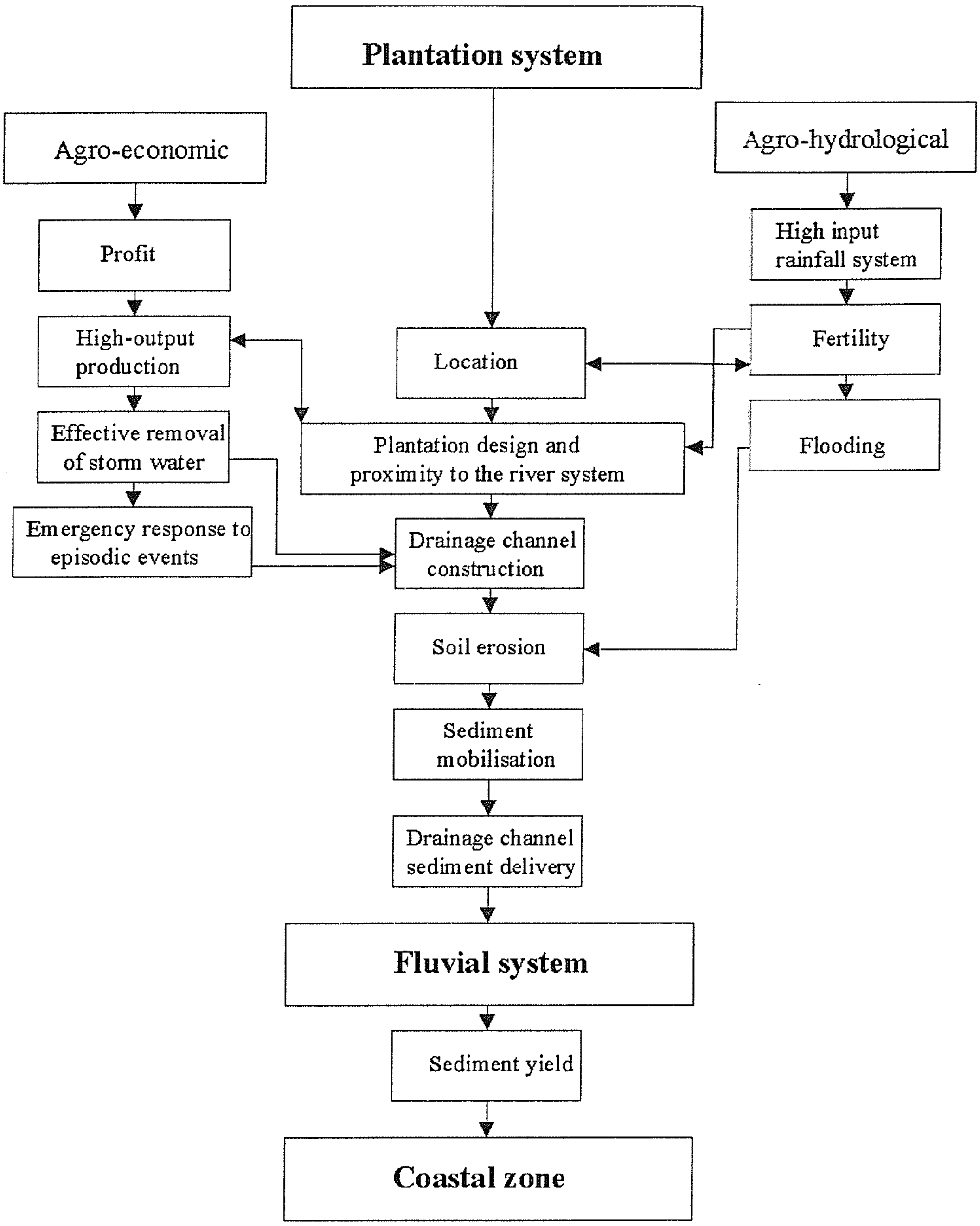


Figure 6.11: System interactions following agronomic and agrohydrological forcing

§6.4.2 Plantation drivers over time and space

The value of using experimental plots is well recognised within LOICZ research for they facilitate the extrapolation of findings and frameworks to parallel systems (IGBP, 1995). However, this scaling up may be inappropriate for the Belizean banana industry and thus it is essential that the ramifications of change within an extended time frame and within a wider and more varied spatial area be considered.

Spatial change

The experimental plantation area was located within the southern coastal plains of Belize, where the majority of the banana industry is concentrated. The plantation unit was closer to the mouth of the river system than any of the other banana plantations within the region (Figure 3.2). Most commercial farms were located within the lower reaches of drainage basin systems on the fertile alluvial soils. A large part of the industry is located on Mango Creek and field observations suggested that the nature of interaction between the plantations and the river was significant. Particular indicators of such interaction were the location of farms on the river floodplain and the re-working of the manageable farm area around areas of plantation incised by fluvial intrusion. Agricultural practices were relatively uniform across the industry, however variations were noted in the spacing of drainage channels and the intensity of re-working following storm events (Pers. comm., B.G.A., 1998). These variations were in part a function of local geomorphology and in part that of individual management preferences. Mean annual rainfall totals have been reported to increase from north to south in Belize (National Meteorological Service, Belize, 1998c), and the Toledo district in particular, has experienced rainfall totals equivalent to those recorded in tropical monsoon areas where some of the highest global rainfall totals have been reported (Heyman & Kjerfve, 1999).

Spatial variations are definitely present on a plantation by plantation basis in Belize, however two characteristics remain consistent, the location of plantations adjacent to the fluvial system and the presence and fluid management of drainage channels. The conceptual framework may therefore be applied to such plantations given the weighting placed on agro-hydrological drivers. However extrapolation of characterised process interactions would be heavily misguided, due to variations in plantation locations throughout the catchment and the characteristics of drainage networks.

To apply the conceptual framework to banana plantations outside Belize would also present a number of problems due to the dynamics of the global banana industry varying considerably with demands on production, the species characteristics of the banana and local climatic conditions (Pers. comm., B.G.A., 1999).

Temporal change

There is great potential for turbulent change within the Belizean banana industry over the next decade. The growing trend towards free trade threatens the industry's survival unless the European Union (EU) maintains a tariff quota system based on present trade links. On the 3rd of May 2000, the Caribbean Banana Producers called for the quota regime to be maintained for a minimum of 10 years to provide time for economic diversification within Caribbean banana producing countries (Caribbean Banana Producers, 2000). If the present quota system remains for the next 10 years then the banana industry will most likely remain at roughly its present size. Land cultivated for banana production may circulate throughout the southern coastal plains depending on productivity and the need to produce a high quality crop, however it is anticipated that the overall structure of the industry in Belize will not change significantly until 2010. However, land utilised for alternative crops as part of diversification strategies may alter the weighting of drainage basin land use within the Stann Creek District.

The structure and intensity of production within current plantation units is unlikely to change significantly over the next decade. Practice adaptation to environmental conditions has evolved in such a way that it would be difficult to farm the land more intensively than it is presently being farmed. Accelerated erosion and a reduction in productivity as a result of sustained intensive production may result in industrial development expanding elsewhere within the region. At the present time there are expansion plans within the South Stann Creek catchment although it is unclear how these will be affected by WTO rulings (Pers. comm., B.G.A., 1999).

Temporal change may therefore have a profound impact on the development of the banana industry in Belize. However if the new EU banana regime is tolerant to Caribbean Banana Exporters Association's (CBEA) requests, the nature of production, and therefore the applicability of the LOICZ framework will remain in place.

§6.4.3 Changes within the fluvial transfer system

A number of changes may take place within the transfer systems of South Stann Creek and other coastal plain river networks over time and space. Climatic conditions recorded during the field season were not extreme for Belize and monitoring did not encompass episodic events such the flooding associated with Hurricane Mitch in October 1998. Such conditions are not rare throughout the Yucatan region, and the return frequency of episodic events is sufficiently high to pose serious questions about interactions between the fluvial sediment delivery system and the dynamics of such within the coastal zone (Arenas, 1983). The interaction of the characterised continuum with such extreme events requires attention, although it is recognised that the logistical difficulties associated with this are considerable!

Future agricultural and economic developments within the drainage basin are likely to alter the quantity of sediment discharged from the river system to the coastal zone and hence alter the proportional influence of plantation sediment delivery drivers within the budgeted reach. Likewise, continued development of plantation activities on the banks and within the floodplains of rivers may alter the weighting of the continuum towards that of in-stream bank erosion associated with exposed plantation reaches. Increased vulnerability within this area may result in agro-hydrological drivers assuming a lesser role within the sediment flux compared to fluvial processes.

The fluvial system offers an effective environment for monitoring such change. The concept of transfer through a fluvial budget providing an "indication" of catchment erosional processes will remain valid over time and space within the continuum and will be of considerable value for understanding the proportional role of the plantation system within fluvial sediment delivery to the coastal zone.

§6.4.4 Coastal sediment delivery

The nature of coastal sediment delivery associated with the land-ocean continuum will experience a multitude of changes over time and space. The delivery system will be an integrated function of temporal and spatial changes within the plantation and fluvial environments (discussed above) along with the nature of change at the river mouth and in near-shore – coastal ocean sediment dynamics.

Short term temporal changes in the coastal sediment flux are likely to exist between the dry and rainy season periods, associated with changes to climatic and agro-hydrological/agronomic drivers. Both of which may be conceptualised within the characterised framework, but the magnitude of activity and interactions with drivers during the rainy season will, on the basis of preliminary results, be far greater than dry season months.

The interaction of the continuum with longer trends of change within the climatic and agro-hydrological systems of Belize is an area where calibration will advance the model significantly and facilitate its insertion into wider system models. Biogeomorphological changes within the near-shore system such as those associated with mangrove interactions with sediment delivery fluxes (Zisman, 1992) represent a particularly important dimension.

The delivery process will also be affected by a number of spatial controls. The location of the river mouth relative to the coastal lagoon system will have significant influence over near-shore sediment dynamics (§6.3.3). The size and mixing functions of the estuary are also an important control. Likewise, coastal-ocean circulation patterns and changing fields of wind and wave action within the delivery environment will alter the translation of the continuum through the system and subsequently alter the weighting attributed to the effectiveness of the delivery process.

§6.4.5 Key areas for further calibration

Emphasis has been given to the potential for advancing the characterised framework through further calibration. This section gives brief consideration to the areas where such calibration would be most appropriately focused.

The plantation driver:

Analysis of estimates of plantation sediment delivery to the fluvial system identified the highly dynamic nature of the agro-hydrological system. Therefore, calibration of the system within the conceptual framework would require enhanced information on both the relationship between plantation sediment delivery and agro-hydrological/agronomic variables and the spatial and temporal dynamics of such. This may be focused on the following areas, which require attention temporally, spatially and over a wide range of conditions:

- Hydrology: - a continuous data set detailing rainfall duration / rainfall intensity information.
- Sediment mobilisation and loss: - localised soil erosion studies on the plantation surface/within drainage channels and the prediction of soil loss equations based on hydro-physical variables.
- Sediment delivery in drainage channels: - an intensive or a fixed monitoring programme sampling SSC and Q in channels discharging directly to the fluvial system
- Agricultural practice: - a continuous record of practice adaption to environmental conditions.

Although it is well recognised that field research in the tropical environment will be accompanied by numerous logistical challenges there is potential for advancing the monitoring equipments and techniques used providing the equipment requirements outlined in §4.41 are considered. Turbidimeters with continuous loggers may provide a valuable dimension on sediment flux dynamics. Agro-chemical tracing techniques would also provide data for soil loss estimations – although further consideration will be given to these below, within a fluvial context.

The fluvial transfer system

The fluvial sediment budget identified a cumulative flux of sediment transfer within a reach. Further calibration is required in three areas. Firstly, the measurement of fluvial variables requires refining at both sites, secondly the temporal and spatial dynamics of the sediment flux require definition, and thirdly interactions between the plantation system and the reach require isolative quantification.

- Fluvial variables

Fluvial stage at site A and site B requires continuous monitoring using an automatic logging device. The stage – discharge relationship for site A requires testing over a range of discharge conditions – especially during flood flows, whilst stage and discharge for site B need to be measured and a relationship identified accordingly. Error margins also require quantification.

- Sediment flux dynamics

A turbidimeter at both sites with automatic logging devices would facilitate the identification of sediment flux dynamics over an increased temporal resolution – hence removing uncertainty between pump sampled sediment load measurements. Equipment would however, need to be robust and water tight and frequent accuracy assessments performed, hence raising the cost and labour intensity of the programme. Turbidimeter records would be required over a wide range of discharge and local agro-hydrological conditions.

- Isolation of plantation interactions

Further calibration of plantation – river interactions may be achieved through the use of sediment fingerprinting or tracing techniques. Using agro-chemicals as a basis for quantifying plantation inputs would provide a valuable dimension on process interactions (Walling, 1990). Particle size investigations may also be of use for calibrating sediment sourcing over time and space. Pump sampler apparatus is appropriate for obtaining this data (ISCO, (1986), Foster, *et al.*, (1995)), however samples will be required over a high frequency for the analysis and calibration of storm events and must not be filtered through cellulose nitrate or glass-fibre filter papers as the subsequent extraction procedure will alter the properties of the variable being monitored (Pers. comm., Lab. Technician, University of Southampton).

Coastal sediment delivery

Sediment output from the drainage basin and coastal SPM dynamics require calibration and integration to improve understanding of coastal sediment delivery mechanisms. The main focus for calibration needs to be on improving the time series of sediment load output from the river and the integration of this with fine spatial resolution data within the coastal zone.

- Fluvial output time series

A continuous record of fluvial sediment load delivered to the coastal zone at the furthest downstream point prior to estuarine influence will enhance understanding of the link between material discharged from the basin outlet and inputs from the monitored reach. This may be used for integration with coastal SPM estimates at the river mouth.

- Coastal SPM dynamics

Regular estimations of secchi transparency dynamics at the river mouth are required over a range of discharge conditions and years. This data requires calibration with *in-situ* SPM measurements and other variables that affect water transparency to ideally develop a site-specific algorithm for converting secchi depth to coastal SPM. Pending future advancements in the spatial and temporal characteristics of ocean colour sensors – satellite data may provide a cost-effective means by which some of this data may be sampled, however cloud still remains a significant problem (§5.7).

- Environmental forcing

To calibrate inter-relationships between local agro-hydrological forcing and sediment plume dynamics detailed information is required on wind/wave conditions during the monitoring period, oceanographic currents and the velocity of the emanating plume. In addition information on agro-hydrological conditions within the lower reaches of the river (see above) is required to ensure that full temporal and spatial integration takes place over a wide range of conditions. Inputs from other river systems to the coastal lagoon should also be considered for calibrating the near-shore estimations of SPM from South Stann Creek, especially during storm events when sediment plumes may interact.

To effectively calibrate the system the agro-hydrological, fluvial and near-shore/coastal systems require temporal co-ordination to facilitate the collection of meaningful data.

§6.4.6 An appropriate framework?

A framework has been offered for the development of understanding interactions between banana plantation agriculture and the fluvial suspended sediment flux to the coastal zone. Future calibration areas have been discussed, building on the model overviewed in Figure 6.3(b). However, before further work is developed and the wider picture is considered, it is important to briefly assess the level of confidence that should be placed in the continuum and the framework within which is has been characterised.

The LOICZ framework has facilitated the integration of process interactions at the plantation – river interface with those at the river-coastal-ocean interface. In particular, it has facilitated the identification and conceptualisation of local system drivers and the understanding of conveyance and delivery processes through the system. LOICZ provides a base for identifying local-regional interactions with the wider scale of change and promotes (although it does not guide) subsequent management.

However, there are a number of limiting factors. Firstly, whilst the identification of a continuum within a complexed system is a valuable tool, the dangers of over-simplification are considerable. Indeed, the generation of such, on the basis of knowledge in one disciplinary area may result in a rather warped understanding of the system. At the opposite extreme the launch of calibration studies based on the characterised model may lead to the over-sophistication the system to an extent where understanding is lost. A balance is clearly required, and in some respects this may be achieved through weighting calibration towards specific areas where process interactions are unclear. Such information may then be inserted into the conceptual framework for identifying resultant areas of uncertainty. Linking industrial land use to coastal zone processes may also result in a number of political problems. The description of local drivers within LOICZ research require immediate positioning and weighting against other drivers at local and regional scales, to prevent un-substantiated assumptions about direct cause and effect relationships.

§6.5 Interactions between the continuum and the Belizean marine environment

The characterised framework has offered a means by which the continuum of sediment movement from the drainage basin to the coastal zone may be conceptualised and calibrated. Change within the continuum over space and time may also be understood within this framework. It is now important to identify the potential for interactions between the continuum and Belize's marine environment. The diversity of coastal ecosystems detailed in Chapter 2 are well recognised for their sensitivity to change (Foer & Olsen, 1992), however, consideration should be given to the interaction of this change with characterised processes identified in this research.

§6.5.1 Near-shore patch reefs

Terrestrial sedimentation process interactions with patch reefs located within the coastal zone have received extensive research attention over recent years (e.g. Rice & Hunter, 1992). A large portion of this has been associated with the dynamics of anthropogenically driven change within the near-shore sediment system (e.g. Ochoa-Lopes, *et al.,* 1998). A number of studies have reported that accelerated sedimentation within the water column associated with near-shore patch reefs will affect and indeed, inhibit, coral growth (Rogers, 1990). More recent reports have suggested that this is not always the case and that in some instances increased sediment within the water column has found to not be mutually exclusive with a reduction in coral growth (Woolfe & Larcombe, (1998), Woolfe, & Larcombe, (1999)). Either way, it is generally recognised that increased sediment within the patch reef environment will alter processes within the bio-physical system and exert significant control over development and diversity within coral ecosystems (Hughes, 1980).

Changes reported for within near-shore patch reef environments as a result of elevated coastal sedimentation may be divided into three categories:

1. Increased sediment supply to the system
2. Increased sediment flux through the system
3. Increased water column turbidity within the system

An increase in sediment supply to bio-physical system is the most commonly recognised "effect" of coastal sedimentation (e.g. Roberts, (1990), Grigg & Dollar, (1990), Hunte & Wittenberg, (1992)). However, a flux of sediment through the system is often mistaken for sediment supply (i.e. accumulation) due to difficulties with distinguishing differences between the two using traditional sediment trap methods (Woolfe & Larcombe, 1999). Sediment flux is also likely to have a profound influence over the patch reef environment as coral may be damaged by abrasion of impact by sediment particles (Rogers, 1990). Turbidity within the water column will alter the light available for photosynthesis and subsequently affect coral physiology. However, a range of variables apart from sediment may influence water column turbidity and although elevated sedimentation will exert a major influence over this process, other factors such as phytoplankton concentrations and D.O.M should be considered as potential controls (§5.3.2).

Results reported in §5.5 illustrated the spatial characteristics of water transparency throughout the Stann Creek lagoonal system during 1998. Whilst it would be inappropriate to assume a linear relationship between transparency and coastal SPM it is clear that water turbidity, a major control over patch reef development, is likely to have similar spatial dynamics to those identified through secchi depth observations, due to the same conditions affecting both measurements (Mausel, *et al.,* 1991). Analysis of interpolated secchi surfaces and secchi transparency plots identified areas of reduced turbidity of approximately 20km extending from the land-ocean interface to the coastal system. Patch reefs located near to Pelican, Lagoon and Quamina Cays were located within this area of reduced water transparency. This clearly indicates an area for further calibration of the system. Investigations would need to identify whether this transparency is related to coastal SPM and will define areas for further focus within the framework to detail interactions between fluvial sediment delivery and coastal-patch reef SPM dynamics. Further investigations will also be required within the patch reef system to identify whether changes to water transparency of magnitudes defined through turbidity/SPM calibration are synonymous with modified conditions within the biophysical environment, ranging from declines in coral growth rates to species diversification and adaption responses.

§6.5.2 The Belizean barrier reef

Examining the continuum within the wider framework of the barrier reef system requires a brief overview of the concept of "thresholds" within marine ecosystems. Jan Sapp's book "What is natural?" (Sapp, 1999) asks questions about the crown of thorns crisis within this context and positions the *Acanthaster planci* within a network of "natural" and anthropogenic "culprits" responsible for global coral reef deterioration. In contrast, recent research on coral bleaching within the Belizean Barrier Reef (Aronson, *et al.,* 2000) identified mass mortality of scleractinian corals (*Agaricia tenuifolia*) as a "result" of elevated sea surface temperatures. However, whilst reporting high water turbidity recorded within the coastal zone as an "effect" of elevated sea surface temperature it failed to consider the multitude of controls that may "affect" water turbidity apart from elevated sea surface temperature. Consideration should be given to whether the philosophy for monitoring change within the Belizean Barrier Reef should either be one of identifying cause and effect mechanisms for particular "culprits" or whether it should be one of piecing together the web of inter-related components that combine to drive and interact with change. Ideally it should comprise both. Where cause and effect mechanisms are inserted into the wider system framework to facilitate understanding of process interactions and the scaling of causal factors. Figure 6.12 illustrates the range of processes that may interact to drive sedimentation within the Belizean barrier reef.

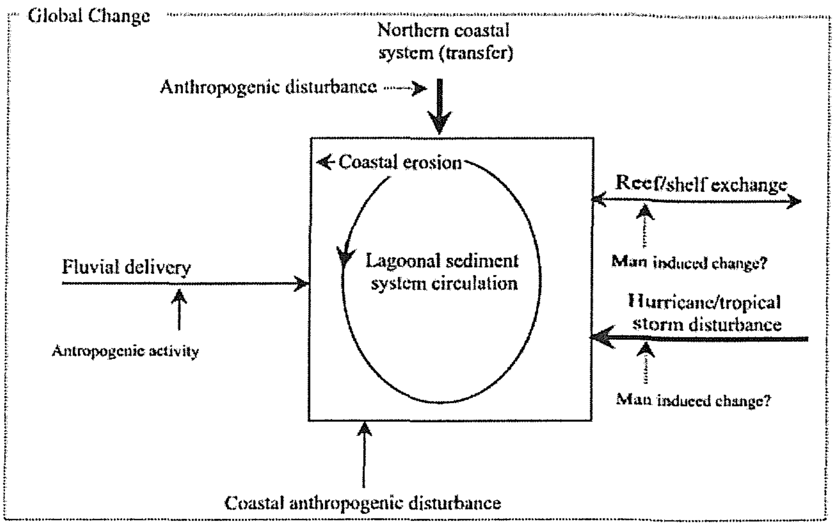


Figure 6.12: The web of interactive causal factors that drive barrier reef sedimentation within Belize

The interaction of the continuum within this web may be considered in three ways. Firstly, through examining the influence of potential changes to transparency dynamics within the barrier reef system. Secondly, through exploring second order coastal changes induced by near-shore transparency dynamics affecting patch reef physiology, and thirdly, through conceptualising the continuum for as a factor influencing the sedimentation "threshold" at which a decline in bio-physical conditions occurs within the coastal-barrier reef system.

Whilst changes to water transparency were recorded within the near-shore environment of the Stann Creek Lagoonal System, research identified that further spatial and temporal calibration of the model was required before the potential for changes in transparency and SPM concentrations within the barrier reef could be identified (§5.5.4). Indeed, the notion of the coastal lagoon operating as a form of "buffer" against direct transfers from the fluvial to reef systems remains a well recognised theory (WRIScS, 1999). However, high levels of turbidity have been reported for a large part of the southern reef system (Aronson, *et al.,* 2000) and further investigations within the framework need to establish whether patterns in water transparency and SPM within the barrier reef system are temporally and spatially integrated with processes operating the fluvial discharge network.

The interaction of the continuum with near-shore catch reefs (§6.5.1) may also have knock-on effects on the barrier system and hence, influence change indirectly. Sediment transport and nutrient exchange between near-shore and barrier reef systems are well documented (Ullman & Sandstrom, 1987) and the potential for change between the two systems should be explored further with respect to this process.

The time series of fluvial sediment delivery to the coastal system and the documented interactions of this with the plantation unit offers the best mechanism at this stage for conceptualising the interaction of the continuum with the marine environment. Research identified that a dis-proportional change took place in the sediment yield of the catchment adjacent to the plantation area (§6.2.1). Whilst significant calibration will be required to understand the dynamics of this process over time and space it is clear that a mechanism exists by which the supply and routing of suspended sediment may be accelerated towards the coastal zone. Whilst conveyance mechanisms still again require calibration, the increased availability of material may lead to sediment-water-reef interactions crossing a threshold over which accelerated degradation may take place to biological feed-back mechanisms and systemic response (e.g. Woolfe, & Larcombe, 1998). High levels of sedimentation and water quality stress reported throughout the Belizean reef system at the present time (Harbourne, *et al.,* 2000) may have originated from a range of processes (Figure 6.12). Physiological responses of marine organisms tend to be adaptive to such pressures to a point, beyond which a downwards spiral of degradation occurs. Accelerated sediment delivery to the coastal zone via the mechanisms characterised within the conceptual framework may be understood rhetorically as a potential "straw that breaks the camel's back".

§6.6 Addressing issues through a sustainable monitoring and management programme

Whilst the dynamics and extent of interconnectivity between the continuum and the Belize marine environment still require further definition, the industrial focus of this research necessitates the identification of monitoring and management options for immediate consideration. Despite the uncertain future of the banana industry in Belize the potential for change within the land and ocean system over the next decade underpins the importance of addressing issues here and now, opposed to waiting until the system has been fully calibrated. Through constructing a framework for interconnectivity between the driver, the transfer and the delivery process a platform has been offered for monitoring and management to be integrated in a fluid manner.

Agronomic perspective

Processes operating at the interface between plantation unit and the fluvial system have been identified to interact with the transfer of fluvial sediment to the coastal zone. Initial quantifications have been provided for key stages of the continuum although the need for significant calibration has been defined. To address issues from an environmental management perspective, the ideal scenario would be to integrate system calibration with the monitoring and management of change.

Estimated erosion rates of 1.6 tonnes/hectare/year are not catastrophic for tropical banana plantation agriculture (Jackson, 1989), but, from an agronomic perspective fertile soil is a prime economic resource and must be preserved (Lal & Russell, 1981). The drivers and routings of sediment transport identified, suggest the potential for elevated activity within the continuum given changes over time and space. The central issue for the industry is the maintenance of a balance between soil conservation measures and the insurance of a profitable and environmentally sound plantation system. Areas of "common ground" between agronomic and water quality monitoring objectives will be addressed in Chapter 7.

Water quality monitoring and management perspective

The complexity of change within such a dynamic system as that identified here necessitates the immediate monitoring of processes within the continuum. Specific areas have been identified for further attention where calibration and the ultimate parameterisation of processes would contribute greatly to system understanding. In particular, an approach to a complexed system has been offered by which multi-level and interdisciplinary understanding can be achieved. The challenge is now to integrate this with the fluid management of process change.

§6.7 Summary

This chapter has attempted to integrate processes characterised in Chapters 3, 4 and 5 within a multi-level sediment delivery framework. Interactions between the plantation and fluvial environment have been conceptualised within a sediment driver – sediment transfer system where the potential for preliminary process quantifications to be calibrated has been outlined through examining future mechanisms of spatial and temporal change. Crude estimations of delivery drivers and the accumulation of sediment within the budgeted reach suggest that initial figures are reasonable although further definition is required to enhance understanding. Interactions between the plantation and the coastal zone were conceptualised within a sediment driver / sediment delivery framework where drainage basin output to the coastal system was examined through identifying periods of sinuosity between agro-hydrological and agronomic plantation drivers and proportional contributions to basin sediment yield. A preliminary framework was constructed to promote the understanding of this process as change transferred from the unilateral fluvial system to the multi-directional environment of the coastal zone.

The characterised land-ocean continuum was suggested to be a combined function of climatic and local agro-hydrological/agronomic processes where the dynamics of forcing within the fluvial and plantation systems produced definable although not mutually exclusive temporal signatures. To build on this characterisation further calibration of the continuum was considered within the IGBP-LOICZ framework. Providing the dangers of over-simplifying / over – sophisticating the system are recognised the LOICZ framework was identified to offer a valuable mechanism for addressing a multidisciplinary continuum.

Consideration of the continuum within the wider system of change suggested on the basis of evidence in this thesis that patch reef environments are a key area where change is readily conveyed. Interactions between sedimentation within the barrier reef system and the continuum were understood through the notion of a "threshold" model, where cumulative anthropogenic change presents a considerable, but manageable challenge.

Through examining the wider context of interaction between the LOICZ continuum and change within the coastal zone, the importance of monitoring and managing the system at a range of levels has been recognised. The following chapter will explore these issues further with a view to providing a sustainable monitoring and management strategy for banana industry and the water quality management organisations concerned with this issue within Belize.

Chapter 7

Monitoring and management options for the banana industry

§7.1 Introduction

Interactions between banana plantation agriculture and the land-ocean suspended sediment flux have been initialised in Chapter 6 with respect to system drivers and their dynamics over time. Whilst further research will be required to calibrate the continuum over time and space the industrial emphasis of this research has necessitated the immediate consideration of options for present and future system management. Such options have demanded appraisal from a dual perspective where industrial and environmental pressures have been assigned equal importance.

The sensitive balance between environment and development maintained by the banana industry to sustain efficient production in Belize now requires mirroring within the coastal zone, where efficient environmental management takes place in conjunction with industrial development. However, to achieve this, environmental monitoring and management strategies require integration within industrial policy demanding an appraisal of cost-benefit and an assessment of feasibility.

This chapter discusses the potential for monitoring change within the fluvial transfer system as a cost-effective mechanism for calibrating the conceptual model whist developing an integrated management framework. Consideration is given to options for collaboration between the banana industry and the water quality organisations in Belize prior to a discussion of recommendations for strategic change and environmental policy within Fyffes, UK and the B.G.A., Belize.

§7.2 Why monitor?

It has been identified that processes interactions between system components operate within a complexed and changing system. Subsequently to advance understanding within the LOICZ framework the continuum requires monitoring at key stages of the model. Within Chapter 6 specific areas within the conceptual framework were identified for such focus to promote calibration over time and space (§6.4.5).

However, monitoring within an anthropogenic land-ocean sediment delivery continuum is a complexed issue and requires addressing at a range of levels, from the political to the economic to the geomorphological, prior to its integration with management. The following sub-sections address the need for monitoring in light of such pressures and consider options within a cost-benefit framework for the monitoring agencies involved.

§7.2.1 Identifying change within a LOICZ monitoring strategy

The level at which monitoring options should be addressed may be considered from three different standpoints. Firstly, future monitoring could be geared towards calibrating the conceptual LOICZ framework at all levels within the continuum. This would take place using the model described in Figure 6.3b to build up the characterised system to achieve greater understanding of driver interactions with the land-ocean sediment flux over time and space. Secondly, in contrast the system could not be monitored and left un-calibrated – adopting the "do nothing" strategy (Newson, 1992). This would be an option until issues accompanying unacceptable change necessitated intervention. Thirdly, a compromise could be achieved through implementing a cost-effective monitoring strategy, where an indicative variable could be monitored that facilitates calibration of the monitored part of the system and details gross changes within the continuum over time.

Clearly the selection of an appropriate monitoring strategy depends on the financial and logistical resources available for its implementation. The advantages and disadvantages of the three strategies for implementation by the banana industry have been considered in Table 7.1 below:

Table 7.1: Advantages and disadvantages of strategies for monitoring the continuum

Strategy	*Advantages*	*Disadvantages*
1) Full calibration	Maximises system understanding	Labour intensive Expensive (equipments etc.) Time consuming (i.e. several years) Logistics (e.g. accessibility) Conditions change
2) "Do nothing"	Low cost (i.e. no expenditure on monitoring equipments)	Delaying opposed to addressing potential conflicts. Fails to provide a platform for subsequent management.
3) Cost-effective monitoring of an indicator	Achievable Promotes the image of the banana industry within Belize	Requires reconnaissance research

To co-ordinate a monitoring strategy attempting a full calibration of the system would be a difficult task. Whilst it is acknowledged such a calibration would maximise understanding of system components, it should be noted that in terms of addressing the integrated management of a changing system, the potential costs of this approach are likely to outweigh the benefits, especially given the time-frame involved. Likewise, through essentially ignoring the option to monitor and adopting the "do nothing" approach, potential conflicts between environment and development will only have been postponed. Future management would not have grounding within a continually monitored system and subsequently stem from an uncertain foundation. The cost-effective monitoring of an indicator within the system offers a compromise, although it should be noted that this would again require initial reconnaissance research to be effective.

The following section considers the potential for adopting a cost-effective indicator approach within the plantation, fluvial and coastal components of the continuum.

§7.2.2 Identifying an indicator of system change for cost-effective monitoring within the continuum

The concept of monitoring an "indicator" of system change is well recognised within earth system science and "indicators" are very much a formal part of national, EU and global agendas for sustainable management (Parry, *et al.*, 1998). The cost-effectiveness of this approach suggests that it would be ideal for the initial involvement of the banana industry within the Belizean water quality monitoring sector. It is subsequently important to establish where to focus such monitoring to facilitate the understanding of change within the continuum.

Monitoring within the plantation environment:

A number of areas have been highlighted for model calibration within the plantation environment to identify change within drivers and interactions between these and alternative forcing functions within the delivery system (§6.4.5). However, whilst in an ideal case scenario the conceptual framework would be greatly enhanced by all of the recommended focus studies, the reality suggests that such attention would be best placed on specific indicator areas – identified to be broadly representative of the delivery system.

However, within the plantation environment this would be a difficult task. Firstly, due to the high level of spatial variability identified within the system (§3.7) the identification of change based on one specific area would be inappropriate. Secondly, due to the significant level of interaction between system components (§3.4) it would be particularly difficult to isolate a specific area of the system that represented change throughout. It should also be noted that a profitable plantation is a particularly dynamic environment where the establishment of a monitoring programme may not only face a number of logistical problems but also interfere with the variables being monitored.

Monitoring change solely within a local driver for a land-ocean sediment delivery system, may also present a number of problems with respect to the understanding of cause and effect scenarios. Whilst change may be identified at one level it has to be transferred through the river system where its dynamics and characteristics may be altered temporally and spatially prior to delivery and potential effect within the coastal zone.

Monitoring within the Coastal Zone

The coastal zone has been identified to be an area where the calibration of system models and future monitoring of the continuum should take place (§6.3.3). However in a programme limited by cost-efficiency the advantages and disadvantages of focusing on the continuum within the coastal zone require consideration.

Monitoring within the coastal system using calibration procedures identified in §6.4.5 would be particularly useful for identifying marine threshold change and calibrating the delivery mechanism. However, to understand interactions between such change and local and regional drivers would prove particularly difficult unless sophisticated (and expensive) techniques such as agro-chemical tracing, were employed (e.g. Walling, 1990).

The value of remote sensing as a monitoring tool within the coastal zone has already been established (§5.3.3). Whilst, at the present time it does not offer the level of information required for monitoring change within the continuum, it should be noted that future developments could facilitate the monitoring of change qualitatively and cost-effectively, for subsequent integration with an indicator quantitative monitoring programme (§7.3).

It should also be noted that to focus exclusively on change within the coastal delivery system would essentially ignore the thrust of the conceptual framework where the interactive components of the delivery process have been omitted and the basis for system management subsequently removed.

Monitoring within the fluvial system

Monitoring change within the fluvial system has been identified to provide initialised information on processes operating within adjacent driver and delivery systems. Therefore for the cost-effective monitoring the continuum at the transfer stage, information on interactions with the plantation system and subsequent off-site effects within the delivery system may be understood.

The fluvial system offers an environment for monitoring where the logistical challenges are not extreme and the political pressures are manageable. At the present time water quality monitoring and agricultural development are taking place within the fluvial system (Table 7.2) and therefore the development of a monitoring programme based on this initial structure is achievable.

Whilst further attention will be given in the following sections to specific monitoring design, brief attention should be focused on the level of monitoring required for data to be indicative of the continuum and facilitate the calibration of the conceptual framework within the fluvial system.

Local and regional hydrological forces may be used to distinguish between fluvial and agro-hydrological forcing functions within the fluvial system. Through the continuous monitoring of upstream / downstream suspended sediment dynamics and yield based on a robust and high temporal resolution data set, interactions between the plantation and the fluvial system may be initialised over time to calibrate the system. Furthermore, through monitoring suspended sediment yield time series at the river mouth either as part of the budget or as a separate venture, the representativeness of interactions may be expressed relative to basin output to the coastal zone. Figure 7.1 illustrates a model for using the fluvial system as an indicator of the continuum:

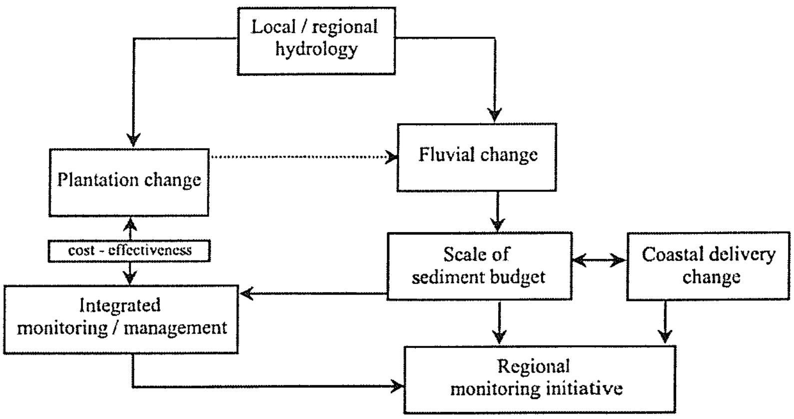


Figure 7.1: A model for monitoring change within the continuum through the fluvial system

Through monitoring fluvial change, the scale of the sediment budget may be used to identify the gross characteristics of interactions between the plantation and the fluvial system over time. At the same time resultant changes to coastal sediment delivery may be identified for subsequent insertion into regional scale monitoring initiatives (e.g. WRIScS). Changes to interactions between the plantation and the river may be subsequently integrated with continued monitoring and management strategies within the plantation environment as a response to economic and environmental pressures within the continuum.

§7.2.3 Integration of monitoring agencies within the fluvial system

The fluvial system may be seen as an environment where a wide range of interests meet. Therefore when monitoring change within the river to understand changes within the land-ocean sediment flux and the interaction of this process with agricultural development, a range of organisations become involved. Within Belize a mottled history of communication between industrial and environmental agencies (G.O.B, 1991) and the demand for a cost-effective approach to system monitoring necessitates the careful consideration of a strategy for integrating environment and development interests within the fluvial system.

Table 7.2 provides an overview of agencies involved or concerned with water quality monitoring within the continuum.

Table 7.2: Principal agencies concerned with water quality monitoring within the continuum (data compiled from notes taken at WRIScS, 1999)

Agency	*Concern*	*Monitoring role*
Fyffes International	Cost-effective production Meeting demand Environmental image (UK)	*
Banana Growers Association, Belize	Cost- effective production Meeting the EU quota Environmental image (Belize)	Agro-chemical monitoring within the fluvial system**
Fyffes Bananas, UK	Efficient Production Meeting the EU quota Environmental image (Belize)	*
Private enterprise	Efficient Production Meeting the EU quota Environmental image (Belize)	*
Environmental and Social Technical Assistant Project (ESTAP)	Development of a regional development plan for all parts of southern Belize likely to be affected by the development of the Southern Highway	Sampling of water parameters**
Department Of Environment (DOE)	Oversees the role of agencies and organisations associated with natural resource management.	Co-ordination of monitoring programmes *
WRIScS	EU funded research programme concerned with land-use effects on the reef system (1997-2000)	Physical process monitoring ***(1997-2000) Co-ordination of existing programmes
Hydrology and Meteorology Departments, Belize	Hazard advisory Information provider on natural water resources to government and research Contributor to the EIA process	Hydrological and meteorological monitoring ***
University College, Belize (U.C.B.)	Research	Various monitoring programmes for research projects**
The Belize fisheries department	Coastal water quality	Monitoring **
Coastal Zone Management Unit (CZMU)	Water quality monitoring programme	Remote sensing of coastal resources Monitoring of base-level information for Belize's coastal and marine environments**
LOICZ / IGBP	Synthesis	Data assimilation framework*

KEY: * Continuous monitoring programme ** Regular monitoring * Not concerned with or carrying out no monitoring at present**

Whilst many organisations are involved within water quality research and management in Belize there is a lack of overall integration within the monitoring framework. In particular, there is a lack of communication between land and environmental managers despite many of their interests culminating in similar water quality objectives. To establish a monitoring initiative focused within the fluvial system associated with the banana industry it is therefore important that where monitoring objectives overlap those of other agencies, data collection is assimilated opposed to replicated. Further consideration has been given to guidelines for the assimilation of water quality monitoring in WRIScS, (1999).

Given the present status of water quality monitoring within southern Belize, the following options for an integrated monitoring initiative are proposed for the banana industry based on the existing organisational structure of monitoring networks:

- Enhance the agro-chemical monitoring programme co-ordinated by the B.G.A. to include the monitoring of SSC and integrate agro-chemical data within the fluvial model.
- Combine fluvial water quality monitoring and calibration with the ESTAP programme, which has already set out plans to monitor SSC within the southern coastal plains (WRIScS, 1999).
- Establish rating curves for monitored rivers based on data collected by the Hydrology and Meteorology departments for subsequent integration with a sediment monitoring programme established by the banana industry on South Stann Creek and Monkey River.

Analysis of the agencies involved, highlighted in Table 7.2, also suggests that the capacity is available for further calibration of the continuum based on need identified within the indicator system. Indeed, within the LOICZ framework data may be provided from such agencies operating within the land, fluvial and coastal systems to enhance system understanding given future change. However, there are a number of obstacles to this process such as the need for universal monitoring standards and the willingness for organisations to exchange, collate and present data.

§7.3 Recommendations for an indicator monitoring strategy

This section presents a series of recommendations for the banana industry to lead the monitoring of the continuum within the fluvial environment. This approach is advantageous to the industry and the water quality monitoring sector for a number of reasons. Firstly, in terms of collating information on the land-ocean sediment flux within Belize the banana industry has the capacity to provide the funding available to support a local-regional monitoring initiative and providing calibration of the interaction of a local driver with system components. Secondly, through supporting a fluvial monitoring initiative the banana industry will encourage constructive interaction between the environment and industrial development sectors of the south. The information collected would detail gross patterns of interaction between the plantation and the river and hence alert the industry to potential problems with soil erosion and sediment loss that may threaten the efficiency of production.

Table 7.3 illustrates a preliminary base-level design of a fluvial monitoring strategy that would most appropriately be led by the banana industry but integrated with other interested agencies at the same time:

Table 7.3: Base-level design of a fluvial monitoring strategy

Procedure	*Requirements*	*Equipment options*	*Timing*	*Potential funding / monitoring organisations*
Monitor fluvial sediment yield upstream of the influence of banana plantations	Continuous record of SSC	Turbidimeter	Continuous	Fyffes/B.G.A./Private Enterprise
	Calibration	USDH-48	Instantaneous (regular)	ESTAP
	Continuous record of Q	Stage record and logger	Continuous	Hydrology department
	Calibration	Manual measurements	Instantaneous (regular)	ESTAP/ Hydrology/ B.G.A.
Monitor fluvial sediment yield downstream of the influence of banana plantations	Continuous record of SSC	Turbidimeter	Continuous	Fyffes/B.G.A./Private Enterprise
	Calibration	USDH-48	Instantaneous (regular)	ESTAP
	Continuous record of Q	Stage record and logger	Continuous	Hydrology department
	Calibration	Manual measurements	Instantaneous (regular)	ESTAP/ Hydrology/ B.G.A.
Monitor fluvial sediment yield at the river mouth	Continuous record of SSC	Turbidimeter	Continuous	Fyffes/B.G.A./Private Enterprise
	Calibration	USDH-48	Instantaneous (regular)	ESTAP
	Continuous record of Q	Stage record and logger	Continuous	Hydrology department
	Calibration	Manual measurements	Instantaneous (regular)	ESTAP/ Hydrology/ B.G.A.

The design described above effectively constitutes a continuous sediment budgeting exercise, where continuous monitoring equipments have been suggested for the identification of change requiring limited logistical intervention. Whilst turbidimeters require calibration for SSC monitoring, providing the equipment used is robust and discretely located, they may be set up for continuous use and only accessed for data collection and servicing unlike the ISCO pump sampler (§4.4.1) (Gipple, 1989). They have been suggested for use on the basis of research undertaken in Indonesia (Mitzuyama, *et al.*, 1995) where they were used to identify the effectiveness of erosion control works on the suspended sediment yield of an afforested catchment through detailing an upstream/downstream sediment budget. The ESTAP project is already actively monitoring SSC using the universal standard USDH-48 (Figure 4.1) (WRIScS, 1999) and therefore could provide an excellent opportunity for calibration in exchange for continuous turbidity information within the monitored rivers. Regular calibration should involve sampling at all stages throughout the sedigraph. Likewise, collaboration could take place with the Hydrology Department to improve the record of discharge available for monitored rivers, subsequently facilitating the computation of sediment load.

Table 7.4 suggests a potential framework for organisational involvement in data handling:

Table 7.4: Data handling

Procedure	*Potential organisational involvement*
Laboratory analysis	B.G.A. agro-chemical monitoring laboratory, Big Creek.
Data assimilation	U.C.B / Fyffes bananas / B.G.A
Data analysis	U.C.B. / Fyffes bananas / B.G.A
Data presentation	Periodical collaborative report (UCB/Fyffes/Hydrology/B.G.A.)

The B.G.A. laboratory in Big Creek (presently used for agro-chemical monitoring) has the facilities available for sediment weighting analysis and could provide an ideal location for calibration studies. Agro-chemical residence information for the monitored section of river could also be obtained and analysed at the laboratory without significant expenditure and could provide valuable information on sediment delivery and erosion rates (§3.2). However, it is recognised that agro-chemical monitoring is an area that may present some difficulties in terms of collaboration between environmental and developmental organisations due to the monitoring process being readily associated with the assessment of "pollution" opposed to sediment tracing.

Monitoring outputs

Data outputs from the monitoring programme will detail changes to sediment dynamics and the representativeness of such within drainage basin suspended sediment yield. This information would detail gross patterns in the upstream/downstream delivery system and facilitate the progressive calibration of the conceptual framework within the fluvial environment.

A platform for management?

Outputs from the monitoring programme would be of considerable value as a basis for subsequent system management. A continuous data set could provide current information for decision makers and enable the consideration of management options in light of cumulative and systemic change. Subsequently the monitoring programme may be used to gauge the effectiveness of management change and highlight areas in time and space where further monitoring would be most appropriately focused. Depending on extent of change within the system, the monitoring programme could be used to pin-point focal areas for calibration and model refinement strengthening the understanding of interactions between system components. Figure 7.2 illustrates a potential route for driver calibration within the plantation system following output development from the initial monitoring framework:

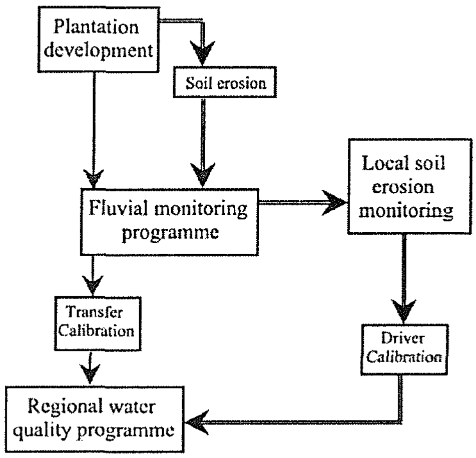


Figure 7.2: Driver calibration following change indicated within a fluvial monitoring programme

Data integration within the continuum and the sensitivity of monitored change

It is important to consider how monitoring recommendations for the banana industry may be inserted back into the wider scale of change and what they contribute to understanding of the continuum. Meaning will be most effectively derived from the monitoring programme with respect to LOICZ when data is contextualised within the framework of the coastal zone. In Chapter 6 anthropogenic drivers of the continuum were considered as contributors to cumulative change within the marine environment. However, depending on existing pressure within the marine system the sensitivity of change within the continuum is of greater or lesser importance. So, with respect to the analogy used in §6.5.2 where the continuum potentially represents the "straw that breaks the camel's back", the sensitivity of change depends on the weight of straw on the camel's back at that same time. Likewise, within the plantation system, change will be of greater importance as a result of economic costs associated with accelerated soil erosion and nutrient/agro-chemical losses, where the delivery of sediment to the continuum will have greater or lesser repercussions depending on the vulnerability of the plantation environment to such change.

Through monitoring the continuum the banana industry could develop an active response mechanism to the initial indicators of un-acceptable sediment delivery, where economic losses resulting from soil erosion would necessitate the consideration of management options. However, from the perspective of change within the marine system the monitoring outputs require contextualising against the state of the coastal zone (Figure 7.3). Therefore it is important that a framework is established for the monitoring programme to contribute to wider system studies using spatial analysis tools such GIS for data integration.

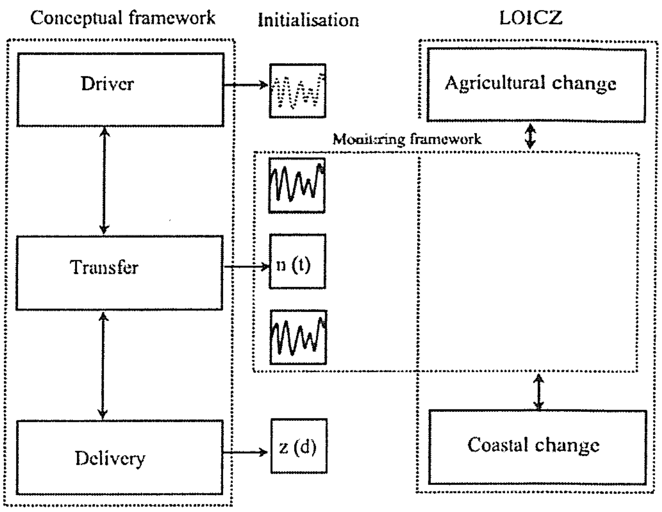


Figure 7.3: Contextualising monitored change within the LOICZ framework

The effectiveness of the monitoring strategy in terms of contributing to model calibration and the understanding of LOICZ change within Belize will develop from collaboration with organisations that have the capacity to collate data at the regional level. Potential options are the Coastal Zone Management Unit (CZMU) and University College Belize (UCB), although it is recognised that funding will exert a major control over the success of this venture.

§7.4 Management options

Whilst it is recognised that the characterised continuum does not provide the information necessary to establish management guidelines at this stage, it is important to consider future options within the context of identified change. Interactions between climate, hydrology, geomorphology and land use will determine the extent to which management of the continuum is viable at the level of the agricultural driver. These interactions may only be fully understood through further calibration of the system – a process that may take several years (Table 7.1). However, following reconnaissance research, cost-effective management options may be considered in conjunction with the monitoring programme to develop an integrated response system for the industry within the framework of LOICZ (Figure 7.3).

§7.4.1 Assessment of management options within the plantation environment

It is well understood that a wide range of factors drive soil erosion and sediment mobilisation within the plantation environment (Lal, 1983). Drainage channels have been identified to interact with hydrological events to sustain a profitable plantation environment (§3.7). However, their design replicates the erosive gulleys reported in many agro-systems to be the *result* of in-sufficient land management planning (Cooke & Doornkamp, (1974), Lal, (1981)). Unlike these environments, management of the commercial tropical banana plantation necessitates the construction of such gulleys (drainage channel networks) to promote efficient water management, despite their inability to promote efficient soil management (Fyffes, (1972), Holder & Gumbs, (1982)). The situation within the tropical banana plantation is one of balancing the resources required for cultivation. Whilst soil is well recognised to be a non-renewable resource (Walling, 1990), essential for the long-term sustainability of the industry, the short-term benefits of water management outweigh the longer-term advantages of soil conservation. Subsequently whilst the maintenance of a balance between the two would create an economic and environmental ideal, considerable difficulties have been experienced with the cost-effective achievement of such (Pers. comm. B.G.A., 1998).

Soil conservation

Morgan (1995) identified three soil conservation strategies that have been widely employed for erosion control within agro-systems:

1. Agronomic: Methods such as utilising the role of vegetation to protect the soil against erosion.
2. Soil management: Preparing the soil to promote plant growth and improving its structure so that it is more resistant to erosion.
3. Mechanical or physical methods: Often involving engineering methods that manipulate surface topography and change drainage conditions.

Within tropical agro-system management, general preference has been given to agronomic strategies for soil conservation over methods involving soil management or mechanical methods due to the longer-term sustainability and cost-effectiveness of their implementation (Lal, 1983). In particular agronomic strategies have been particularly important for the plantation monoculture, where:

> ***"... (erosion) risks are high from a land use system that simplifies an ecosystem"***
>
> (Lal, 1990)

Many of the traditional and most successful soil conservation techniques for tropical plantation agro-systems have subsequently involved the diversification of cropping and the growth of symbiotic species to stabilise soils. Table 7.5 considers the advantages and disadvantages of some erosion control measures utilised within tropical banana plantations:

Table 7.5: Short term erosion control measures for erosion within tropical banana plantations

Erosion control measure	*Benefits and examples of regions applied:*	*Considerations*
Mixed cropping system	Identified to be an effective erosion control measure (Lal, 1990). It has been especially successful in Cameroon where shade-loving plants such as coffee and cocoa are grown under banana trees.	Plantation managers are not able to produce any crop apart from bananas under their present contract with the multinationals.
Vegetative buffer strips and barriers	These permanent contour strips of grass or shrubs have been identified to reduce run-off and cause deposition of silt behind barriers (Webster & Wilson, 1980)	Often not fully effective because; a) gaps in the vegetation encourage gulleying; b) they tend to spread – necessitating labour intervention (Webster & Wilson, 1980). Requires additional labour.
Stepped drains	Suriname (Pers. comm. B.G.A., Belize (1998).	Slows down opposed to reduces sediment delivery. Costly over a large plantation area (Morgan, 1995) Requires additional labour.
Mulch (Mixture of wet straw/leaves used to protect the roots of plants)	Reduced erosion from 161 t/ha to 0.5 t/ha 1 year after treatment within a Tea plantation in Kenya (Othieno, 1975). Lal, (1990) also noted that mulching was an effective erosion control measure in all fruit orchards, reducing erosion from approx. 14-46%.	Availability of mulch material May be produced in situ – however agro-chemical problems and disease control may compromise this. Impedes effective drainage. Does not address erosion problems within drainage channels. Requires additional labour.
Cover plants (e.g. Guinea/Weeping love grass)	An effective erosion control measure on banana plantations in Taiwan, reducing erosion from 63.7ha/yr to 1.8 t/ha/yr (Liao & Wu, 1987).	Controls the strength of the soil surface; increases surface roughness; reduces the kinetic energy of incident rainfall; and increases surface soil water loss through transpiration. Potential competition with banana for basic requirements. May only need to be restricted to local and vulnerable areas. Requires additional labour. May be used in drainage networks – although will reduce the rate of water removal.

Whilst all the control measures identified above are likely to reduce on-site erosion and sediment delivery away from the plantation environment to varying extents, the cost-effectiveness of their implementation presents a major constraint. For example, mulching, a well recognised soil conservation technique, may address problems associated with on-site erosion, however, it hampers effective drainage (§3.4.1) and creates favourable conditions for pests and disease (Webster & Wilson, 1980). Likewise, the development of a mixed cropping system would promote the reduction of on-site erosion from processes such as rain-drop impact, wash flow and rilling, however, its implementation would also be hampered by a number of constraints: Firstly, the industry within Belize has been prevented from growing any other crop for commercial gain as part of their contract with Fyffes (Pers. comm. B.G.A. 1999). Secondly, this option does not address the problem of drainage channel erosion and sediment re-mobilisation. Thirdly, the seeding of non-commercial crop (unless entirely symbiotic) would impose commercially unjustifiable restrictions on the productivity of the plantation, due to the costs involved with physiological competition for basic requirements (Pers. comm. B.G.A., 2000).

The stepping of drains within the plantation system offers a potential management option. This has been successfully used in Suriname to reduce erosive flow velocities in plantations where slope has presented a major control (Pers. comm. B.G.A., Belize, 1998). However, whilst tackling erosion and sediment delivery problems within the drainage network it only delays, rather than prevents processes from taking place over time and does not address erosion and water transport issues on the surface of the plantation where a number of problems may originate (Wrigley, 1981).

Cover crops have been well reported to be an effective control over erosion and sediment transport from tropical plantation agriculture (Webster & Nilson, (1980), Wrigley, (1981), Boardman, *et al.,* (1990)). Crops such as *Creeping Legumos* are commonly used and provide a dense and protective cover whilst enhancing rainfall infiltration by improving the organic matter content of the soil (Webster & Nilson, 1980). Some problems have been experienced with cover crops competing with the plantation trees and reducing production, although it has been found that this can be reduced by periodic pruning and the use of fertilisers (Wrigley, 1991). Again, the implementation of this control will depend on a series of trade-offs between productivity, labour costs and the demand for an effective control at the time of implementation.

Therefore, whilst there are a number of potentially effective options for reducing or preventing erosion and sediment mobilisation within the plantation system, it is clear that all compromise to varying extents the efficiency and productivity of the system. The following section examines the potential for management at the interfluve to examine whether addressing interactions at this level presents less of a challenge to industrial development.

§7.4.2 Assessment of management options at the interfluve

Addressing sediment delivery within the plantation environment presents a number of conflicts with respect to cost-effective agricultural development. Addressing change at the interface between the plantation and the fluvial system may offer an effective alternative.

There are two methods that have been commonly used for moderating inter-connectivity between agricultural land and the fluvial system with respect to sediment delivery (Table 7.6):

Table 7.6: Measures for altering process interactions at the interfluve

Interfluve option	*Examples*
Riparian buffer strips	Barling & Moore, 1994: - Australia
	Coleman & Kupfer, 1996: - Tennessee
Sediment ponding	Fleischer, *et al.*, 1997: - Sweden

Riparian buffer strips have been well reported with respect to their role as a sink and as a source of non-point suspended sediment to the fluvial system (Dillaha & Inamdar, 1997). Buffer strips, usually varying in width between 6 and 100 metres (Snyder, *et al.*, 1998) are either natural or rejuvenated vegetated areas located between the area of agricultural production and the river system. They have been identified in some cases to be effective filters of surface run-off from agricultural production, where the fluvial delivery of sediments, nutrients and contaminants becomes markedly reduced (e.g. Snyder, *et al.*, 1998).

However, initial research suggests that considerable interaction between the plantation and the fluvial system takes place as a function of point source sediment delivery in agricultural drainage channels (§3.7). Riparian buffers are not recognised to have a marked influence over sediment delivered *via* point source sediment input to the fluvial system (Barling & Moore, 1994) and subsequently their value is questionable in this regard. Likewise, riparian buffers become less effective at sediment trapping as particular size decreases and hence fine sediments and contaminants associated with agriculture in the Stann Creek coastal plains may not be as efficiently filtered as managers funding the insertion of buffer zones would desire. It is also well recognised that riparian buffers do not always play an effective role in controlling sediment delivery to the fluvial system from agricultural land. Whilst commonly operating as sediment transfers and sinks, riparian buffer strips have been reported to release large quantities of sediment to the fluvial system during episodic high discharge events (Dillaha & Inamdar, 1997), and subsequently should not be exclusively regarded as a long-term sediment control measure, especially within the tropics.

Despite this, it is still widely recognised that riparian buffer zones improve the water quality of fluvial systems draining agricultural land, where sediment trapping, nutrient filtering and bank stabilisation are just some of the advantages that have been associated with their utilisation (Aller, *et al.,* 1998).

A difficulty with the consideration of riparian buffer strips for implementation within Belize is that it is already a legal requirement for plantations to be located over 50 metres from the fluvial system (Hall, 1994). This is not enforced. Agricultural land within 50 metres of the river system is some of the most fertile in Belize and therefore despite potential risks associated with flooding, crop damage and erosion it is economically advantageous for plantation managers to utilise this land for cultivation (Pers. comm. Stann Creek farm managers, 1998). Again, the short-term economic gains outweigh the longer-term economic and environmental losses in an industry with an uncertain future.

Sediment ponds offer an alternative where point sources of suspended sediment can be channelled away from the fluvial system into an area where settling may take place (Fleischer, *et al.,* 1987). This technique has been widely and successfully used for point sedimentation problems in many regions (e.g. Cooke & Doornkamp, (1974)). However the large quantities of agro-chemicals and dissolved nutrients discharged via drainage channels to the surrounding environment hamper the potential efficiency of this option in the tropics due to eutrophication taking place with ponds and the problem being relocated opposed to being addressed (Pers. comm. Stann Creek plantation managers, 1998).

Whilst management options at the interface between the plantation and the fluvial system offer some scope for moderating inter-connectivity between the two environments, their principal functions tend to be more related to delaying and re-locating process interactions opposed to addressing their development at the level of the driver.

§7.5 The potential for re-distributing plantation resources towards soil conservation measures

Whilst there are range of potential options for the industry in terms of conserving soil and managing sediment delivery to the fluvial system, the challenges associated with maintaining a cost-effective operation threaten the reality of their implementation. In particular, the potential demands imposed on plantation labour resources decrease the economic viability of soil conservation management options. Subsequently to address change in a cost-effective manner it is important to consider options associated with the re-distribution of plantation resources opposed to the re-design of the plantation system:

> ***"Increasingly it is recognised that strategies for soil conservation must rely on improving traditional systems instead of imposing entirely new techniques from outside.."***
>
> (Roose, 1992)

A number of studies have emphasised the advantages of adapting and re-distributing plantation resources towards soil conservation management for environmental and economic gain (e.g. Cooke & Doornkamp, 1974). This will depend on the extent to which external and internal pressures necessitate change within the plantation environment and the degree to which change can be controlled by addressing crop management issues. For example, mulching has been identified to be an effective erosion control technique for tropical banana plantations, where banana leaves may be used to control runoff and erosion (Table 7.5). Despite this, it has not been practiced much within the commercial plantations of the tropics due to the cost of labour, the expense of cutting, carrying and applying the mulch and the rapidity with which it decomposes (Webster & Wilson, 1980). However, if erosion and sediment loss were anticipated to reach a threshold at which a decline in productivity was unacceptable, then plantation labour may be cost-effectively channelled towards such techniques without compromising plantation efficiency. Likewise, if environmental pressures within the surrounding environment necessitated intervention, a re-distribution of plantation resources towards a traditional measure such as mulching could offer a cost-effective management response where the resources for implementation would already be in place.

§7.6 The potential for re-distributing capital towards soil conservation measures

Whilst external and internal pressures may initially be addressed by re-directing resources towards soil conservation measures the efficiency of this approach depends on the stage at which the industry addresses the issue, if at all. Response at a later stage, necessitated by internal and external pressures is likely to involve the utilisation of measures seeking to exert greater control over soil erosion and sediment mobilisation within the plantation environment than could be addressed by re-directing plantation resources (Cooke & Doornkamp, 1974).

Issues of longer-term change may be addressed through re-distributing capital in a cost-effective manner. For example, capital lost from sustained under-productivity within the plantation system may be re-directed towards funding a control measure such as the growth of cover plants on the banks of drainage channels or within areas identified as being vulnerable to erosion (Table 7.5). This would however, need to follow initial reconnaissance research, so that the suitability of different methods could be ascertained without significant capital expenditure at the stage of implementation and any potential risks associated with competition and pest control can be address at the preliminary level.

There are two principal advantages that the industry will gain from employing methods such as this to support erosion prevention practices. Firstly an option such as cover cropping does not rely on labour resources to such an extent as crop management, so therefore once the decision has been made to act the control measure will in some respects sustain itself, although it will require some labour expenditure at key stages. Secondly through adopting a strategy by which the industry is seen to be "doing something", pressures associated with environmental development within the region may be dissipated. The sensitivity of the industry's location within the Belizean coastal zone necessitates the confrontation of environmental perception issues in association with cost-effective management practices.

§7.7 An integrated monitoring and management strategy?

Whilst to advance understanding of the system within the LOICZ framework monitoring may take place at a key "indicator" stage, to address issues of temporal and spatial change within the driver, management options require inserting into the industrial decision process. Figure 7.4 illustrates a potential strategy within which the monitoring and management of the system may be integrated:

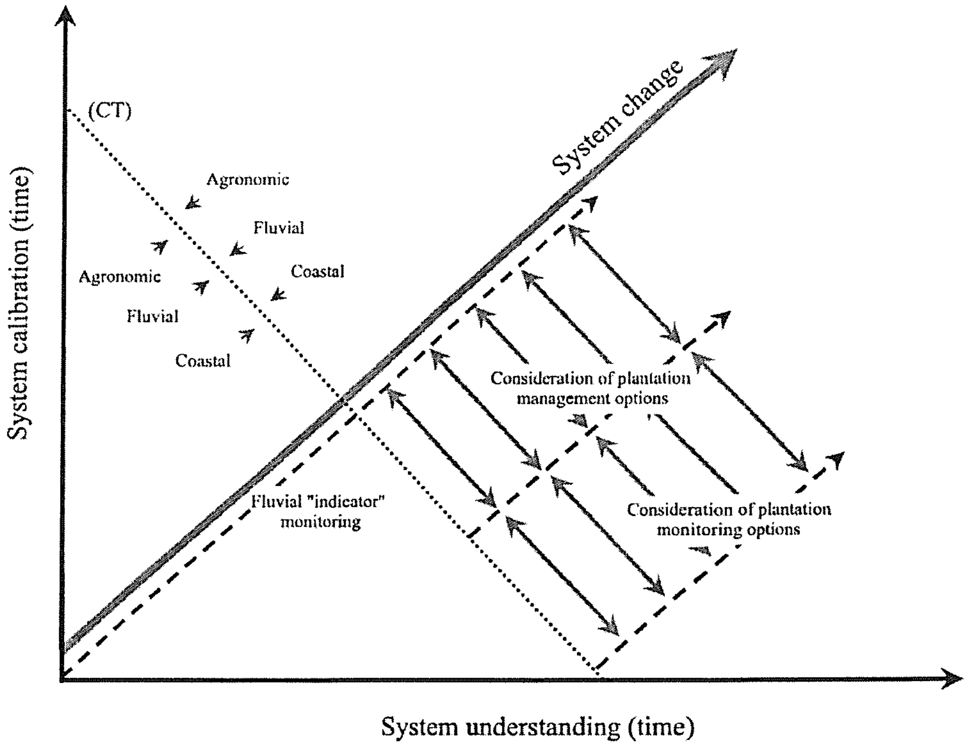


Figure 7.4: A strategy for integrating monitoring and management

Where, "CT" is the Critical Threshold at which economic and environmental forces necessitate the consideration of management options. This threshold may be determined within the agronomic environment by an unacceptable decline in productivity within the plantation environment associated with a monitored increase in sediment yield within the fluvial indicator, suggesting that sediment loss within the plantation environment was likely to exceed the level required for sustainable production. The critical threshold may also be determined within the fluvial environment by an analysis of proportional change within the catchment at the regional scale suggesting that sediment yield associated with the indicator reach was accelerating disproportionately to basin output. However, the sensitivity of basin output is interdependent with the nature of coastal change and therefore it is important that research be contextualised within a collaborative, regional, coastal initiative to establish the demand for and potential effectiveness of monitoring and management intervention at the driver (Figure 7.3).

Reconnaissance research at the critical threshold would enable the consideration of preliminary monitoring and management options within the plantation environment whilst calibrating the system further. For example, plantation resources may be temporarily channelled towards a soil conservation practice such as mulching where dried banana leaves are used to protect the soil from raindrop impact within particularly vulnerable areas. At the same time a reconnaissance monitoring programme could be used to ascertain the effectiveness of this technique with respect to productivity, plantation soil erosion and change within the fluvial indicator. This integration of monitoring and management would continue until the pressures at the critical threshold returned to acceptable levels.

Collaboration

Inter-connectivity between the plantation, fluvial and coastal systems of the continuum necessitates collaboration between the agencies concerned with monitoring and management to promote cost efficiency and data assimilation. Whilst this issue has been considered with respect to system monitoring within §7.3 it is important to give brief consideration to how the range of interests may be responded to and incorporated within an industrial environmental management programme.

Over recent years change has been monitored within the fluvial system by various government agencies concerned with water quality research and management (Stednick, *et al.,* 1998). A conflict of interest has subsequently resulted in some tension between industrial development and water quality management. Figure 7.5 illustrates a framework for industrially led monitoring and management strategy that may promote collaboration between the two sectors based on mutual interests.

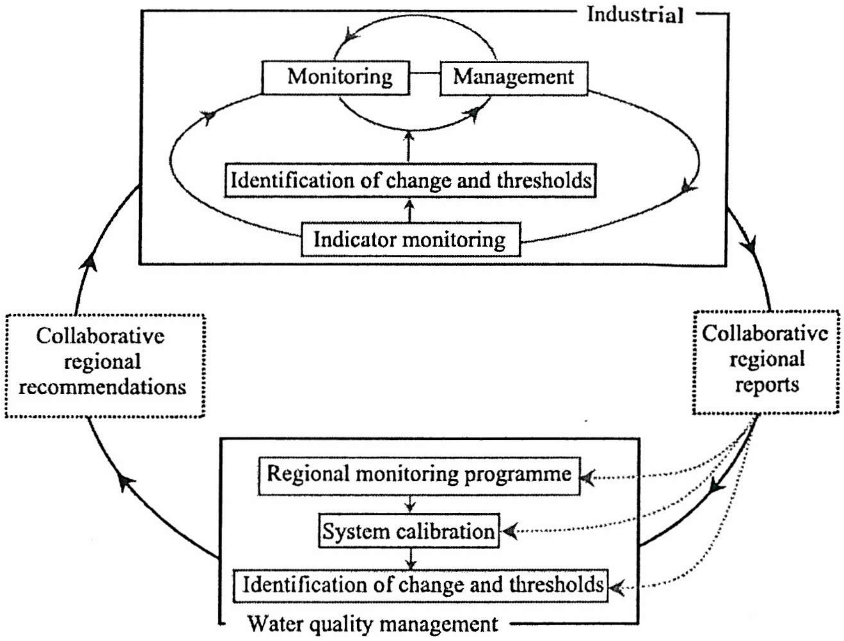


Figure 7.5: A framework for an industrially led monitoring and management strategy

Mutual interests between monitoring and management agencies may be summarised as follows:

Table 7.7: Mutual interests in an industrially led monitoring and management strategy

Agency	*Example*	*Benefits*
Banana industry	Fyffes	Soil conservation management
		Availability of expertise for erosion control
		Environmental image within Belize
Organisations concerned with water quality monitoring	D.O.E.	Improved investment potential
		Improved data collection techniques and data availability
		Laboratory facilities
Regional monitoring programme	CZMU	Integrated management framework
		Data availability and assimilation potential
		System calibration

The framework offers an opportunity for the water quality organisations with Belize and the banana industry to collaborate on mutually advantageous terms. At the agronomic level it enables the industry, if and when necessary, to perform a thorough assessment of erosion risk (calibration of the system within the plantation environment) at the same time as addressing potential management options:

"Too often expensive conservation work has been carried out on areas of land which were thought to be important sediment sources but in fact were not"

(Perrens & Trustrum, 1984)

At the same time the water quality industry benefits through the development of an improved monitoring system where high resolution data may be collected within the fluvial system. Unlike traditional research ventures where the changing system never becomes fully calibrated and parameterised for subsequent management (Parry, *et al.,* 1998), a collaborative monitoring and management strategy confronts change within the system as a function of pressures associated with economic and environmental loss.

§7.8 Recommendations for environmental policy within Belize: Fyffes, UK, B.G.A., Belize

Whist a number of options have been proposed for integrated environmental monitoring and management at the local to regional scale within Belize, it is important that such change is inserted into wider environmental policy within Fyffes, UK to promote the sustained involvement of the industry within environmental issues of host countries. Three recommendations have subsequently been made to Fyffes and the B.G.A.. Firstly, that an active involvement with environmental and water quality organisations is initiated in Belize. Secondly, that the industry embarks on and leads an environmental monitoring and management programme with respect to plantation interactions with the continuum of sediment delivery from the drainage basin to the coastal zone, thereby leading industrial water quality research and management within the Belizean coastal zone. Thirdly, that an environmental audit is undertaken by the industry with respect to its development in Belize as a protocol for development in other regions.

Environmental involvement

The involvement of the European banana industry in environmental issues within Belize offers an opportunity for present conflicts between environment and development to be openly confronted. It also may be used to promote strategic change within the European and American banana market where "green bananas" are becoming a principal weapon of the trade wards (Egan, 1999) and environmental policy has become an important mechanism by which companies can generate strategic advantage over competitors (Boseman, & Phatak, 1989).

At the present time there is considerable potential for environmental involvement within Belize due to the large number of initiatives that have developed over recent years (WRIScS, 1999). Through liasing with some of the more prominent initiatives, the industry could develop a favourable environmental profile, which could be used as a mechanism for instigating pro-active change in Belize.

Support monitoring and management initiatives within Belize

Whilst it is essential to develop a sound grounding within environmental research and management in Belize it is also important that the European industry supports monitoring and management initiatives led by the B.G.A. and Fyffes, Belize. For the initiatives to function effectively the sampling and assimilation of data will require small-scale financial and logistical support facilitating the development and publication of reports compiled jointly by water quality organisations and the industry in Belize. Support from the European industry would facilitate the implementation of an integrated strategy proposed in §7.7 where development may be managed in accordance with environmental system change.

Environmental audit

Through leading an integrated monitoring and management strategy within Belize, Fyffes, UK and the B.G.A., could begin to formulate an environmental audit of present activities within Belize, thereby modifying environmental policy at the strategic level. Despite the potentially short-term future of the industry within Belize the development of an initial audit would enable proactive interaction with local environmental law and establish a protocol for sustained future developments in Suriname, Europe, the U.S.A. and Honduras.

Table 7.8 illustrates the principal aspects of an environmental audit for Fyffes and the B.G.A in Belize:

Table 7.8: Principal aspects of an environmental audit for Fyffes and the B.G.A. Belize (Adapted from EC draft eco-audit directive (Ledgerwood, *et al.*, 1992)

Objectives	Systematic, objective and periodic review of environmental performance
	Provision of information to the pubic
Initial phases	Production in Belize
Validating authority	Designated by the Belizean government
Elements of policy	Review of present situation
	Assessment of organisation and equipment required for monitoring
	Identification of areas for improvement and management
Stages of policy	Internal
	Appraisal by an independent advisor; - as specified by the validating authority
Area of focus	Plantation sediment delivery to the fluvial system (Interactions between industrial development and LOICZ)
Publication	Fyffes publish an environmental statement for submission to the validating authority and the general public.

Key aspects of this process would involve the establishment of an external validating authority and the standardisation of criteria for the monitoring and presentation of research. Through reviewing the present situation and change over time with an auditing procedure, the development, implementation and success of environmental policies and monitoring programmes may be measured.

This research has provided information on the elements required for an initial appraisal of policy within banana operations in Belize. However, advancement through a professional auditing procedure within the area of focus – interactions between industrial development and LOICZ, would facilitate the positioning of the banana industry within the network of organisations concerned with coastal zone research and management.

§7.9 Summary

This chapter has explored a range of options for the integrated monitoring and management of interactions between banana plantation agriculture and the land-ocean sediment flux within Belize. It has been identified that the fluvial system may be monitored to indicate sediment delivery patterns within the continuum for subsequent consideration at the management level. The advantages of data assimilation opposed to replication have been emphasised with respect to channelling financial and logistical resources within the region towards a collaborative strategy.

Preliminary monitoring options have been offered in light of such considerations with the utilisation of continuous monitoring equipments for calibrating the fluvial sediment budget. However, it has been identified that whilst providing an initial indicator of change within the plantation environment, promoting the consideration of industrial management options, the sensitivity of the coastal zone to such will depend on the state of the marine system, which is much more difficult to assess. Therefore plantation management has been identified to be an area where immediate response options can be considered through an integrated monitoring and management strategy led by the banana industry.

Specific management options have been offered on the basis of successful plantation soil conservation techniques employed elsewhere in the tropics. Agronomic methods were favoured due to their cost-effectiveness, longer-term sustainability and the potential for re-distributing opposed to re-allocating system resources. On the basis of such options, recommendations have been made for short-term environmental policy within Fyffes, UK and the B.G.A. Belize, striving towards the development of a protocol environmental audit for the future integration of environment and development within the industry.

Chapter 8

Conclusions and a perspective on research findings

§8.1 Conclusions

To promote understanding of interactions between the plantation, fluvial and coastal systems of the Stann Creek District, this thesis has offered a characterised conceptual model based on the LOICZ framework. The driver, transfer and delivery components of the sediment delivery system linking the plantation to the coastal zone were investigated during a four-month field season.

The 5.5km plantation unit on South Stann Creek provided the focus for driver research where interactions were investigated between climate, hydrology and agricultural practice. Within the transfer system a provisional fluvial sediment budget was calculated from suspended sediment concentration (SSC) and discharge dynamics upstream and downstream of the characterised banana plantation unit. The delivery system was investigated through a feasibility study of *in-situ* and remote methods for monitoring the sediment flux discharged from South Stann Creek to the Belizean coastal zone. Key deliverables of the research were as follows:

- Agricultural drainage channels - essential for rapidly discharging excess storm water away from the plantation to the nearest creek, were identified as fundamental mechanisms for delivering suspended sediment to the fluvial system during local storm events.

- Sediment load increased by approximately 200 tonnes within the budgeted reach of South Stann Creek adjacent to the banana plantation unit, constituting a net increase in basin sediment yield to the coastal zone of 16% during the monitoring period.

- Characterisation of the Stann Creek coastal zone was provided through integrating spatial estimates of secchi transparency with fluvial sediment yield. The conceptual model was developed for future monitoring of the sediment flux pending forthcoming advances in satellite observation technologies.

Interactions between the driver, transfer and delivery components of the system were explored over time and space within an integrated framework to provide a platform for future model calibration and understanding within the continuum and within the wider Belizean coastal zone. A cost-benefit model was used to consider monitoring and management options for the banana industry, promoting the integration of science and management within the wider scale of change.

§8.2 Perspective

The next decade promises uncertain times for the banana industry in Belize (European Commission, (1995), Oxfam, (1998) G.O.B, (1999)). Changing environmental, political and economic conditions will challenge future sustainability and bring environment and development issues to the forefront of industrial management. However, unlike previous obstacles encountered by the industry, development in the face of environmental change may be addressed progressively and cost-effectively, unlike the radical industrial reform that followed hurricanes Fifi and Greta (B.G.A. (1993), King, *et al.,* (1993)).

Obstacles on the horizon, such as the WTO rulings may present greater challenges to development, although present conflicts should not be ignored in light of the industry's uncertain long-term future. Change within the Belizean barrier reef system has received growing coverage since the onset of this research (1997) (e.g. Aronson, *et al.,* 2000), and it is anticipated that research programmes being undertaken at the present time (e.g. WRIScS, CARICOMP) will continue to emphasise the demand for increased monitoring and management of anthropogenic activities within the coastal zone.

Ideally the banana industry will be at the forefront of such change, where the sensitive balance already maintained between environment and development may be extrapolated to develop regional and international co-ordination between land-use, monitoring and management agencies. The potential for greater "environmental responsibility" within agricultural development is significant, where strategies offered in Chapter 7 may be mutually advantageous for all parties involved in coastal zone management and the development of the banana production industry. Indeed, there is scope for this responsibility to be transferred to the level of the consumer, where the business case for "green production" has strengthened over recent years in light of successes such as those achieved by the sustainable timber movement (e.g. Timberlands Ltd, 1999). A perspective on such for the banana industry in Belize has been offered as a business case below:

A business case for green production within the Belizean banana industry:

- Consumers increasingly desire their consumption to be sustainable, and there is increasing evidence that at least some are prepared to pay a small premium for such (Ikerd, J.E., 1999).
- The additional plantation management costs necessary to control fluvial sediment yield (§7.6) may therefore ultimately be reflected within consumer prices.

Despite a number of practical difficulties associated with achieving this in a highly competitive industry, experiences such as those of the sustainable timber movement (Timberlands Ltd, 1999) suggest that it is **well worthwhile** for industries to adopt **self-regulation** and badging of their greenness. Ultimately the competitive advantage will swing in favour of those who are **in** the scheme rather than not.

To secure the feasibility of this "environmental responsibility", the development of banana plantation agriculture within the coastal zone must be considered as a possible "driver" of LOICZ where the potential for impact from land-use change is conceptualised outside the drainage basin system. The sensitivity of the Belize coastal environment is generally perceived to be of greater importance as the potential anthropogenic impact nears the reef system, where marine species biodiversity increases from the coastal wetlands to the coral, conch, shrimp and seagrass populations of the outer reef (Figure 8.1).

However, the distance from the anthropogenic driver (e.g. plantation agriculture) also increases with such biodiversity (Figure 8.2) clouding the differentiation of cause and effect and challenging wider system management.

This challenge may be confronted by conceptualising system interactions within the wider framework of change, to promote pro-active monitoring at the stage where the potential for the conveyance of effect can be detected (i.e. the fluvial system but potentially within the estuarine and coastal systems) and fluid management at the stage where key drivers and their interactions with the surrounding environment may be most effectively understood (i.e. the plantation).

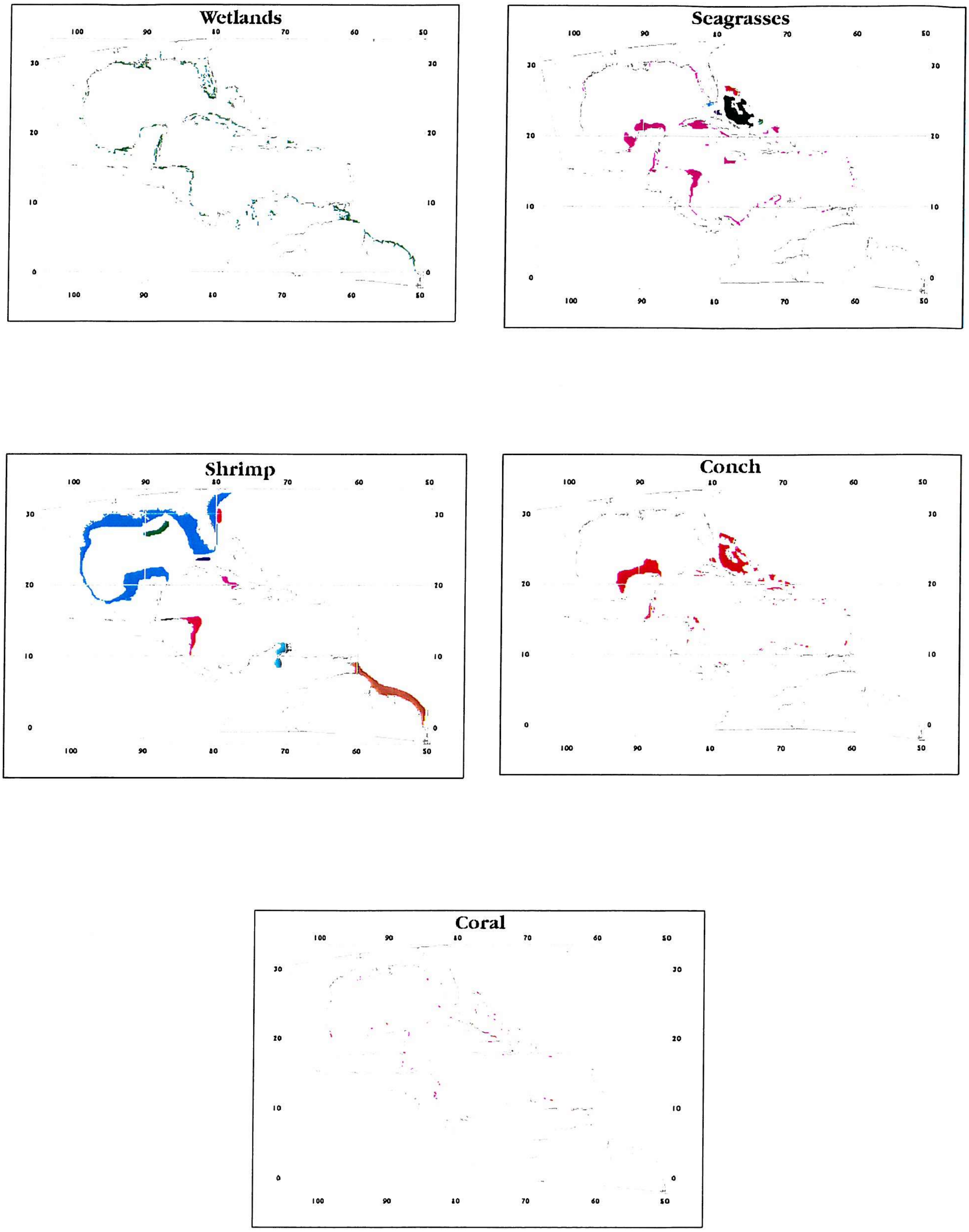


Figure 8.1: Marine species biodiversity, Belize (UNEP, 2000)

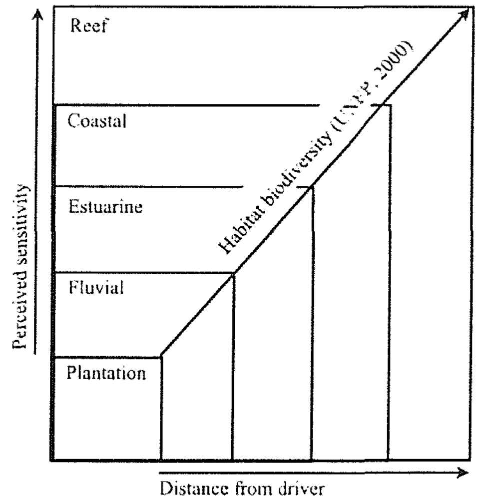


Figure 8.2: Distance from the plantation driver contrasted with habitat biodiversity and perceived sensitivity within the Belizean coastal zone

Through conceptualising system interactions at the level of maximum potential sensitivity research may be openly conducted in such as way as to facilitate integration between science and management and reduce potential conflicts between environment and development. This provides leverage for understanding the interaction of anthropogenic and "natural[1]" components of the LOICZ framework within the Belizean coastal zone.

The conceptual model used in this thesis for characterising interactions between banana plantation agriculture and pressures within the coastal zone may also be used for exploring interactions between anthropogenic activities such as fishing, tourism and urban development and LOICZ Belize. The barrier reef will remain fundamental to the continued development of Belize's economy (G.O.B, 1999) and therefore changes within the multitude of inter-related factors must be conceptualised within a universal framework to promote effective system management based on understanding at local, regional and global scales:

> ***"Science should support management, by developing clear visions about the entire ecosystem, its natural variability, the boundary conditions that sustain the system and the managerial possibilities.***
>
> IGBP, (1999)

[1] **"Natural" refers to environment that has not been extensively disturbed by human activity here, although the difficulties associated with the definition of "natural" environments are well recognised (Sapp, 1999).**

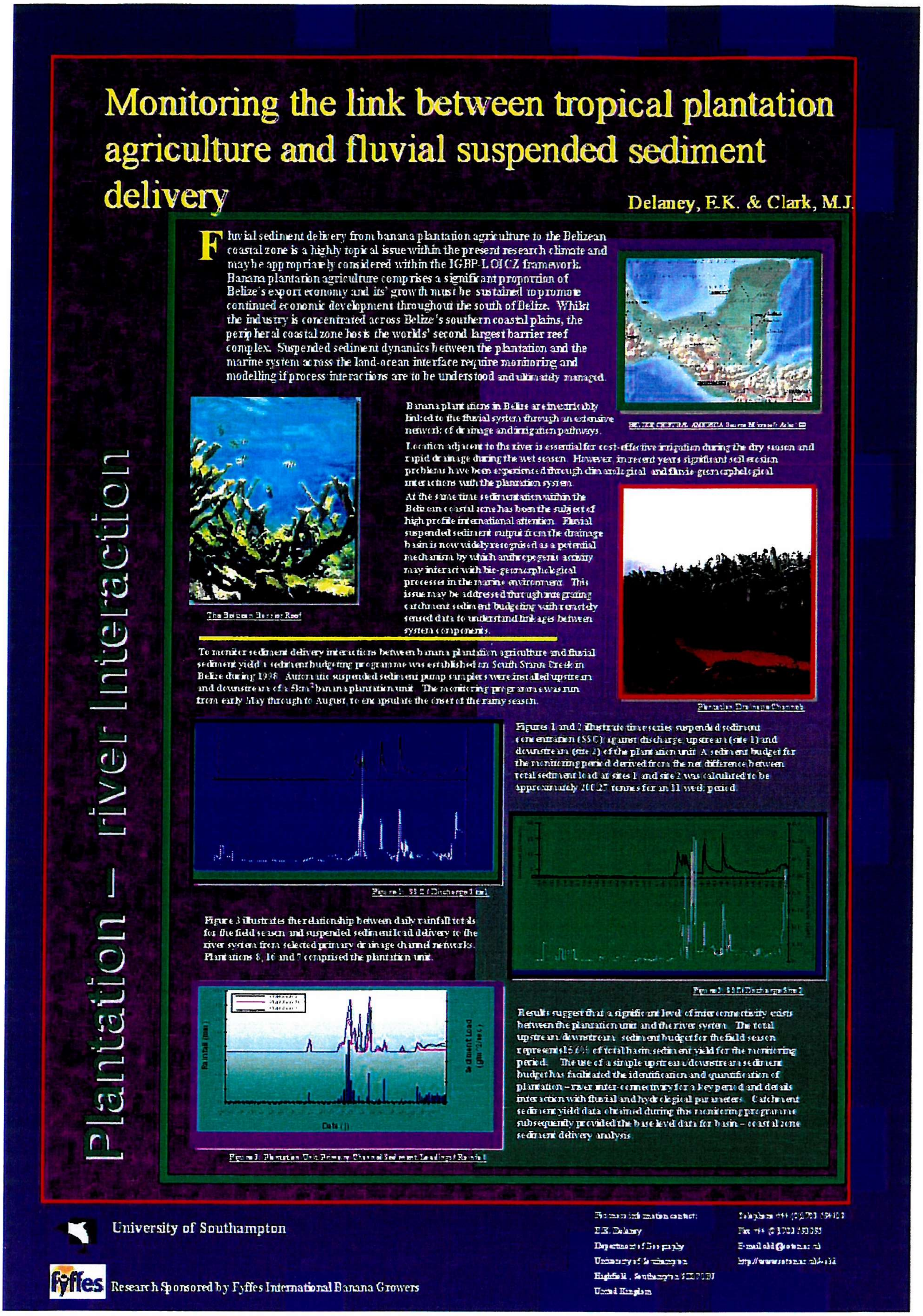
Appendix 1

List of acronyms

AVHRR: .... Advanced Very High Resolution Radiometer
BGA: .... Banana Growers Association
$BZ: .... Belize Dollars
CBEA:.................. Caribbean Banana Exporters Association
CCAD: .... Comission Centroamericana de Ambiente y Desarrollo
CZMU:................. Coastal Zone Management Unit
DPSIR:................. Driver-Pressure-State-Impacts-Response framework (LOICZ)
EIU:...................... Economist Intelligence Unit
EOS:..................... Earth Observing Sensor
ESA:..................... European Space Agency
ESTAP:................ The Environmental and Social Technical Assistant Project
EU: .... European Union
GOB:.................... Government Of Belize
GIS:...................... Geographic Information System
HRV:.................... High resolution visible
IGBP: .... International Geosphere – Biosphere Project
IOC: .... International Oceanographic Commission
IRS: .... Indian Remote Sensing
IUCN: .... The World Conservation Union
Landsat TM: .... Landsat Thematic Mapper
Landsat ETM+: .. Landsat Enhanced Thematic Mapper Plus
LOICZ:................ Land-Ocean Interactions in the Coastal Zone
MERIS:................ Medium Resolution Imaging Spectrometer
MSS: .... Multi-Spectral Scanner
NASA:.................. National Aeronautics and Space Administration
NOAA:................. National Oceanic and Atmospheric Administration
OS: .... Ordnance Survey
SaGiTun .... Sava, Gina, Tun *(Creole)*
SeaWiFS:............. Sea-viewing Wide Field of View Sensor
SSC: .... Suspended Sediment Load
SPM: .... Suspended Particulate Matter
SPOT: .... Systeme Probatoire d'Observation de la Terre
UNEP:.................. United Nations Environment Project
WMO:.................. World Meteorological Organisation
WWF: .... World Wildlife Fund for nature

Appendix 2

Poster presentation: 4th LOICZ Open Science Meeting: Bahia Blanca, Argentina


Monitoring the link between tropical plantation agriculture and fluvial suspended sediment delivery
Delaney, F.K. & Clark, M.J.
Plantation – river Interaction
Fluvial sediment delivery from banana plantation agriculture to the Belizean coastal zone is a highly topical issue within the present research climate and may be appropriately considered within the IGBP-LOICZ framework. Banana plantation agriculture comprises a significant proportion of Belize's export economy and its' growth must be sustained to promote continued economic development throughout the south of Belize. Whilst the industry is concentrated across Belize's southern coastal plains, the peripheral coastal zone hosts the worlds' second largest barrier reef complex. Suspended sediment dynamics between the plantation and the marine system across the land-ocean interface require monitoring and modelling if process interactions are to be understood and ultimately managed.
Banana plantations in Belize are inextricably linked to the fluvial system through an extensive network of drainage and irrigation pathways.
Location adjacent to the river is essential for cost-effective irrigation during the dry season and rapid drainage during the wet season. However, in recent years significant soil erosion problems have been experienced through climatological and fluvio-geomorphological interactions with the plantation system.
At the same time sedimentation within the Belizean coastal zone has been the subject of high profile international attention. Fluvial suspended sediment output from the drainage basin is now widely recognised as a potential mechanism by which anthropogenic activity may interact with bio-geomorphological processes in the marine environment. This issue may be addressed through integrating catchment sediment budgeting with remotely sensed data to understand linkages between system components.
The Belizean Barrier Reef
To monitor sediment delivery interactions between banana plantation agriculture and fluvial sediment yield a sediment budgeting programme was established on South Stann Creek in Belize during 1998. Automatic suspended sediment pump samplers were installed upstream and downstream of a 5km² banana plantation unit. The monitoring programme was run from early May through to August, to encapsulate the onset of the rainy season.
Plantation Drainage Channels
Figures 1 and 2 illustrate time series suspended sediment concentration (SSC) against discharge, upstream (site 1) and downstream (site 2) of the plantation unit. A sediment budget for the monitoring period derived from the net difference between total sediment load at sites 1 and site 2 was calculated to be approximately 200.27 tonnes for an 11 week period.
Figure 1. SSC / Discharge Site 1
Figure 3 illustrates the relationship between daily rainfall totals for the field season and suspended sediment load delivery to the river system from selected primary drainage channel networks. Plantations 8, 16 and 7 comprised the plantation unit.
Figure 2. SSC / Discharge Site 2
Rainfall (mm)
Sediment Load (gm^2/sec)
Date (J)
Figure 3. Plantation Unit Primary Channel Sediment Loading / Rainfall
Results suggest that a significant level of inter-connectivity exists between the plantation unit and the river system. The total upstream/downstream sediment budget for the field season represents 15.6% of total basin sediment yield for the monitoring period. The use of a simple upstream/downstream sediment budget has facilitated the identification and quantification of plantation – river inter-connectivity for a key period and details interaction with fluvial and hydrological parameters. Catchment sediment yield data obtained during this monitoring programme subsequently provided the base level data for basin – coastal zone sediment delivery analysis.
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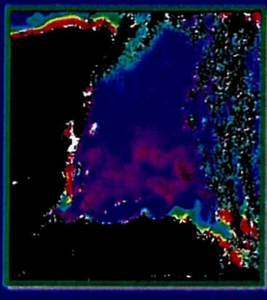
Remote sensing as a tool for monitoring tropical suspended sediment delivery to the Belizean Coastal Zone

Delaney, E.K. Clark, M.J & Nunny, R.

Coastal Sediment delivery

In recent years, new techniques for monitoring river inputs to ocean systems have contributed greatly to the understanding of sediment dynamics at the interface between the land and the ocean. Remote sensing has rapidly become a standard technique for the detection of material transported in suspension in coastal waters[1]. Through measuring the upwelling light at various wavelengths within the visible and infrared parts of the spectrum, the concentration of material in suspension such as sediments, chlorophyll and yellow substance (organic matter) can be estimated. More specifically, instruments such as SeaWiFS, Landsat TM, MSS, IRS 1-C SPOT and MERIS should be able to detect sediment plumes[2]. In comparison to sampling procedures carried out locally (i.e. ship-borne), which provide relatively accurate concentration data but usually poor spatial coverage, remote sensing provides a tool that gives excellent spatial and temporal information about the nature of sediment plumes.

There are however, some problems with using this method for examining sediment plumes in coastal environments. Perhaps the largest drawback is related to the varied nature of suspended material. It has been very difficult to establish a single universal algorithm. Most relationships seem to be site, sensor and season specific, making it very difficult to use remote sensing as a predictive tool. Another problem with using remote sensing to examine the properties of a sediment plume emitted from a tropical river is that during high discharge episodic events, (when it is anticipated that there would be the largest concentrations of suspended material), cloud cover would also be at a maximum. Despite these drawbacks, remote sensing provides a useful tool for examining the interface between the land and the ocean over spatial and temporal scales.



SeaWiFS LAC image of the Belizean Coastal Zone (courtesy of Plymouth Marine Laboratory)

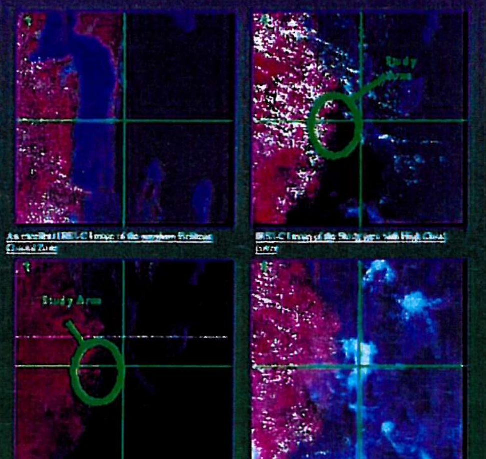
To further understand interactions between banana plantation agriculture and fluvial sediment delivery to the Belizean coastal zone, high resolution spatial and temporal information about suspended sediment dynamics at the land – ocean interface was required. In theory this would take place through the merging of medium-high spectral resolution data with high temporal and spatial resolution remotely sensed data for the Belizean Coastal Zone. Merged data would subsequently provide a tool for integrated coastal zone management in Belize and facilitate the linking of system components. This poster discusses the identification of key imagery resources for this procedure and highlights a number of problems that require consideration prior to its effective utilisation in the future.

Merging remotely sensed data obtained from NASA's SeaWiFS (Sea Viewing Wide Field of View Sensor) with imagery obtained from the European Space Agency's MERIS (The Medium Resolution Imaging Spectrometer), equated to an ideal procedure for monitoring suspended sediment delivery from rivers and creeks to the Belizean coastal zone. The medium spatial resolution of MERIS (300m) merged with Local Area Coverage SeaWiFS (1000m) was thought to provide sufficient – although a little coarse – spatial coverage of the process. This data was to be calibrated with secchi disk data for the same area. SeaWiFS has a particularly high return interval of 48 hours and when merged with the high spectral resolution of MERIS it was anticipated that significant information would be obtained about the nature of fluvial – coastal sediment dynamics within the Belizean Coastal zone.

Unfortunately despite this project being accepted by the European Space Agency as a future project following the Announcement of Opportunity in 1997, the delayed launch of MERIS prevented its implementation for this research. However the merging of SeaWiFS with MERIS may prove to be a useful device for continued coastal zone monitoring in Belize following the launch of MERIS in 2000 / 2001.

It was subsequently decided that instead of using MERIS to sharpen the spatial resolution of SeaWiFS imagery, Landsat Thematic Mapper (TM) imagery (with 30m resolution or IRS –C imagery (wit 180m resolution) would be used to reach the same end. However, a number of problems were experienced in connection with this.

Primarily the merging of Landsat TM or IRS 1-C with SeaWiFS required considerable inter-spectral mixing to achieve a sequence of images detailing the extension of a sediment plume over time into the Belizean Coastal Zone. Secondly the cloud coverage for Landsat TM and IRS 1-C images obtained during the field season of 1998 was very high for quantitative or even qualitative information to be derived from such. Indeed, this problem has been well recognised as a limitation of remotely sensed spectral data for the monitoring of suspended sediment dynamics within tropical environments. It is also questionable whether merging the 30metre Landsat TM pixels with 1000m resolution SeaWiFS imagery would provide any meaningful spatial results. The IRS1-C imagery archive for 1998 was extremely limited and the images displayed here are only reasonable ones obtained during the field season. It was therefore decided that whilst the value of merging high temporal and spectral resolution imagery with medium spatial resolution data is potentially ideal for monitoring sediment dynamics at the interface between the land and the ocean in Belize, the practicalities of obtaining cloud free imagery during a period of considerable hydrological activity is somewhat more challenging.



An excellent IRS-1C image of the northern Belizean Coastal Zone

IRS-1C image of the Study area with High Cloud cover

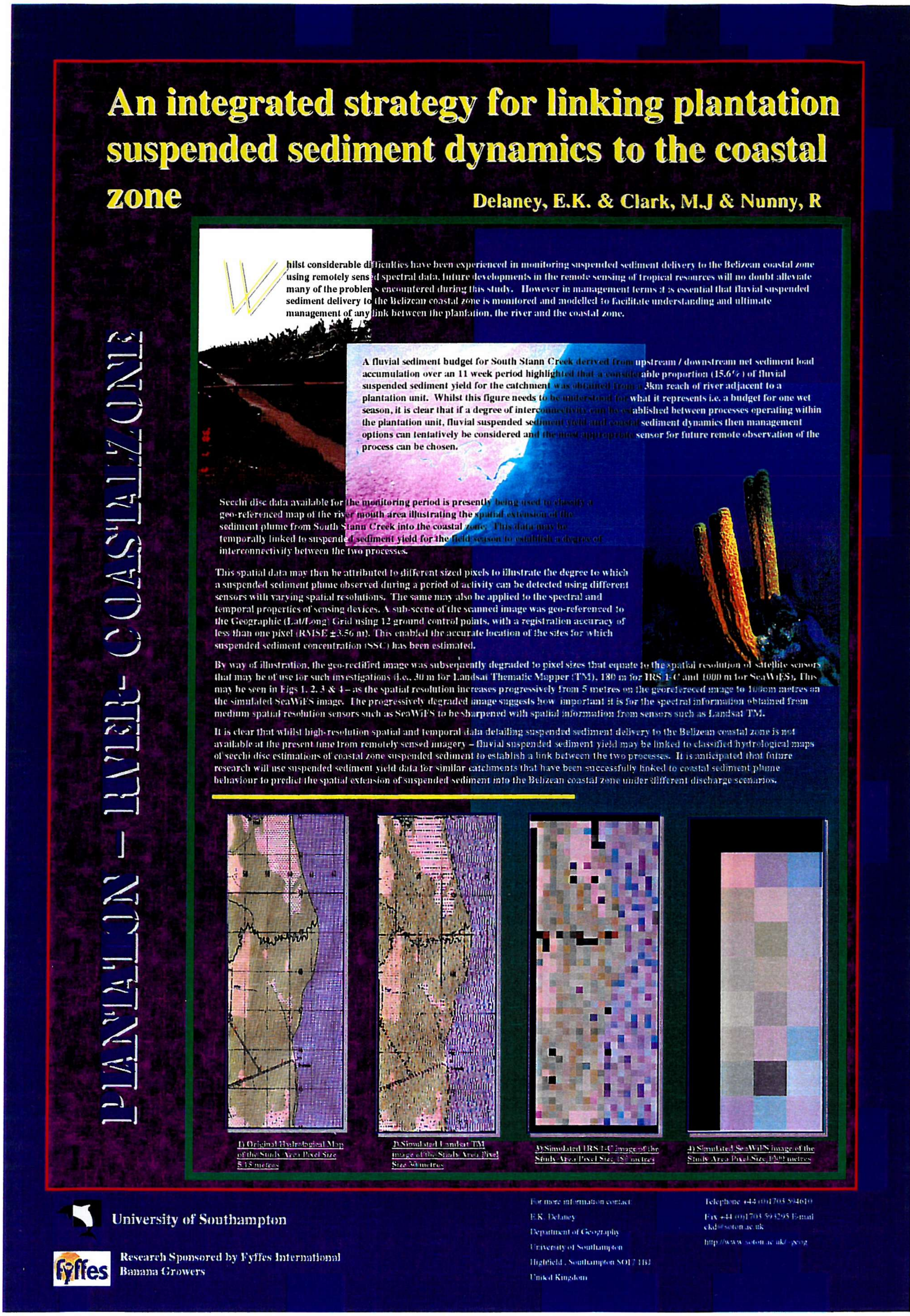
A dark IRS-1C image of southern Belizean Coastal Zone

Typical Cloudy Image for the Belizean Coastal Zone

Images on this page supplied by [illegible]

[1] [illegible], J. C. (1991) Application of [illegible] analysis to remote sensing of coastal water quality. *International Journal of Remote Sensing*, 1991, Vol 12, No 7 1441-1452

[2] Froidefond, J. et al (1991) Analysis of the Turbid Plume of the Gironde (France) Based on SPOT Radiometric Data. Remote Sensing of the Environment 36:149-163 (1991)


An integrated strategy for linking plantation suspended sediment dynamics to the coastal zone
Delaney, E.K. & Clark, M.J & Nunny, R
PLANTATION - RIVER - COASTAL ZONE
Whilst considerable difficulties have been experienced in monitoring suspended sediment delivery to the Belizean coastal zone using remotely sensed spectral data, future developments in the remote sensing of tropical resources will no doubt alleviate many of the problems encountered during this study. However in management terms it is essential that fluvial suspended sediment delivery to the Belizean coastal zone is monitored and modelled to facilitate understanding and ultimate management of any link between the plantation, the river and the coastal zone.
A fluvial sediment budget for South Stann Creek derived from upstream / downstream net sediment load accumulation over an 11 week period highlighted that a considerable proportion (15.6%) of fluvial suspended sediment yield for the catchment was obtained from a 3km reach of river adjacent to a plantation unit. Whilst this figure needs to be understood for what it represents i.e. a budget for one wet season, it is clear that if a degree of interconnectivity can be established between processes operating within the plantation unit, fluvial suspended sediment yield and coastal sediment dynamics then management options can tentatively be considered and the most appropriate sensor for future remote observation of the process can be chosen.
Secchi disc data available for the monitoring period is presently being used to classify a geo-referenced map of the river mouth area illustrating the spatial extension of the sediment plume from South Stann Creek into the coastal zone. This data may be temporally linked to suspended sediment yield for the field season to establish a degree of interconnectivity between the two processes.
This spatial data may then be attributed to different sized pixels to illustrate the degree to which a suspended sediment plume observed during a period of activity can be detected using different sensors with varying spatial resolutions. The same may also be applied to the spectral and temporal properties of sensing devices. A sub-scene of the scanned image was geo-referenced to the Geographic (Lat/Long) Grid using 12 ground control points, with a registration accuracy of less than one pixel (RMSE ±3.56 m). This enabled the accurate location of the sites for which suspended sediment concentration (SSC) has been estimated.
By way of illustration, the geo-rectified image was subsequently degraded to pixel sizes that equate to the spatial resolution of satellite sensors that may be of use for such investigations (i.e., 30 m for Landsat Thematic Mapper (TM), 180 m for IRS 1-C and 1000 m for SeaWiFS). This may be seen in Figs 1, 2, 3 & 4 – as the spatial resolution increases progressively from 5 metres on the georefereced image to 1000m metres on the simulated SeaWiFS image. The progressively degraded image suggests how important it is for the spectral information obtained from medium spatial resolution sensors such as SeaWiFS to be sharpened with spatial information from sensors such as Landsat TM.
It is clear that whilst high-resolution spatial and temporal data detailing suspended sediment delivery to the Belizean coastal zone is not available at the present time from remotely sensed imagery – fluvial suspended sediment yield may be linked to classified hydrological maps of secchi disc estimations of coastal zone suspended sediment to establish a link between the two processes. It is anticipated that future research will use suspended sediment yield data for similar catchments that have been successfully linked to coastal sediment plume behaviour to predict the spatial extension of suspended sediment into the Belizean coastal zone under different discharge scenarios.
1) Original Hydrological Map of the Study Area Pixel Size 5.15 metres
2) Simulated Landsat TM image of the Study Area Pixel Size 30 metres
3) Simulated IRS 1-C image of the Study Area Pixel Size 180 metres
4) Simulated SeaWiFS image of the Study Area Pixel Size 1000 metres
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Appendix 3

Contact information for listed organisations

Banana Growers Association .... Big Creek
Independence
Belize
Central America

Fyffes International Banana Growers... Big Creek
Independence
Belize
Central America

Fyffes Ltd., UK .... Houndmills Road
Houndmills Ind. Est.
Basingstoke
United Kingdom

Hydrological Monitoring Service, Belize .... Airport camp
9½ miles,
Northern Highway
Ladyville, Belize

Raleigh International .... Raleigh House,
Parsons Green Lane,
London
United Kingdom

Watershed – Reef Interconnectivity SCientific Study .... 7½ miles,
Northern Highway
Ladyville, Belize

Appendix 4

Filter paper handling procedures

Various methods were investigated to ascertain the potential errors associated with handling procedures and to determine the influence of drying and desiccating on their pre-field and post-field states. Samples were pre-dried and post-dried at 121°C as this has been found to be the most appropriate drying temperature for the papers under normal conditions (Whatman pers. comm.). However cohesive sediments have been reported to de-nature under such high temperatures and the material would subsequently be useless for particle size analysis – eliminating the possibility of subsequent follow-up research. Therefore laboratory tests were also carried out at 80°C as this has been reported to be the maximum drying temperature at which particle size deformation was not expected to take place (Whatman International Ltd, not dated).

Table 1: Cellulose Nitrate Handling Procedure Test Methods

Method	*Oven Dry at 121°C*	*Oven Dry at 80°C*	*Desiccator*	*Sealed plastic wallet for 24 hours*	*Wet Sample*	*Place in sealed plastic wallet for 24 hours*	*Air .Dry*	*Oven Dry at 80°C*	*Oven Dry at 121°C*	*Desiccator*
#1	√		√	√	√	√			√	√
#2		√	√	√	√	√		√		√
#3				√	√	√	√			
#4				√	√	√			√	√
#5				√	√	√		√		√

Each method was tested on cellulose nitrate filter papers twenty times. The virgin and final weight of the filter paper was determined using an Ohaus balance and readings were taken to the 4th decimal place. Whilst weighing the filter papers the door to the balance always remained shut to prevent disturbance from breeze. Table 2 details the average of the differences for each of the methods and the subsequent justification for selecting the chosen method.

Table 2: Cellulose Nitrate Handling Procedure Test Results

Method	*Mean difference between virgin and final filter paper weights (gms) for 20 samples*	*Comments*
#1	-0.0008	Temperature unsuitable for later particle size analysis
#2	-0.0005	Good method – however difference in error margins between this and #5 failed to justify the difference in preparation time.
#3	+0.0001	Time consuming method and difficult to achieve high level of accuracy unless under extremely controlled conditions
#4	-0.0009	Temperature unsuitable for later particle size analysis
#5	-0.0002	Chosen Method

Appendix 5

Description of main features

127-170(j): SSC at site A between 127 and 139(j) appears unusually high when set against discharge levels for the same period. This is particularly evident when analysing discharge and SSC for the period 140 – 169(j) where the variables appear to have been behaving in a similar manner and fluctuate within a similar order of magnitude. Indeed, during these dry season months with low discharges steadily fluctuating between 0.16 and 1.46 m^3sec^{-1} SSC levels fluctuate between 0.0006 and 0.04 prior to 140(j), however, during the remaining dry season period SSC only ranged between 0.001 and 0.02 g/lt.

When examining this pattern relative to discharge it appears that something in addition to discharge was operating within the upstream catchment to influence sediment behaviour. Precipitation statistics for the same period indicate that no rainfall had fallen within the catchment during that time. It is possible that erosional processes within the upper reaches of the catchment associated with the undercutting and bank collapse of previously exposed sections resulting from low discharges may have been partially responsible for this period of activity. As SSC levels for the same period appear particularly high at site B (Figure 4.8) it is suggested that this activity may have been related to processes operating upstream of monitoring site A. However SSC activity at Site B appears to fluctuate within even greater margins where significant activity occurs between 0.0003 and 0.06 g/lt. Modifications to catchment dynamics during periods of agricultural activity associated with the expansion of banana plantation areas approximately 3km upstream of monitoring site A may have been related to this period of high SSC. However between sites A and B the significant increase in SSC suggests that this period of activity may be more related to the collapse of banks previously exposed by erosional events. There is a possibility that fluctuations may have been associated with problems in the operation of pump sampling apparatus. However, calibration readings for this period suggest that a high level of confidence may be placed in the automatically collected data.

Following this period little activity was recorded until 171(j) where SSC increased at both sites A and B in a similar manner to discharge. However at site B on 168 (j) SSC reached a peak of 0.03 g/lt, which appears to have been associated with activity taking place between site A and site B. The net increase in SSC between sites A and B throughout the dry season period is quite significant and it is important to consider the contribution of in-stream erosional processes to the sediment budget for this area. South Stann Creek meanders significantly throughout the coastal plains and it is possible that disturbance to fluvial and agricultural bank profiles during past season hydrological events exposed significant sections of material – especially on meanders, which subsequently became more vulnerable to collapse during dry season undercutting processes.

171-176(j): Between the latter half of 171 and 173(j) a dramatic rise in discharge was only associated with a comparably minor increase in SSC at site A, little different from those levels experienced during the low discharge periods of the preceding dry season. Indeed, as discharge fluctuated between 17 and 13 m^3sec^{-1} it was only on the falling limb that SSC reached a peak of 0.34(g/lt) on 176(j). However at site B SSC responded in a slightly different manner. Whilst between the latter half of 171 and 173(j) little SSC activity was evident at site B on the rising discharge limb – peak discharge for this event towards the end of 173(j) was accompanied by a series of peaks in SSC between 0.12 and 0.25 g/lt, despite little activity recorded at site A. It is clear that some form of sediment mobilisation was taking place at this stage in the reach between sites A and B during 174, 175 and 176 (j). Whilst further analysis would be required with respect to specific interactions with plantation practices, it is evident that sediment mobilisation as a function of interaction between the channel peripheral to the plantation system and SSC behaviour may have been a strong possibility during this period. Indeed, localised storm activity was particularly concentrated over the plantation unit area during this time.

There are a number of factors that may have been responsible for the lag between peak Q and peak SSC at site A between 174 and 176(j). Primarily, localised hydrological variations may be responsible for some lag between the two variables, however given that this time lag is almost 48 hours after the initial peak discharge and that high rainfall totals were recorded in the area this theory seems somewhat unlikely. Perhaps more feasible is that some form of bank and bed armouring was operating within the river system, where coarser sediments protected the river bed and banks during initial high discharge activity before eventually weakening and allowing finer sediments trapped underneath to be mobilised (Knighton, 1984). This explanation goes some way to explaining the magnitude of the lag between the two peaks at site A, especially when given what is presently known about South Stann Creek's mixed substrate of coarse sands and fine cohesive sediment. An alternative theory is that some form of bank stabilisation was taking place during periods of high discharge when the water prevented bank collapse and only during the falling discharge limb was pressure released and material slumped freely into the river system. In reality, this lag may be a combination of these factors.

This theory may explain the downstream peak on 176(j), which may have been the same peak as identified at site A. If so, it would suggest that the bank armouring or stabilisation influence on lag between SSC and discharge might have been operating upstream of the monitoring area as peak instantaneous concentration decreased between sites A and B.

177-182(j): However, following the peak identified on 176(j) the highly fluctuating SSC at site B ranging between 0.008 and 0.36 g/lt on 177 and 178 and 179(j) may again be explained by agricultural / hydrological interactions between sites A and B as little activity was recorded at site A during this period. Indeed this period of high fluctuating SSC may be linked with significant rainfall activity taking place within the field area during the same time frame. Further analysis of the relationship between localised hydrological activity and plantation sediment delivery would however be required prior to any conclusions being drawn about factors responsible for differences between upstream / downstream SSC behaviour.

The second peak of SSC on 179(j) at site A was recorded to be of similar magnitude to the first and also appears to have lagged approximately 48 hours after the last peak of high discharge activity during the period 171 – 179(j). This may be explained by the same armouring and stabilisation theories as discussed for the first peak at site A. The high SSC peak at site B on 180 (j) may be explained in the same way, where despite that preceding and subsequent peaks may have been related to sediment dynamics between sites A and B as a result of agricultural/hydrological interactions, the pulse of sediment recorded on the falling limb for 180(j) was the downstream function of previous armouring or bank stabilisation within the channel during the high discharge event that only transpired during falling discharge.

Between 179 and 182(j) the falling discharge limb at site A was mirrored by SSC until the high discharge event on 182(j) when an instantaneous peak in SSC occurred only a short period after the peak discharge event. It is interesting that SSC behaviour following this event was recorded to be somewhat different to that before, although it should be noted that data can not be analysed to a higher degree of accuracy than with which it was monitored. It is possible that if bed/bank armouring was taking place then coarse material trapping fine-cohesive sediments was removed during earlier events and thus by the third period of high discharge activity exposed fine sediments were disturbed more effectively. It is also possible that this material may have originated from a different source to before. Ideally future studies would investigate the particle size composition of the sediments mobilised during consecutive events to facilitate understanding of the contribution from different sources more effectively. Indeed the theory is strengthened somewhat by the same pattern emerging for site B where peak SSC on 182(j) mirrored peak discharge 4 hours later. The fact that this peak at site B was 0.01 g/lt less than that recorded at site A suggests that whilst a slight material sink occurred between sites A and B, there is a strong possibility that this peak was the same pulse of material originating from an upstream source that was recorded at site A.

182-188(j): Between 182 and 187/8 (j) the falling discharge limb was almost mirrored by SSC at sites A and B. This pattern increases confidence in the bank/bed armouring theory. If coarse sandy sediments were flushed through the system during earlier events then exposed fine cohesive silts and clays, being the natural substrate of South Stann Creek, may have been mobilised more effectively relative to discharge behaviour. On 188(j) the high discharge event was again mirrored by SSC at site A where lag was recorded approximately 8 hours between discharge and SSC peak events. At site B the same was evident on 188(j) although the peak SSC appeared to lag by a slightly longer period.

SSC behaviour was again different between site A and site B on the falling discharge limb. Whilst at site A SSC rapidly fell to a comparatively low concentration, at site B SSC remained within the same order of magnitude. This may be again explained by hydrological / agricultural interactions within the site A site B reach as extensive storm activity was taking place within the plantation area during this period (National Meteorological Service, Belize (1998b)).

189-196(j): The falling discharge limb was followed less smoothly by SSC at sites A and B than during previous events where considerable disturbance within SSC dynamics may be noted. In particular, on 191(j) the small fluctuation in discharge appears to have been reflected by an SSC peak of 0.047 g/lt a short period later at site A. Whilst at site B the small fluctuation in discharge appears to have been reflected by an SSC peak a similar period later, of 0.079 g/lt. If this SSC peak is assumed to be the same pulse as that recorded at site A a net accumulation of 0.032 g/lt took place between sites A and B.

However prior to the small discharge fluctuation at site A, a larger SSC of 0.657 g/lt was recorded. It is difficult to identify whether the larger SSC peak was a lead event or a function of internal sediment dynamics and subsequently less related to discharge than other variables. This pattern is also evident at site B although peak SSC is slightly less than the lagged peak. The fact that this occurred at both sites and that the lead peak at site B was recorded to be less than the lagged peak for site B indicates that the lead peaks were more likely to have been a pulse of material moving down stream from an unknown source, depositing some material between sites A and B.

A similar pattern may be observed on 196(j) where another small fluctuation in discharge at site A may have been associated with SSC activity at two stages. Given the previous pattern of SSC activity it appears likely that a slightly lagged peak of 0.032 g/lt occurring after the discharge event was directly related to flow behaviour. However it is again evident that a slightly larger peak of 0.051g/lt precedes the fluctuation in discharge by a short period. The recurrence of this feature suggests that there may have been an additional link between upstream hydrology and sediment dynamics that interacted to drive system behaviour in such a way.

At site B, two peaks may also be associated with the minor discharge fluctuation. Primarily a lagged SSC peak of 0.332 g/lt follows discharge, however a significant peak of 0.11g/lt lags the event by approximately 24 hours. Given the time lag between the discharge fluctuation and the high SSC peak and that no rainfall was recorded for the plantation area during that period it appears that significant activity took place within in-stream channel sediment dynamics between site A and site B for such a high and lagged peak to emerge, especially that the peak was an order of magnitude higher than either of the peaks recorded at site A during the same period. It is possible that the minor blip in discharge served to trigger a mass mobilisation of suspended sediment within the channel system, either from bank collapse or the removal of a localised section of material that was functioning as an armouring device. However, due to the fact that no rainfall was recorded during this period, the previous theory that plantation interaction with hydrological events was driving the delivery process cannot be applied in this instance.

196-209(j): The disturbed profile of SSC from 190(j) to 202(j) at both sites suggests that sediment dynamics were driven by a highly episodic system where factors such as local hydrological and erosional events were influencing delivery behaviour to a greater extent than river discharge. SSC fluctuated over this period between 0.008 and 0.05 g/lt at site A whilst at site B it fluctuated between 0.017 and 0.11g/lt, however, discharge remained within the same order of magnitude. Between 202 and 209 discharge and SSC behaviour fluctuated considerably at both sites. SSC increased dramatically towards the end of the field season despite only a small rise in discharge. Of note, the SSC peak of 0.14 g/lt on 207 (j) does not appear to have been directly related to an individual discharge event, and at site B a seemingly unrelated peak was identified to have a concentration of 0.266 g/lt. Indeed, as the monitoring period progressed it appears that SSC behaviour became less and less related to discharge activity and alternative drivers operating within the catchment system appeared to control SSC dynamics. In particular extensive storm activity between 202 and 209(j) within the plantation area may have been intrinsically related to a significant net increase in SSC between site A and site B towards the end of the field season. Clearly, more detailed investigations into hydrological interactions between SSC and discharge dynamics would facilitate calibration of initial observations further.

Appendix 6

The South Stann Creek drainage network

Location of the plantation unit wihtin the Sonth Stann Creek drainage basin (1:150,000)

Appendix 7

Belize: Seas at the Millennium

Belize

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Abstract

Belize, Central America, contains some of the most important marine resources in the Caribbean including a 220 km barrier reef, shelf lagoon, three offshore atolls and extensive mangroves. The distribution of benthic communities within these systems is influenced by a range of factors, such as depth and wave action, but the effect of annual seasonal variation is limited. More important are stochastic events including coral bleaching, from increased seawater temperatures and solar irradiance, and hurricanes. Although the Belize Barrier Reef is known to be part of a highly linked "Meso-American" system which extends into Mexico and Honduras, national and international sources and sinks of larvae to benthic and pelagic communities are poorly understood.

In addition to entrained larvae, pollutants are transferred via oceanographic corridors and must be managed on a regional scale. These threats are synergistic with national threats which are mainly over-fishing, sedimentation, agricultural run-off and urban pollution, particularly sewage. The effects from these threats are still small relative to many areas of the Caribbean, largely because of a low population density and distance from the mainland to the reefs. However, the increasing tourism and a desire to diversify the economy must be carefully managed and, for example, the major fisheries (lobster and conch) are already presumed to be over-exploited. Similarly, agricultural practices have almost certainly caused damage to some near-shore lagoons by sedimentation and contamination, mangroves have been lost during the expansion of coastal zone towns and there have been localised effects by effluents from industrial plants. Sewerage is poor in towns within the coastal zone but there is little evidence of eutrophication although nutrient enrichment may play a key role in the increase in macro-algae throughout the Caribbean. Effects from aquaculture, oil exploration and diver damage may increase significantly in the future.

Healthy reef systems are vital to tourism and fisheries, two of Belize's biggest industries, and there are a range of initiatives to protect the coastal zone. These efforts, supported by all agencies in Belize and recently consolidated within a Coastal Zone Management Authority, have established adequate environmental legislation but enforcement and monitoring are limited. A

central component of the management initiatives is a series of marine protected areas and some have been given World Heritage status. There has been limited monitoring of the efficacy of these reserves but research has shown their use for regulating tourism and increasing fish populations. A holistic approach has been possible because Belize is a small country, impacts are limited and management measures relatively easy to implement and aided by significant national and regional funding. However, long-term financing and enforcement of regulations in all areas of the coastal zone are essential to maintaining the diverse marine and estuarine systems.

1. The defined region

Overview

Belize is small relative to many other countries in the wider Caribbean but contains some of the most important marine resources in the region. The coastal zone of Belize is well known for the longest barrier reef in the western hemisphere but also includes three of the Caribbean's atolls, extensive mangrove forests, seagrass beds and estuarine systems. The significance of the coastal zone to Belize is highlighted by the fact that over 50% of the national territory is marine (23,657 km^2 of territorial sea from a total of 46,620 km^2; Hartshorn et al., 1984).

The continental shelf is 240 km long and varies in width between 13 and 48 km. The Belize Barrier Reef is nearly continuous for 220 km along this shelf from the Sapodilla Cays in the south to the Mexican border. The barrier reef system also encloses approximately 6000 km^2 of lagoon (Sedberry and Carter, 1993) and includes 450 cays (islands).

Regional interactions

Although commonly referred to as the Belize Barrier Reef, the reef complex can be followed as an ecological and geological unit along the Yucatan Peninsula for approximately 450 km (Craig, 1966). After the reef nearly merges with Ambergris Cay at Rocky Point it parallels the Mexican coastline to Tulum and then consists of scattered coral heads to Cozumel. This direct association with other Central American countries, combined with the connections caused by currents carrying pollutants and entrained larvae, indicate the importance of treating Belize as part of a larger system inextricably linked with Mexico and the Gulf of Honduras (Gibson et al., 1998). For example, the currents which flow south along the continental shelf mean that the population of Chetumal (Mexico) may cause equal or greater effect to Belize's coastal zone than many of its own towns (McField et al., 1996).

In addition to interactions with bordering countries, Belize is connected to most reefs in the wider

Caribbean via the Guiana Current that flows north from Brazil before joining the North Equatorial Current. Such gross oceanographic patterns have lead to a high similarity between biological communities throughout the region. These patterns also provide a conduit for facilitating the spread of waterborne pollutants and pathogens. Perhaps the most devastating result of the regional currents has been the die-off of *Diadema antillarum* sea urchins in the early 1980's (reviewed by Lessios, 1988). During this period a host-specific pathogen caused mass mortality of *Diadema*, initially close to the Panama Canal and then spreading east to Tobago, west to Costa Rica and north to Florida and Bermuda via Belize and Mexico along known surface currents. Such region wide threats have led to management beyond geo-political boundaries including the Meso-American Reef Initiative along nearly 1000 km of reefs from the Yucatan Peninsula to the Bay Islands (Cortés and Hatziolis, 1998).

Although Belize can, and has, been affected by other countries in the region, it also has significant effects on downstream areas. Cortés (1997) indicates that Belize is probably among the most important source area of fish, coral and other invertebrate larvae in the area and this is supported by analysis of Caribbean reef connectivity (Roberts, 1997). However, there are minimal data to assess the proportion of larvae remaining within Belize compared to those settling in other countries and the results are equivocal. One of the few studies was carried out was on the lobster *Panulirus argus* (Glaholt and Seeb, 1992). This study showed that Belizean lobsters are genetically different to those in Florida and their larvae do not contribute significantly to Florida's population. In addition, lobsters within Belize are genetically very similar and could be self sustained but equally could receive foreign larvae across a broad geographic area. However, the higher frequency of a rare homozygote on Glovers Reef may indicate a separate system. Further studies are required to investigate the origin of larvae in Belize but it seems likely that the atolls may be more self-seeding than the barrier reef system.

2. Seasonality, currents and natural environmental variables

Seasonality

Belize is in the subtropical belt and experiences a dry and wet season (June to October). There are significant changes in all climatological parameters between these seasons and variation across the country. Variation in rainfall varies more between seasons than temperature, evaporation, wind or humidity (Heyman and Kjerfve, 1999) and noticeably affects salinity patterns. Hence the southern section of the continental shelf has a fresher water lens than the northern section because of the increased rainfall and more numerous rivers. Water is known to be less saline around the Sapodilla Cays (Perkins, 1983) but generally there is a well mixed surface layer of isohaline and isothermal water to a depth of 50 m (James and Ginsburg, 1979).

Although seasonality in Belize affects water parameters throughout the country there is little documented evidence of significant changes to the biota. Seasonal changes in macroalgal and seagrass growth are well known in reef and lagoonal systems throughout the Caribbean and are highest in summer and lowest after winter storms (Aronson et al., 1994). There is also an indication that the northern winds which often occur between November and March as cold and wet air is pushed south by Arctic air masses affect the movement of lobsters (Perkins, 1983). Sedberry and Carter (1993) document seasonality in the recruitment of grunts (Haemulidae) in a barrier reef lagoon but this did not cause variation in relative abundance or biomass.

More significant than annual seasonal patterns are coral bleaching events during occasional periods when climate conditions, for example caused by ENSO events, raise seawater temperatures and solar irradiance. Coral bleaching, the paling of coral tissue from the loss of symbiotic zooxanthellae, has often occurred on corals in Belize but until 1995 there had not been a widespread, major bleaching event (McField, 1999). During this event, when high seawater temperatures (over 29.4°C) and solar irradiance coincided with low wind speeds, 52% of the corals studied were affected and an estimated 10% of all colonies experienced partial tissue mortality by May 1996 (McField, 1999). Major reef builders, such as *Montastraea annularis* and *Agaricia tenuifolia*, were most affected and may cause long term threats to reef integrity, especially if recovery rates are slowed by stress from other sources (Cortés and Hatziolis, 1998). More recently, in 1998 a second bleaching event occurred in Belize although few data are currently published. However, the effects of the bleaching event on juvenile corals has been documented (Mumby, in press) and data on adult tissue mortality have been collected.

Currents

Prevailing winds in Belize are from the east and typically 15 km hour^{-1} (James and Ginsburg, 1979) causing currents that are much more influential than tidal ones. The predominant surface current inside the barrier reef is southerly, with a northerly current seaward of the three atolls and some westerly flow around their northern ends and within their lagoons (Perkins, 1983). The northerly current is a continuation of the current which flows west from Venezuela and north past Mexico. The hydrography of Belize is also influenced by the counter-clockwise surface gyre between Roatan (Honduras) and Glovers Atoll (Perkins, 1983). Furthermore, deep, nutrient rich oceanic waters occasionally enter the Gulf of Honduras from the Caribbean (Heyman and Kjerfve, 1999).

Water movement is known to be a key factor affecting coral reef zonation, along with nutrient requirements for particulate food and light, sedimentation and predation (reviewed by Sheppard, 1982). In Belize, 95% of waves are from the east and the remainder, from the west, have little mechanical effect on the forereef (Burke, 1982). Waves from the east are significantly modified by the atolls and this has a vital role in causing the variation in zonation seen between the three provinces of the barrier reef (Section 3). For example, the zone of high spur and groove formations in shallow water is only seen in areas of modified wave force and a ridge on the forereef only occurs when there is a wave force less than 40% of the unmodified level.

Hurricanes

The effect of hurricane disturbance on reef geo-morphology and benthic communities is well documented and is an important environmental factor in Belize. Hurricanes affect the reefs every three to six years, with a catastrophic hurricane every 30 years (Perkins, 1983). Hurricanes have been recorded since 1787 and are reviewed by Stoddart (1963) but perhaps the best studied was Hattie in 1961. Hattie's effects were studied by Stoddart, in a series of papers comparing the reefs and cays to their pre-hurricane condition (for example Stoddart, 1963). Within a swathe of heavy damage that crossed Turneffe Atoll and the central section of the barrier reef, Stoddart reported the removal of almost all trace of spur and groove formations on the barrier reef along with 80% of corals, virtually no living corals on the east side of Turneffe Atoll and a spectrum of coral resistance to mechanical damage from *Montastraea annularis* (most resistant) to *Acropora cervicornis* (least resistant). He also noted the higher levels of damage on the barrier reef than the atolls which may have been caused by the channel between them increasing wave height. Stoddart suggested a recovery period of 20-25 years but commented in 1969 that recovery was limited by mobile debris, algal competition and increased turbidity.

Subsequent hurricanes have also been studied, with further evidence of their importance in shaping zonation of the barrier reef and atolls. Rützler and Macintyre (1982) highlighted that Hurricane Greta (1978) caused significant lagoonward movement of *Acropora cervicornis* but that this transport and the establishment of living fragments is a key factor in its distribution. Hurricane Mitch (1998) caused 7 m seas for several days but there are currently little data on its effects. However, Mumby (in press) reports that approximately 90% of living *Acropora palmata* was removed at some sites on Glovers Atoll and a combination of bleaching and hurricane disturbance reduced coral recruit densities to 20% of levels recorded previously, with evidence that the effect of Mitch was more significant.

3. The major shallow water marine and coastal habitats

Geological setting

Extensive work has been carried out on the geology of Belize and although a full review is beyond the scope of this chapter, a brief synopsis is included here to assist an understanding of the distribution of marine resources in the area. Readers are referred to Stoddart (1962), Miller and Macintyre (1977), James and Ginsburg (1979), Precht (1993) and Macintyre and Aronson (1997) for more comprehensive information and an introduction to the literature. The following is a summary of the main conclusions of these studies.

Belize's geology is controlled by passive plate location rather than volcanic activity. Belize is on the Yucatan continental block which split from the Nicaraguan-Honduras to form the Cayman Trench, which lies seaward of the three atolls, and a series of submarine ridges. Two of the ridges are in deep water but the best developed ridge forms the southern edge of the continental shelf and continues as the base for Glovers Atoll and Lighthouse Reef. A fourth ridge underlies the central section of the barrier reef and Turneffe Atoll, while a fifth ridge is the base for the northern section of reef. The topography of the continental shelf reflects that of the mainland which has a flat lying north and a southern part uplifted by the Maya mountains. The shelf (lagoon) can be divided into three sections: the southernmost section where reefs are currently being drowned; a central section with maximum relief and luxuriant reef growth, including numerous patch reefs; and a northern section with relatively low relief but many small patch reefs. The distribution of recent sediments is significantly influenced by this topography.

Belize Barrier Reef

The Belize Barrier Reef and its associated ecosystems a resource of immense social and economic importance to the country. The following section provides a brief overview of its key features and habitats.

The barrier reef is not continuous along its length but consists of linear segments separated by a series of channels. However, the reef has built within 20 cm of sea level along 57% of its length (Burke, 1982). Variation of reef characteristics has led to Burke (1982) and later Macintyre and Aronson (1997) to describe three distinct provinces. The northern province, 46 km long from Reef Point to Gallows Reef Point, contains 31% of the barrier platform. The central province, 91 km from Gallows Reef Point to Gladden Spit, contains 62% and finally the southern province is 10 km long from Gladden Spit to the Sapodilla Cays. A major influence on the forereef structures within these provinces is the wave energy reaching them after attenuation by the atolls.

The central province contains the best reef development and is also the most well known (Macintyre and Aronson, 1997) but detailed habitat descriptions are also available for many other areas. The central province has long wide sections of unbroken reef with three distinct structural features (Burke, 1982). These are two zones of spur and groove formations and a shelf edge coral ridge. A transect across this reef profile at Carrie Bow Cay has been described in detail by Rützler and Macintyre (1982) but only a brief summary is included here. There is a shallow back reef, containing at least five sub-zones (Macintyre and Aronson, 1997), bordered on the seaward side by an intertidal reef crest. East of the reef crest is an inner forereef to a depth of 14 m with high relief spur and grooves to 10 m followed by lower relief formations. An outer forereef then slopes to a sand trough, followed by a coral rich outer ridge and escarpment. The characteristic corals of these zones include *Acropora*, *Montastraea*, *Agaricia*, *Porites* and *Millepora*. Although there is variation along the reef, this profile is typical of much of the reef platform.

Atolls

Belize's three atolls, between 7 and 45 km from the barrier reef, are considered the best developed in the Caribbean (Perkins, 1983). Glovers Atoll (132 km^2) has the best reef growth but Lighthouse Reef (126 km^2) and Turneffe Atoll (330 km^2) also have extensive reef resources. Their development has been more influenced by wave exposure than regional factors, such as sea level rise, which has caused Glovers and Lighthouse to be more similar to each other than the more protected Turneffe (Gischler and Hudson, 1998). Glovers and Lighthouse have deep, well circulated lagoons with numerous patch reefs and land area covering less than 3% of the atoll. In contrast, Turneffe has a land area of 22%, a shallow, poorly circulated lagoon and few patch reefs, except in the north of the atoll where there is little shelter from Lighthouse.

All the atolls have sides sloping into abyssal waters and their zonation has been described as early as Stoddart (1962). Again, wave exposure has a key role and Lighthouse and Glovers have, for example, more *Acropora palmata* and pavements of *Lithothamnion*. Similarly, there are significant differences between the leeward and windward reef on each atoll.

Patch and reefs and faroes

Throughout the Belizean shelf lagoon there are numerous patch reefs from small collections of coral heads to areas 80 m across (James and Ginsburg, 1979). These reefs are much more abundant in the southern lagoon than the north and support a wide variety of coral communities depending on shelf position, wave and current energy and depth (Precht, 1993). In addition to the patch reefs within the southern shelf lagoon, there are a series of rhomboid shaped atoll-like features (faroes) which may be formed by submerged sand or rubble cays (James and Ginsburg, 1979). They have similar zonation patterns to the patch reefs and generally have steeply sloping sides with deep (often 15-30 m) channels and central lagoons (Miller and Macintyre, 1977).

Increase of macro-algae

Most reefs within the Caribbean have experienced a dramatic decrease in coral cover and concomitant increase in macro-algae over the last two decades. This pattern has been attributed to a number of factors, particularly the mortality of *Diadema* urchins in the 1980's, removal of herbivorous fish and increased nutrients within the water column. Belize has been cited as an undisturbed system but data from the barrier reef (Aronson et al., 1994) and Glovers Atoll patch reefs (McClanahan et al., 1999) show algal cover increasing from approximately 5% to current levels of over 60%.

This ecological shift, however, has not been consistent in Belize and suggests a complex set of synergistic factors varying within the coastal zone. For example, on the barrier reef and Glovers Atoll patch reefs the changes paralleled the decimation of *Acropora* from white-band disease and show the role of coral mortality along with putative changes in herbivory and nutrients (McClanahan et al., 1999). The physico-chemical environment must also have an important role since the increased flushing on the forereef at Glovers Atoll seems to have limited disease effects and the increase in macro-algae is less apparent (McClanahan and Muthiga, 1998). In contrast, on the rhomboid reefs close to Carrie Bow Cay the result of *Acropora cervicornis* death is an alternative community state dominated by *Agaricia tenuifolia* (Aronson et al., 1998). Aronson et al. (1998) suggest that this shift seems to have been caused by intense herbivory by the urchin *Echinometra viridis*, reducing macro-algae and facilitating *Agaricia* recruitment.

Mainland fringing reefs

Reef growth along the Belize mainland is limited by fluctuations in salinity and high turbidity. The only growth possible is north of Port Honduras where terrigenous sediments are removed most efficiently and Perkins (1983) reports some reef development between Placencia and Punta Ycacos. These reefs are species poor and support only resistant genera such as *Siderastrea* and *Porites*.

Lagoonal shelf

The lagoonal shelf of Belize is dominated by seagrass beds, particularly *Thalassia*, which significantly modify the sediment regime and are important nursery and feeding grounds for many species. The lagoon is also a sink for estuaries from 16 major watersheds (Mcfield et al., 1996) and has a coastal strip of terrigenous sediments bordered by sand beaches or mangroves. Trawls near Ambergris Cay indicate that the fish community is dominated by grunts (Haemulidae) and consists mainly of juveniles of reef species (Sedberry and Carter, 1993).

Mangrove

Belize has 783.16 km^2 of mangroves (Gray et al., 1990) and this is likely to represent 90-95% of historically known cover (McField et al., 1996). Mangroves fringe most of the coastline and brackish rivers and cover many cays, playing an important role in processes such nutrient cycling and sediment trapping and acting as a nursery area. Gray et al. (1990) describe the main mangrove communities and their extent.

Cays

Belize has approximately 450 cays on the barrier reef and atolls (Perkins, 1983). Detailed descriptions are outside scope of this paper and readers are referred to the work of Stoddart (1962, 1982).

Biodiversity

The diversity of reefal, lagoonal and mangal systems within the coastal zone of Belize, combined with significant research efforts, has resulted in a good understanding of biodiversity compared to many countries in the Caribbean. The biodiversity within many taxa is regarded as high for the region with, for example, at least 94% of the zooxanthellate scleractinian species known from the Caribbean having been found (Fenner, 1999) and over 50% of the tubificidae (Erséus, 1990). Extensive fish species lists have been compiled for marine, brackish and freshwater systems with other studies having documented the diversity of many additional taxa.

Belize also supports important populations of manatees (*Trichechus manatus*) and crocodiles (*Crocodylus acutus* and *C. moreletti*). Manatees were surveyed by O'Shea and Salisbury (1991), indicating the largest number in any Caribbean country because of the high quality habitat and low level of killing. In contrast, Platt and Thorbjarnarson (1997) indicates that densities of *C. acutus* are amongst the lowest reported for the region, probably caused by over-exploitation, habitat quality and competition with *C. moreletti.* Green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*) and loggerhead (*Caretta caretta*) turtles are also known to nest in Belize and there is anecdotal evidence of leatherback (*Dermochelys coriacea*) and Kemps Ridleys (*Lepidochelys kempi*) being present (McField et al., 1996).

4. Offshore systems

Deep reef habitats

The deep slopes of Belize are well studied compared to many areas of the Caribbean and show reef organisms at great depths because of clearer water. For example, at Glovers Atoll scleractinians were found at 100 m, *Halimeda* at 100m and crustose red algae at 250m (reviewed by Stoddart, 1976). Beyond this photic zone submersible studies, particularly by James and Ginsburg (1979), have shown at least two different profiles. In the southern barrier reef, the eastern side of Glovers and Turneffe Atolls and both sides of Lighthouse Reef the steep escarpment continues without interruption to over 1000 m because of the influence of the Cayman Trench. In contrast, the western side of Glovers and Turneffe Atolls and the central barrier reef changes at 300-400 m and begins to slopes much more gently. Within both profiles there are talus accumulations of blocks between 120-150 m followed by cliffs separated by gullied, sediment slopes from 150-200 m. Beyond 200 m there are fewer cliffs.

Research has also documented a true deep-reef fish fauna in Belize and Jamaica, although some of the juveniles of these species can be found at less than 50 m (Colin, 1974). Working on Glovers Atoll, Colin (1974) also found 60 species of reef fish between 50 and 305 m. This study indicated that the small, cryptic fauna was very poorly known.

Pelagic waters

Offshore fisheries are limited throughout the Caribbean despite 80% of the water being deeper than 1,800 m (UNEP / ECLAC, 1984). This is largely caused by the stable thermocline and onshore winds which limit upwellings and hence nutrient supply. However, the potential of deep sea fisheries beyond the barrier reef has not been fully explored, possibly because of a lack of capital funding. There have been proposals to further develop the fishery but extraction is currently limited to a few fisherfolk with snapper reels (McField et al., 1996).

5. Populations affecting the area

Population and demography

Modern Belize is a diverse ethnic mix including eight ethnic groups (Creoles, East Indians, Caribs, Kekchí, Ladino, Mennonites, Mopan and Yucatec) in addition to Latin Americans, Europeans and Chinese (Hartshorn et al., 1984). The population in 1997 was 228,700 (EIU, 1998-99) giving a density of approximately 10 persons km^{-2} with an annual increase smaller than other Latin American countries. Surveys indicate that approximately 90% of the population live in cities or towns and that 75% of the land is effectively uninhabited (Hartshorn, 1984). Belize City is the largest population centre and an order of magnitude larger than any other town.

Table 1 shows the main towns and cities in the coastal zone and highlights that the proportion of the population in this area is reducing, partially caused by an increasing number of refugees (McField et al., 1996). Most of the cays support only shifting fishing populations and most cays are still public land. A majority of people living in rural areas is considered unusual compared to global averages and is a key factor assisting coastal zone management (McField et al., 1996).

Use of the coastal zone

Belize has a long history of artisanal use of the coastal zone, which can be traced to the Mayan Indians between 300 BC and 900 AD. The Mayans used cays in the lagoons as fishing stations, ceremonial centres and burial sites and utilised a range of fisheries, including conch, finfish, turtle eggs and manatees (Perkins, 1983). The first Europeans arrived in the late 1500's to harvest logwood, subsequently moving to the extraction of mahogany and then piracy. Caribs also arrived from Roatan (Honduras) in the 17^{th} century to fish and harvest timber. Belize was formerly known as British Honduras, a name which dates back to 1840, subsequently became a British colony in 1862 and gained independence in 1981.

The population of Belize has continued to place modest pressure on the coastal zone, with the principal uses being an artisanal fishery, tourism, small-scale shipping and oil exploration (Perkins, 1983). However, independence from the UK in 1981 has increased the need to attain economic viability and reduce the dependence on imports and the country's natural resources will play a key role. Exploitation of these resources seems particularly likely through tourism but increasing the attractiveness of the country to tourists will place heavy demands on the coastal zone. Cortés (1997) lists the major threats to the reefs of Belize as fishing, sedimentation, tourism, agro-chemicals, sewage, solid wastes and dredging. Tourism and its associated demands can exacerbate all these other detrimental factors. It seems likely that sustainably managing the tourist industry and its associated infrastructure is vital to the integrity of coastal resources.

Assessing changes from anthropogenic impacts relies on baseline data for comparison. Apart from occasional collections of marine organisms the first studies were between 1920 and 1960. However, the first detailed studies and documentation of the barrier reef and atolls was by Stoddart (e.g. 1962). A few years later Craig reviewed the fisheries of Belize in detail (Craig, 1966). These and other studies provide a baseline for a large amount of subsequent research and are useful for assessing recent changes. However, Jackson (1997) indicates that despite the limited impacts in Belize, reefs in the 1960's were far from pristine and that data for a truly natural Caribbean reef are not available. Such problems with data interpretation may be aided by working on both ecological and paleobiological time scales, such as the study by Aronson et al. (1998). Future work will be assisted by significant habitat mapping projects by a range of Belizean and international agencies, NGO's and academic institutions over the last decade.

6. Rural factors

Agriculture

Overview

Land–ocean interactions in the Belizean coastal zone are attracting considerable research interest. Approximately 35% of the total land area of Belize is considered potentially suitable for agricultural use, although only between 10 to 15% is cultivated during any one year (Programme for Belize, 1995). Belize's commercial agriculture is concentrated on bananas, sugar and citrus fruit, although numerous crops such as rice, kidney beans, and maize are also grown. Sugar-cane cultivation is predominately concentrated in the northern districts whilst banana plantation agriculture is located across the highly fertile alluvial plains of the south. Citrus production is less defined spatially, although the bulk of the industry is located throughout the southern Stann Creek and Toledo districts of Belize. Aside from commercial activities the traditional system of "milpa" farming (shifting cultivation) utilises small plots of cleared tropical forest for rice, kidney bean and plantain cultivation across the foothills of the Maya Mountains.

It has long been recognised that land-clearance for commercial agriculture will alter the drainage basin water and material flux to the coastal system and affect water quality within the catchment (Holligan and de Boois, 1993). Relative to potential impacts on peripheral marine resources, the suspended component of river load with associated nutrients and contaminants may be considered the most important dimension of this process (Martin et al., 1980). Agricultural impacts on the riverine flux of material from the watershed to the marine system in Belize may be divided into two distinct processes, (a) initial land clearance and (b) agricultural practices. The commercial cultivation of citrus, sugar cane and bananas in Belize involves the large-scale clearance of natural vegetation cover (King et al., 1993). In the case of citrus and bananas this vegetation is predominantly moist tropical forest on the southern coastal plains whilst further north savannah grasslands and scrub-land are cleared for sugar-cane production. Most deforestation is for agriculture rather than forestry which is largely for mahogany and pine (McField et al., 1996). It is well reported that material mobilised as a result of climatological and hydrological interactions with such activities may potentially be conveyed via the river system to the peripheral coastal zone of Belize (Archer, 1994).

Whilst land-clearance is an extremely important dimension of anthropogenic material transfer, agricultural practices serve to sustain the relationship between the field and the marine system, where hydrological, geo-morphological and climatic factors moderate the delivery process. This is particularly the case when agricultural land is located adjacent to river networks. However, drainage delivery networks are essential for cost-effective production in Belize's challenging growing environment and a fine balance must be maintained between regional economic development and controls over environmental change.

Potential impacts on the marine system

To date, there is little quantitative information reporting the direct impacts of agricultural activities on the Belizean barrier reef environment. This is primarily for three reasons. Firstly, the "gap" between drainage basin land-use and barrier reef system change, represents one not only in time and space but also in inter-disciplinary understanding and monitoring techniques. Secondly, it is difficult to distinguish agriculturally derived "point inputs" of fluvial material from sediment and contaminants originating from other sources within the coastal zone. Thirdly, no long-term monitoring initiatives have been established to quantify the delivery process relative to rural anthropogenic processes. Such information is essential for the compilation of land-ocean continuum model detailing temporal interactions between agro-hydrological, geo-morphological and ecological processes within the Belizean coastal zone (IGBP, 1995).

However, although a direct link between rural anthropogenic activity and process change across the barrier reef system is, at best, difficult to establish, a number of significant off-site effects within the peripheral coastal zone have been identified (GESAMP, 1994). Perhaps the most significant potential impact of rural agricultural practice on the Belizean coastal zone is that of sedimentation and contamination within the near shore environment. Adjacent to the banana and citrus growing regions of Belize, shallow marine habitats such as patch reefs and sea-grass beds are located only 500-1000 m from the mainland. High suspended sediment concentrations (SSC) or turbidity within the near-shore water column may reduce photosynthetic activity by restricting light penetration (Barnes, 1980). In addition, effects may occur directly where sediment and associated contaminants settle on and smother coral polyps, restricting basic physiological functions. Accelerated algal growth related to increased nutrient and contaminant delivery may take place under certain conditions, however it should be noted that significant debate surrounds the cause and effect dimensions of this process. Further north in the citrus and sugar growing regions of Belize, agricultural interactions with the near shore environment are likely to be significantly reduced, as the distances between terrestrial and marine ecosystems are greater.

Potential effects of agricultural practice on the barrier reef may be conveyed through a number of transfer mechanisms. Fluvial suspended material delivery has been reported to directly impact coral growth rates in Puerto Rico (Miller and Cruise, 1995) through the discharge turbid suspended sediment plumes to the coastal zone. In Belize, accelerated sediment, nutrient and contaminant delivery to the barrier reef system may potentially influence coral growth via the same mechanisms as discussed for the near-shore environment. However, investigations into the properties and application of agro-chemicals used by banana and citrus industries have reported that even if pesticides, fertilisers and herbicides were to reach the Belizean barrier reef, their properties would have deteriorated significantly, reducing the strength of detection, quantification and source identification (Hall, 1994). Their effect on offshore atolls will be further reduced and currently may be negligible.

Artisanal fishing

Overview

Fishing has historically been a primary occupation for Belizeans and all fisheries are characterised by small scale commercial operations (Perkins, 1983). In 1995 there were approximately 700 boats and jobs for between 2,000 and 3,000 fisherfolk, organised into five co-operatives with significant political influence (McField et al., 1996). Marine products are highly export orientated and the wild-caught industry is worth approximately US$10 million with 80% of the catch exported and 60% going to the United States of America (McField et al., 1996).

The dominant fisheries are lobster (mainly *Panulirus argus*) and conch (mainly *Strombus gigas*) but significant amounts of finfish are caught, concentrating on higher quality species such as groupers (Serranidae) and snappers (Lutjanidae) (Gibson et al., 1998). There are also small fisheries for turtles, shrimp and stone crabs. Most fishing is conducted in the shallow waters on and inside the barrier reef and on the shallow reefs and lagoons of the atolls (Perkins, 1983).

There are direct threats to the populations of lobster, conch and grouper from over-fishing, with tourist demand a key factor. These fisheries were already considered close to their maximum sustainable yields in the early 1980's (Perkins, 1983) but modelling populations is difficult because catch and effort data are not collected systematically (McField et al., 1996) and the visits of illegal alien fisherfolk. There is anecdotal evidence of decreasing catch per unit effort (King, 1997). However, with the exception of shrimp trawling, since most fisheries are exploited with traditional equipment, indirect damage to benthic habitats is small scale and limited to breakage from anchors, skin divers, nets and discarded gear (Gibson et al., 1998). The use of SCUBA, poisons and explosives is restricted. There is also limited evidence of effects caused by shifting fish community structure and concomitant changes to the benthos.

Lobster

Lobster have been harvested commercially in Belize since at least the 1920's when it was largely controlled by foreign interests. By 1995 fisherfolk were extracting 363,000 kg of lobster with an export market of US$8.8 million (McField et al., 1996). In addition, an estimated 23-45 kg of undersized lobster are caught and consumed locally on Caye Caulker alone (King, 1997). Most lobsters are caught by either skin divers using a hook and stick or traps (Hartshorn et al., 1984). These traps are generally wooden and based on a 1920's Canadian design but are increasingly made from oil drums (King, 1997).

Conch

Conch is the second most valuable fishery in Belize with catches around 180,000 kg (Appeldoorn and Rolke, 1996) worth exports of US$1.15 million (McField et al., 1996). Most conch are taken by skin divers in the back reef and seagrass beds where the aggregating behaviour of individuals makes them susceptible to exploitation (Perkins, 1983). Although the fishery is assumed to be over exploited and there is evidence of increased populations in marine protected areas, catches appear to be relatively consistent. Furthermore, Appeldoorn and Rolke (1996) highlighted the low density of adults in shallow habitats and suggested the paradox could be caused by a deep, unfished stock and that catch may be independent of the spawning stock.

Finfish

Finfish in Belize are generally caught for the domestic market and of the 114,000 kg caught in 1993-94 approximately 80% were consumed locally (McField et al., 1996). Hook-and-line fishing is dominant in Belize and this gear selects for piscivores so the catch is predominantly groupers and snappers (Koslow et al., 1994). There is also a seasonal fishery for estuarine species such as mullet (*Mugil* spp.) and some gill-nets for sharks (McField et al., 1996). The shark fishery is over-exploited but a surplus-production model for the whole fishery provides evidence that there is capacity for further expansion and current effort seems to be only 10% of levels that would maximise landings (Koslow et al., 1994). However, the authors advise that these results must be interpreted cautiously, particularly since it is difficult to model the effects of fishing on spawning aggregations which contributes a significant portion of the catch. At least six spawning aggregations are known in Belize, located at Rocky Point, Cay Glory, Gladden Entrance and the north-east corner of the three atolls (Carter and Sedberry, 1997). Many fish are caught before they spawn and some of the areas are thought to be over-exploited (McField et al., 1996).

Additional fisheries

Belize's coastal zone supports a variety of localised fisheries including shrimp, turtles and crabs. There is also anecdotal evidence of manatees being killed for meat around Ambergris Cay, Dangriga and Punta Gorda and seen in markets in Corozal (O'Shea and Salisbury, 1991). The penaid shrimp fishery supported 11 trawlers in 1988 which exploited stocks in Victoria Channel and the lagoon between Belize City and Placencia (McField et al., 1996). However, the fishery seems limited by a lack of knowledge, expertise and capital (Perkins, 1983) and has declined to a catch of 34,250 kg in 1995 (McField et al., 1996). Stone crabs (*Menippe mercenaria*) and blue crabs (*Callinectes sapidus*) are caught with baited traps and the industry has increased with the introduction of a close season for lobster fishing (McField et al., 1996). Perkins (1983) reports 1,360 kg of turtle meat being sold in the early 1980's but this has declined because of increased regulations and declining populations.

7. Coastal erosion and landfill

Overview

The Belize Barrier Reef and mainland activities are closely linked via the rivers and numerous watersheds on the mainland. Effects are larger in southern Belize because of the greater rainfall and have been studied and modelled in detail by Heyman and Kjerfve (1999). This research concluded that any land-use decisions have ecological and economic effects on the marine resources. Currently development in the coastal zone is relatively low but is increasing, largely associated with the tourism industry, agriculture and aquaculture.

Effects on the coastal zone

Rivers from throughout Belize are known to introduce large amounts of terrigenous material close to the shore but there is little evidence of alteration to patterns of longshore drift by coastal development. Longshore currents are reworked by heavy surf and carried south by currents to form headlands and beach ridges (Miller and Macintyre, 1977). Belize Bight, north of Belize City, is also naturally occurring from longshore currents flowing northwards (Miller and Macintyre, 1977).

Deforestation and other detrimental land uses in Caribbean watersheds have also resulted in significant coastal erosion (Cortés and Hatziolis, 1998). Several areas in Belize have suffered from beach erosion, particularly the mouth of the Sibun River and Commerce Bight south of Dangriga (Hartshorn et al., 1984). Cay development has also caused some erosion and the establishment of piers on larger cays has affected beach profiles (McField et al., 1996). Changes to cay and mainland beaches caused by degradation of the reefs which dissipate much of the wave energy have not been documented.

Direct effects on coastal zone habitats from excavation or conversion has been limited. Perhaps the most dramatic change has been the expansion of Belize City since it was originally a small mangrove peninsula (Hartshorn et al., 1984). Construction around San Pedro (Ambergris Cay) has also involved land clearance, infilling and building unnatural beaches (McField et al., 1996) and uprooting seagrass beds to improve swimming (Perkins, 1983). Furthermore, there has been some mangrove clearance on the offshore cays and significant alteration of the landscape to facilitate a golf course on Caye Chapel but data on changes to adjacent reefs are sparse.

Dredging in Belize should only been undertaken with the appropriate permits but enforcement is limited and there are known to be many cases of illegal activity (Gibson et al., 1998). However, an increasing number of permits for marine dredging have been granted and most aim to fill land for tourism or real estate development (McField et al., 1996). There is also some industrial dredging, such as that related to mining activities at the entrance of North Stann Creek River (McField et al., 1996). Dredging is known to cause both direct and indirect effects such as damage to benthic organisms and suspension of sedinents.

8. Effects from urban and industrial activities

Overview

Initiatives by the Government of Belize to diversify the economy include efforts to increase revenue in all sectors including tourism, manufacturing, aquaculture and oil exploration. Currently most of the Caribbean has limited industrialisation and pollution of the coastal zone has not reached levels seen in many more developed regions (UNEP / ECLAC, 1984). However, increasing development must be carefully monitored since prevailing currents rapidly move water-borne pollutants between countries (Davidson, 1990).

Value-added revenue from manufacturing has risen from US$40.7 million in 1980 to US$59.5 million in 1993 and, although this represents a decreasing proportion of GDP, since all major industries are located in the coastal zone this expansion threatens marine resources (McField et al., 1996). The origins of GDP in Belize in 1997 are shown in Figure 1, which also shows the importance of marine resources. In contrast to many countries in the region, however, management is assisted by the distance of the reef from the mainland (Perkins, 1983).

Furthermore, the lack of a deepwater port limits economic expansion from large-scale coastal industry (O'Shea and Salisbury, 1991). Therefore, Belize has encouraged an open investment climate, such as the sale of cays, which is highly attractive to foreign investors (Katz, 1989).

Artisanal and non-industrial uses

There are numerous small scale enterprises along the coastline of Belize but their effects on marine resources are limited. At the mouth of the Sibun River there has been some mining, by shovel, for quartz sand for cement (Perkins, 1983). Perkins also reports that some coral was mined for the streets of Belize City but this has since ceased. No lime production from coral is known but bio-prospecting seems likely to increase.

There is a small but growing trade in aquarium fish and approximately 27,000 fish and invertebrates, with a value of over US$40,000, were exported in 1994 (Carter and Sedberry, 1997). Further increases may reduce local populations of popular species. There is some sale of curios, particularly on Ambergris Cay, where tourists can purchase species such as tritons, helmet shells, cowries and black coral products from licensed and illegal collectors (Perkins, 1983).

Aquaculture

Encouraging aquaculture is consistent with government aims to diversify the economy. Belize has a great potential for species such as shrimp because there is abundant boggy lowland (Katz, 1989). Coastal areas and rivers are also suitable for raising tilapia (*Oreochromis niloticus*) and oysters. Currently there is little evidence that aquaculture is threatening the health of the coastal zone but there are concerns of nutrient enrichment, oxygen depletion, mangrove clearance, introducing alien species and the spread of disease from shrimp ponds (McField et al., 1996).

Small scale aquaculture has included harvesting sponges, especially on Turneffe Atoll, and the alga *Eucheuma* which is used as a thickening agent (Perkins, 1983). Exploitation of *Eucheuma*, which may have a significant potential, has occurred on Turneffe Atoll and around Placencia and Hunting Cay. There have also been aborted attempts to introduce the American lobster (*Homerus americanus*) and to raise native lobsters in pens on Turneffe Atoll (Hartshorn et al., 1984). More successful projects have raised freshwater Australian red claw lobsters (*Cherax quadricarinatus*) and tilapia (McField et al., 1996).

Pond-raised shrimp farming has increased dramatically over the last two decades and is the fastest growing fisheries sector. Approximately 90% of capital investment in aquaculture is for shrimp farms and there are at least six in Belize with exports of over 590,000 kg and income of at least US$5.25 million (McField et al., 1996). The ponds mainly raise *Panaeus vannamei* but *P.*

stylirostris and *Macrobrachyum rosenbergii* are also used (Hartshorn et al., 1984).

Fishing

As previously discussed, most fishing in Belize is small-scale and organised through a series of co-operatives. Indeed, the small continental shelf may not be able to support an expanded, high-tech fishing industry (Perkins, 1983). However, there is a rapid expansion of longlining by Asian fleets in the Caribbean and this poses a threat to stocks of tuna, billfish and pelagic gamefish (Davidson, 1990). The overall catches for Belize since 1987 are presented in Figure 2.

Tourism

Tourism is the largest generator of foreign exchange in Belize and 134,289 visitors arrived in the country during 1997 (EIU, 1998-99), attracted by the proximity to North America and that it is English speaking and has a good climate. Most of these tourists are SCUBA divers and sports fishermen and 77% snorkel or dive in the coastal zone (Gibson et al., 1998). The tourist centre is San Pedro but there are also many visitors to Caye Caulker, Caye Chapel, St Georges Cay, Placencia and atoll resorts.

Since 78% of hotel rooms are in the coastal zone (Gibson et al., 1998), increasing tourist infrastructure is a key factor contributing to urban pollution and habitat conversion. However, there are also direct effects on the reef and damage inflicted by divers, boats and anchors has been seen at all popular sites, although these are not thought to be severe (Gibson et al., 1998). Furthermore, as there may be over 14,000 sports fishermen arriving each year some target species, such as bonefish and tarpon, may become over-exploited (McField et al., 1996). Tourists may also disturb manatees and bird colonies.

Industrial effects

Although there are not currently effects to the entire coastal zone from industrial activity, localised areas receive significant pollution. The main industrial plants in Belize are detailed by McField et al. (1996) and consist of processing factories for sugar, citrus and seafood, rum distilleries, a brewery, soft drinks bottling, diesel electricity generators and garment factories. Effluents and other wastes from these plants usually have large biochemical oxygen demands (reducing oxygen available to marine and freshwater organisms), are acidic or contain chemical such as sodium hydroxide. Around 950,000 tonnes of sugar cane are processed each year in Belize, along with the production of approximately 100,000 gallon of citrus concentrate.

Effluents and waste products are generally dumped straight into adjacent rivers and the lack of sophisticated aeration ponds means that they do not meet appropriate environmental standards

(McField et al., 1996). New River, close to many of the refineries and factories, is considered the most polluted in Belize with fish kills reported. Fish kills have also been recorded in the Belize River (Hartshorn et al., 1984). Data on the effects of a hydroelectric station on the Macal River are sparse.

Factory wastes and leachates are known to carry toxic metals which can affect the physiology of a range of marine organisms. Despite limited heavy industrial activity a study by Gibbs and Guerra (1997) in the bottom muds of Belize City harbour found levels of cadmium, copper, lead and zinc that will cause environmental problems to the biota. Chromium was also tested but found at natural levels. Gibbs and Guerra (1997) hypothesise that cadmium, lead and zinc originate from a nail and battery factory sited on the Belize River and copper is from antifouling boat paint and electrical and plumbing products.

Urban pollution

The Belize Barrier Reef and atolls are buffered from urban pollution by their distance from the mainland and channels of deep water. However, with population growth and increasing numbers of tourists, sufficient sewerage treatment is vital to protect the integrity of the reefs and associated ecosystems. Belize City is the only coastal area with a central sewerage system and a second system is being established in San Pedro (Gibson et al., 1998). Both of these plants have only secondary treatment via settlement ponds and release nutrients via mangrove stands and, although there is a possibility of localised eutrophication, they are thought to conform to WHO bacterial guidelines (McField et al., 1996). Nutrients are also thought to enter the marine environment via outfall pipes and septic tanks, particularly on the cays. Contamination by human waste from water craft is considerable (UNEP / ECLAC, 1984).

In addition to sewerage from Belizean towns there are significant inputs from Mexican towns which are carried into Belize by the south flowing currents. A study by Ortiz-Hernandez and Saenz-Morales (1999) examined the discharge from Chetumal which is estimated as 200 m^3 day^{-1} via a pluvial system. This research showed that areas used for recreation have a concentration of fecal coliforms above levels given in Mexican legislation. However, this load, combined with the organic matter in the River Río Hondo, does not seem to increase the biochemical oxygen demand of Chetumal Bay and provides evidence of self-depuration processes. Similarly, there is currently limited evidence of wide-scale nutrient enrichment in Belize but the effects on benthic communities are known and are indicative of future changes if nutrient inputs are increased.

Lesser impacts are caused by litter from dumping by mainland populations, often in mangroves, and by boats but is unsightly in many areas (Hartshorn et al., 1984). Solid wastes from Belize

City are dumped at a landfill site which receives around 920 m^3 $week^{-1}$, plus industrial waste, and may leach heavy metals into the coastal zone (McField et al., 1996). Drawing potable water has caused salt water intrusion and fecal contamination in urban areas, especially San Pedro (Hartshorn et al., 1984) and may lead to more common use of desalination plants.

Shipping and offshore impacts

Belize is considered to be a low risk shipping zone (UNEP / ECLAC, 1984) but most exports and imports are carried by sea and there is a constant threat of spills and groundings. There are three main ports at Belize City, Big Creek and Commerce Bight plus Esso's private dock which received 15 tankers of international fuel supplies in 1994 (McField et al., 1996). None of these ports have a deepwater dock and deep draft vessels anchor offshore and use barges. Although there are a minimum of 13 shipwrecks on the barrier reef there has been only minor damage from groundings and spills. Few hazardous substances are shipped though Belizean waters with perhaps only fertiliser and oil spills posing significant threats. Small oil spills have been seen and there are an increasing number of tar balls from ballast water and tanker washing on both international ships and local barges moving fuel to the cays (Gibson et al., 1998). Numbers of cruise ships are also increasing substantially and 13,661 passengers arrived in 1994 (McField et al., 1996).

Most oil is imported into Belize but there has been significant exploration. Perkins (1983) highlights at least 40 exploratory wells, of which 12 are on the continental shelf, although all are capped and abandoned since none found commercially viable deposits despite the proximity to large Mexican and Guatemalan fields. In addition to shot-holes in seagrass beds from seismic testing, if deposits are found there are obvious threats to benthic habitats from drilling, construction and processing.

9. Protective measures

Overview

Management of Belize's coastal zone has evolved from the sectoral management of commercial fisheries and conservation of important bird species to the broader approach of ecosystem management and integrated coastal zone management. This integrated approach, summarised here but with further details in McField et al. (1996) and Gibson et al. (1998), is critical as most of the current threats originate some distance from the reefs. Conservation of the reef ecosystem and sustainable management of marine resources are high priorities of the general population, the many non-governmental organisations involved in resource management in Belize and of most government departments. This broad-based approach is largely responsible for the successes to date, although conflicting views and a general impatience with the slow pace of "sustainable development" are fostering a new international business climate seeking quick profits through massive development initiatives.

Protection of Belize's marine resources is the shared responsibility of several governmental and non-governmental agencies. In 1990 a Coastal Zone Management Unit was established within the Fisheries Department, later assisted by the UNDP/GEF Coastal Zone Management Project in 1993. The Coastal Zone Management Act of 1998 consolidated efforts within the autonomous Coastal Zone Management Authority (CZMA), assisted with implementation and research by an affiliated institute. Although no regulatory powers have yet been developed within the CZMA, it serves as the focal point of marine conservation planning, monitoring and research.

Policy development and integration

Several integrated committees exist which provide broad-based platforms to discuss policy development and the implementation of key programs. The board of the CZMA includes senior government representatives and can approve policies. Similarly, the Barrier Reef Committee was established as a national platform for review of the project development stage of the Meso-American Reef Initiative. A Marine Protected Areas Committee fosters communication and exchanges among protected areas managers and advisory committees. Finally, a National Coral Reef Monitoring Working Group was formed to integrate and co-ordinate various reef monitoring efforts throughout the country.

Regulation of development

Belize's relatively recent introduction to international tourism and commercial development mean that many models are available as guides to assist with ensuring sustainable development. However, as developmental pressures increase so does the potential for serious environmental degradation. Belize has adequate environmental legislation but lacks enforcement and monitoring capacity. For example, under the Environmental Impact Assessment (EIA) regulations of 1995, the Department of Environment enforces regulations and screens projects that may require EIA's. Similarly, the Land Utilisation Authority is responsible for Special Development Areas which are a form of strategic planning, providing for the zoning of land-use. A zoning plan for Belize's marine waters will ultimately be developed within an overall Coastal Zone Management Plan.

Regulation of tourism

The Belize Tourist Board regulates the tourism industry, including the expanding cruise industry, which many view as a growing threat to ecologically sensitive areas. The Tourist Guide Regulations require that all tour guides meet standard levels of professional training and licenses can be revoked for non-compliance with environmental or other regulations. However, dive guides are normally quite effective at "self-regulation" and have initiated a series of "conservation zones". Dive operators also play a major role in the installation and maintenance of mooring buoys. However, these initiatives may be jeopardised by pressure within to accommodate the mass-tourism market rather than current small scale eco-tourism ventures.

Fisheries regulation

The Department of Fisheries manages the fisheries industry which includes aquaculture. No fishing is allowed on SCUBA and there are other gear restrictions, size limits and closed seasons. However, government resources are inadequate to patrol the waters of Belize or to fully enforce these regulations. Six marine reserves have been established to assist fisheries management by replenishing heavily exploited stocks, while also protecting essential habitats (coral reefs, seagrass beds, mangroves).

Control of pollution

The Environmental Protection Act of 1992 provides the framework through which the Department of Environment enforces regulations preventing pollution. The EIA process further ensures proposed industrial activities take environmental protection measures into account during the planning stages. Although enforcement manpower is severely limited, the small scale on Belize's industrial sector aids the identification and control of potential sources of pollution.

Marine protected areas

The establishment of marine and coastal protected areas, summarised in Table 2 and including some with World Heritage listing, has been an essential component of marine conservation efforts in Belize. Currently there are six designated Marine Reserves, administered by the Fisheries Department or local NGO's. Additionally there are four National Parks, two Wildlife Sanctuaries, two Natural Monuments and two Nature Reserves. There are also seven Crown Reserves, which are essentially bird sanctuaries on small cays, and one private reserve in the coastal zone. The role of NGO's and local community-based management is expanding and advisory committees are playing increasingly important roles.

Marine protected areas (MPA's) are a useful tool for addressing a number of threats to coral reefs, particularly those related to tourism carrying capacities, over-exploitation of commercial species and the potential ecological benefits of increased herbivory. Zoning schemes enable multiple uses in these areas, including recreational diving, sports-fishing, and traditional small-scale fishing and full protection (no-take zones) in key areas. Over-success of tourism in parks can be a concern, as in Hol Chan, which receives over 30,000 visitors a year. The value of protected areas in promoting sustainable fisheries and in regulating tourism and other activities is now well documented and the Hol Chan Marine Reserve has been cited as an international model. Research at Hol Chan and Half Moon Caye has illustrated that MPA's can result in fish populations with significantly greater abundance and larger-sized individuals (Polunin and Roberts, 1993; Carter and Sedberry, 1997). It has been recommended that 30% of the coastal zone of Belize should be closed to fishing and the remainder managed by traditional methods.

Challenges

Although the conservation efforts of the last two decades have been successful, there are many challenges to sustaining them. MPA's often suffer from inadequate funding levels and rely on external financing. The Protected Area Conservation Trust raises money through a tourist departure tax and a percentage of park entrance fees but is currently inadequate. Recently there has also been organised opposition from some fishermen who are not convinced of replenishment reserves or complain that the existing park regulations are not adequately enforced. The existing piecemeal approach to MPA management might be better served by a unified Parks Service, as has been previously recommended (Programme for Belize, 1995). A committee has recently been formed to address this issue.

One of the most difficult challenges facing all marine conservation efforts in Belize is the lack of sustainable financing. While many international donor agencies have contributed greatly to these efforts, the reliance on such short term project-based funding reduces the long-term national approach. The CZMA has addressed this issue (Coastal Zone Management Project, 1995) and will continue to seek sustainable revenue-generation, although many of the obvious sources have already been utilised. Like many countries, the government of Belize is facing increasing economic constraints and a variety of revenue generation strategies will be necessary.

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Table 1. The main population centres (greater than 1000 persons) within the coastal zone of Belize. Modified from McField et al. (1996). Original data from Central Statistics Office, Belmopan.

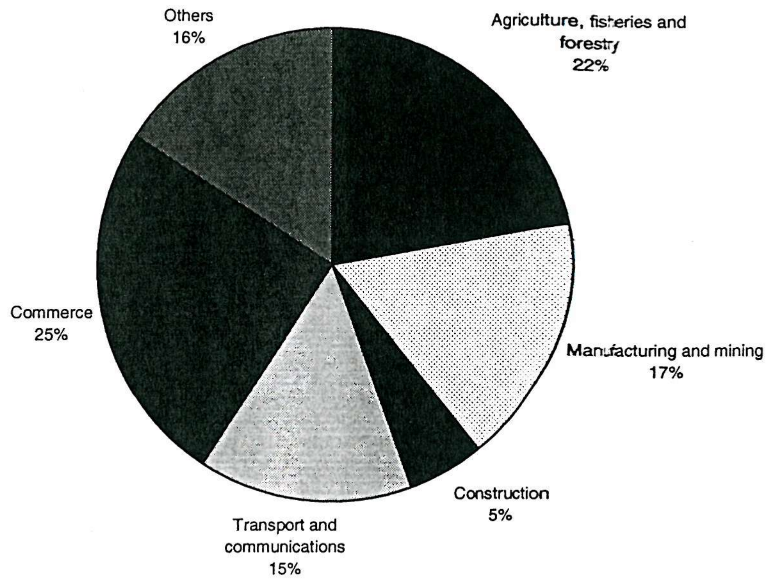
Town	1980	1991	1994 (estimate)
Corozal Town	6899	6926	7644
Sarteneja	1005	1365	1433
Belize City	39771	44031	49122
San Pedro Town	1125	2001	2060
Ladyville	1810	2373	2664
Dangriga	6661	6565	7171
Independence	1474	1921	2115
Punta Gorda	2493	3956	4268
Others (total)	4413	5877	6422
Total (coastal zone)	65651	75015	82899
Total (Belize)	144857	194000	211000
Population in coastal zone (%)	45.3	38.7	39.3

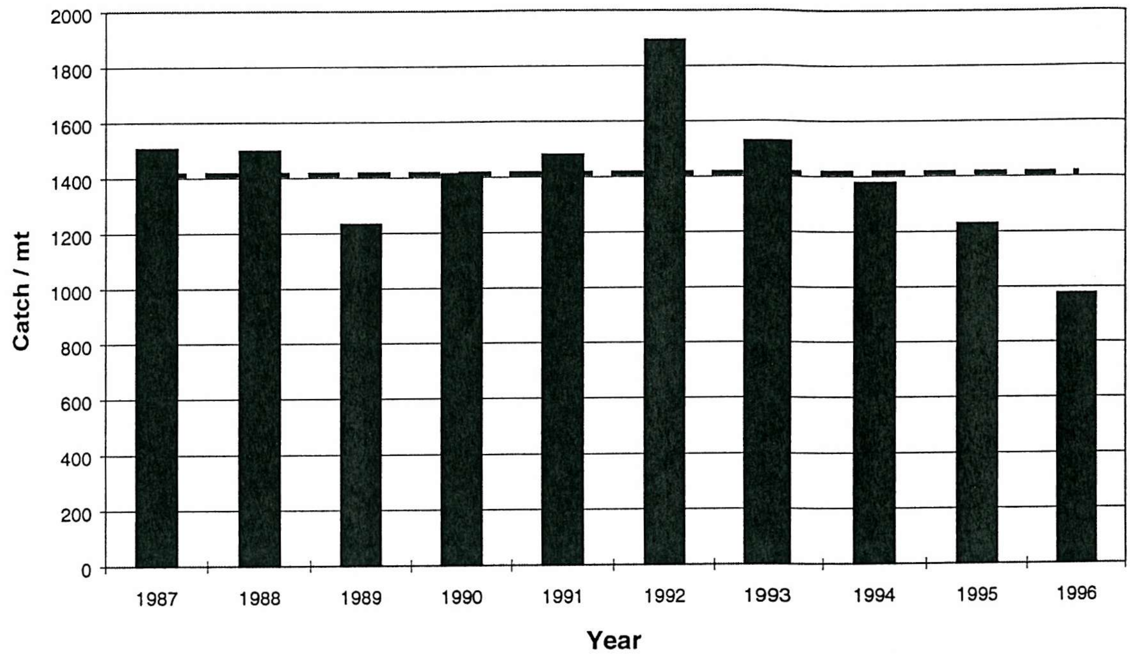
Table 2. The marine and coastal protected areas of Belize. At least nine additional areas are proposed as protected areas. CR = Crown Reserve, FR = Forest Reserve, MR = Marine Reserve, NM = Natural Monument, NP = National Park, NR = Nature Reserve.

Existing protected areas	Area (acres)	Date established	Date of completion of management plan
Bacalar Chico NP & MR	15,117	1996	1996
Bird Cayes (various locations) CR	6,744	1977	-
Blue Hole NM	1,023	1996	-
Burdon Canal NR	5,252	1992	-
Caye Caulker FR	160	1998	-
Caye Caulker MR	10,618	1998	1996
Corozal Bay (manatee) WS	177,762	1998	-
Deep River FR	77,499	1941	-
Gales Point (manatee) WS	9,095	1998	-
Glovers Reef MR	81,175	1993	1988
Half Moon Caye NM	9,771	1982	1986
Hol Chan MR	4,035	1987	1986
Laughing Bird Cay NP	10,119	1991	1994
Paynes Creek NP	31,676	1994	In preparation
Sapodilla Cays MR	33,401	1996	1994
Sarstoon-Temash NP	41,898	1994	In preparation
Shipstern Nature Reserve (private)	18,852	1987	1990
South Water Caye MR	78,374	1996	1993
Total	612,570		
Total with significant marine area (10 protected areas)	421,395		

Figure 1. Origins of gross domestic product in Belize in 1997. Data source: Economist Intelligence Unit. 1998. Country report. Jamaica, Belize, Organisation of Eastern Caribbean States (Windward and Leeward Islands).

Figure 2. Nominal catches from all fisheries in Belize. Dashed line represents mean catch. Data source: FAO. 1996. Fishery statistics capture production. FAO Yearbook Volume 82.


Others
16%
Agriculture, fisheries and
forestry
22%
Manufacturing and mining
17%
Construction
5%
Transport and
communications
15%
Commerce
25%



2000
1800
1600
1400
1200
1000
800
600
400
200
0
Catch / mt
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
Year

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