IMPACTS OF LANDUSE AND RUNOFF WATER QUALITY ON CORAL REEF ENVIRONMENTS IN BARBADOS

by

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ABSTRACT

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The effects of terrestrial runoff on the Bellairs fringing reef environment were assessed by a study of water quality. This study is partitioned into two components. The first documents terrestrial discharge of sediments and nutrients into coastal waters and maps the resulting seawater quality by analyzing samples taken from a grid of stations. Terrestrial water samples were analyzed for turbidity, total suspended solids (TSS), nitrate-nitrite-nitrogen (NO_x-N), and soluble reactive phosphorus (SRP). Seawater was analyzed for turbidity, TSS, and salinity while sedimentation rates were measured upon the seafloor. Results indicated that on all four events, water above the reef exceeded the guidelines for turbidity, TSS, or both. Post-discharge changes in seawater quality around the outlet depend on a runoff event's TSS load and total discharge, though above the reef which lies 600m from the outlet, there is the added dependence of the prevailing winds. Spatial trends were not observed across the reef, though directly in front of the outlet there was an apparent northward trend for plumes. Sedimentation rates on the reef were much higher than guidelines for 35 of the 118 days monitored.

The second component of this study characterizes the watershed draining to the aforementioned coastal outlet in terms of hydrology and water quality, and the latter's relation to landuse. Water samples were taken at the outlet over time as well as at four upstream locations on two events, and were analyzed for turbidity, TSS, NO_x-N, and

SRP. Observed hydrological characteristics included spatially heterogeneous rainfall, flash floods, internal drainage of runoff into the karstic aquifer, and a correlation between event total runoff volumes and event runoff coefficients ($r = 0.89$). Water quality results identified a first flush phenomenon for TSS, and sources of high TSS, turbidity, and SRP to be industry, urban areas, and agriculture. Considering the low proportion of agricultural area, average nutrient concentrations are quite high (0.34 mg SRP/l, 0.7 mg NO_x-N/l). Potential remediation strategies for both problems are presented and discussed.

RÉSUMÉ

M.Sc. Marko Tosic Genié des Bioressources

L'IMPACT DE L'UTILISATION DE LA TERRE ET DE LA QUALITÉ DE L'EAU DU RUISSELLEMENT DE SURFACE SUR L'ENVIRONNEMENT DES RECIFS EN BARBADE

Les effets de ruissellement de surface sur l'environnement des récifs de Bellairs ont été évaluer par une étude de la qualité de l'eau. Cette étude est divisée en deux composantes. La premiere documente les déversements terrestres des éléments nutritifs et des sédiments dans les eaux côtières. De plus, la mer est divisée en grille, permettant l'analyse d'échantillons survenant de chaque région et des tendances de ces résultats. Des prélèvements de ruissellement de surface ont également été analysées pour leur turbidité, le totale des matieres solides en suspension (TSS), les nitrates-nitrites-nitrogen (NO_X -N), et de phosphore soluble réactif (PSR). La turbidité, TSS, salinité, et le taux de sédimentation sur le fond marin ont toutes été obtenus des échantillons maritimes. Les résultats ont démontré que pour les quatre occasions de déchargements terrestres, l'eau au dessus des récifs excédés les limites de conseil de TSS, turbidité ou les deux. Après un événement de déchargement, les changements de qualité d'eau maritime autour d'une sortie dépendent sur le TSS. Par contre, au dessus des récifs, à 600m de la sortie, il y a le facteur supplementaire de vent. Des tendances spatiales n'ont pas été observés a travers le récif, mais une apparente direction des décharges envers le nord a été remarqué en avant des sorties. Le taux de sédimentation excédé les limites de conseil pendant 35 jours des 118 jours d'observations totales.

La deuxième composante de cette étude caractérise le bassin d'évacuation lié à la sortie maritime mentionné en terme d'hygrologie, qualités des eaux, et de la relation entre ce dernier et l'utilisation des terres. Des échantillons d'eaux ont été pris à travers le temps à la sortie, ainsi qu'à quatre endroits d'amont à deux reprise chacune. Les analyses incluent la turbidité, TSS, PSR et NO_X-N. Les caractéristiques hydrologiques observées sont une distribution spatial hétérogene de précipitation, des inondations éclair, un drainage interne des décharges dans les aquifères karst, et une corrélation entre le volume de déchargement totale d'un événement et le coefficient de décharge ($r = 0.89$). Les résultats de la qualité d'eau démontrent un phénomène de flux initial en ce qui concerne le TSS. Les sources de TSS, turbidité, et PSR sont l'industrie, les régions urbaines et l'agriculture. En prenant en considération la petite superficie de région agricole, la concentration moyenne de nutritif et élevée (0.34 mg PSR/l, 0.7 mg NO_x-N/l). Des mesures correctives potentielle sont aborder pour les deux problèmes présenter.

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CONTRIBUTION OF AUTHORS

The work presented here was performed by the candidate and supervised by Dr. Robert Bonnell of the Department of Bioresource Engineering, McGill University, Monreal. Dr. Bonnell provided advice throughout the project and editorial work on manuscripts written by the candidate. Dr. Dutilleul advised on the methods and interpretation of statistical analyses, performed calculations using the matrix normal model, and provided editorial work on the section describing methods for statistical analyses.

The authorship is as follows:

1st paper (Chapter III): M. Tosic, R.B. Bonnell, and P. Dutilleul
2nd paper (Chapter IV): M. Tosic and R.B. Bonnell

A slightly modified version of the first paper has been published in the Proceedings of the 8th International Symposium on GIS and Computer Mapping for Coastal Zone Management held in Santander, Spain. A combination of both manuscripts including the contributions of another co-author, Dr. H.A. Oxenford, and further contributions of the three original authors has been submitted as a chapter to the following book:

Yang X (ed) Remote sensing and spatial information technologies for coastal ecosystem assessment and management: Principles and applications. Springer-Verlag GMBH, Berlin, Germany.

THESIS ORGANIZATION

This thesis' format is manuscript-based and consists of two manuscripts. Though both studies are closely related and some data are used for both, the topics are different enough to necessitate separation for the purposes of clarity. Each manuscript is suitable for journal publication with minor modifications. However, all references made throughout the thesis are summarized into a single references section at the end.

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NOMENCLATURE

A	cross-sectional area
ANOVA	analysis of variance
C	Celsius
cm	centimeters
cm^2	square centimeters
cms	cubic meters per second
CZMU	Coastal Zone Management Unit (Barbados)
d	days
DEM	digital elevation model
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DOP	dissolved organic phosphorus
DP	dissolved phosphorus
EMC	event mean concentrations
f	a function of H
g	grams
GIS	geographic information system
GPS	global positioning system
h	hours
H	stage
$H_2PO_4^-$	dihydrogen phosphate
ha	hectares
HPO_4^{-2}	hydrogen phosphate
IP	inorganic phosphorus
kg	kilograms
km	kilometers
km^2	square kilometers
L	litres

m	a correction factor for meandering of the channel
m	meters
m^2	square meters
m^3	cubic meters
mg	milligrams
min	minutes
ml	milliliters
mm	millimeters
MPCA	Marine Pollution Control Act
n	Manning’s roughness coefficient
N	North
N	nitrogen
N_2	gaseous nitrogen
NH_4	ammonium
NH_4-N	ammonium-nitrogen
NO_2	nitrite
NO_3	nitrate
NO_3-N	nitrate-nitrogen
NO_x	nitrate-nitrite
NO_x-N	nitrate-nitrite-nitrogen
NTU	nephelometric turbidity units
OP	organic phosphorus
P	phosphorus
PO_4-P	phosphate-phosphorus
PP	particulate phosphorus
ppt	parts per thousand
Q	discharge, interval
Q_i	discharge, channel segment
Q_m	discharge, entire channel
Qt	total discharge
R	hydraulic radius

s	seconds
S_e	slope of energy grade line
SP	soluble phosphorus
SPM	suspended particulate matter
SRP	soluble reactive phosphorus
TP	total phosphorus
TSS	total suspended solids
TSSL	total TSS load
V	velocity
V_i	velocity, channel segment
W	West
°	degrees
'	arcminutes
µg	micrograms
µm	micrometers

I. GENERAL INTRODUCTION

1.1 Introduction

Coral reefs constitute one of the world's most diverse and beautiful ecosystems. Popular for diving and integral to the fishing resources of many small island nations, reefs have always fascinated tourists and researchers alike. Globally, reefs have been declining and much research has focused on the causes. Commonly studied effects include those due to overfishing, bleaching, as well as those due to a variety of land-based sources such as sedimentation and eutrophication.

The coral reefs of Barbados have been the subject of many of the earliest studies on coral due to McGill's Bellairs Research Institute in Holetown. Tomascik and Sander's study of the "effects of eutrophication on reef-building corals" (1985) was one of the earliest studies explicitly linking eutrophication to coral health. The study established the presence of a eutrophication gradient along the west coast of the island. Indicated by concentrations of chlorophyll-*a* which increased towards the south, the gradient was also found to exist for coral growth, community structure, and reproduction. Since the gradient's establishment, many studies, far too numerous to mention, continued to document its effect on coral ecosystems.

A similar gradient which may be seen in Barbados is that of coastal development. The city of Bridgetown is located on the island's south west corner and population as well as urban landcover decrease towards the north. Land-based sources of nutrients have often been suggested to be the proximate cause of eutrophication in Barbados and elsewhere. Transported by water along the surface and through the ground, typical sources of nutrients include fertilizers and urban wastewater, whereas sediments are commonly transported from landuse developments, such as deforestation. This study aims to gain an understanding of the exact process by which a heavy storm can result in the disturbance of a coral reef environment.

1.2 Objectives

1) To assess the effects of runoff on the water quality of the Bellairs fringing reef. Parameters to measure will include changes in seawater clarity measured as turbidity and total suspended solids (TSS), and sedimentation upon the substrate.

2) To identify sources of poor water quality contributing to eutrophication and sedimentation of the coastal waters. Poor water quality is defined as water high in nitrate-nitrite-nitrogen, soluble reactive phosphorus, turbidity, and TSS.

II. LITERATURE REVIEW

2.1 Environmental Characteristics of Barbados

The West Indian island of Barbados is the eastern most island of the Caribbean archipelago. Centered at 13°10' N and 59°35' W, its total area is about 432 km^2 having 92 km of coastline. The island is approximately 34 km long and 23 km wide. The highest point of the island, Mount Hillaby, is about 340 m above mean sea level.

2.1.1 Climate

Barbados has a sub-humid to humid maritime, tropical climate with monthly temperatures ranging between 28-31°C. Average annual rainfall totals range between 1400-1500 mm (Government of Barbados 2000). The island experiences a dry season and a rainy season. The wet season extends between June-December, peaking during the months of August-October, and accounts for 60% of total annual rainfall (Jones and Banner 2003).

Rainfall varies spatially with average annual totals ranging from 1200-2100 mm. Rainfall increases towards a point slightly north of the center of the island, coinciding with increases in elevation (Government of Barbados 2000). This spatial pattern varies seasonally with the described pattern prevailing during the dry season. During the rainy season, rainfall increases towards the island's leeward coast (Jones and Banner 2003). However, it must be stressed that these patterns describe long-term totals and that tropical rainfall events are highly localized.

Rainfall in the Caribbean Basin is modulated by tropical waves (Riehl 1954). Also referred to as African easterly waves, tropical waves commonly stem from the coast of Africa and moving westward across the Atlantic, Caribbean, and parts of the east Pacific. These waves cause localized heavy rains and squall conditions, acting as precursors to tropical cyclone development (Avila et al. 2000).

Initially detected as centers of falling and rising sea level pressure traveling westward across the Caribbean, tropical waves are typically the source of a year's strongest Atlantic hurricanes (Landsea 1993). These waves are associated with convection, usually concentrated upon or downstream of the wave axis. Perhaps 9 out of 10 generate little more than localized showers (Simpson et al. 1968) but the chance of developing into large-scale tropical disturbances makes them a seasonal concern to Caribbean inhabitants.

A tropical wave is simply a trough in the trade wind easterlies. Should convection become organized into a discrete system, approximately 150-500 km in diameter, maintained for over 24 hours, it may be termed a *Tropical Disturbance*. Such a disturbance with definite closed circulation but with wind speeds less than 34 knots is defined as a *Tropical Depression*. A depression with maximum sustained wind speeds of 34-64 knots is called a *Tropical Storm*, at which point it is given a name. Above 64 knot wind speeds defines a system as a *Hurricane* categorized according to wind speeds from 1-5, with 5 being the largest (Simpson et al. 1968).

2.1.2 Geology

The island of Barbados has an aquifer primarily composed of Pleistocene limestone (85%) and underlain by oceanic rocks. Up to 100 m thick, the limestone has an average porosity of 45%, ranging between 20-60% (Jones and Banner 2003). Most of the limestone was originally formed by Pleistocene coral reefs, subsequently uplifted by tectonic activity resulting in the formation of three distinct terraces separated by two sets of cliffs (Mesolella 1967). Extending along an average elevation of 100 m, the cliffs further inland (usually called the "second set") have an approximate height of 30 m and are highly karstified containing many caves and traversed by many dry valleys (Jones et al. 2000). Dry valleys, or gullies, have slopes of at least 15° and commonly greater than 30°, and ephemeral channel runoff to the coast following large rain events (Fermor 1972). Gully beds are extremely eroded, can be up to 50 m deep, and are bordered by steep banks covered in dense forest (Stantec Consulting 2003).

Upstream of the west coast area around Holetown, the middle terrace is the most karstified area of land (Huang 2006). Doline, or sinkhole densities along the west coast are highest at elevations between 90-150 m (about 13.7 sinkholes/km^2), accounting for about 1% of the entire northern west coast area. Two subpopulations of dolines exist: a larger one in interfluve areas and a smaller one in the gullies (Day 1983). Discrete infiltration through these areas is the primary method of recharge to the island's aquifer (Jones et al. 2000).

The Pleistocene limestone overlies Tertiary Oceanics upon which the water table is closely tied. In areas where the oceanics are near the beds of the gullies, intermittent springs may be found to flow for short distances. However, above the first terrace the water table is generally 30 m below the gully floors (Fermor 1972).

In one area of the island, the Pleistocene limestone, sometime called the "Coral Cap," has been breached exposing the Oceanics to the surface. Known as the Scotland District, this area is located in the north-east of the island, occupying 15% of the total land area of Barbados (Fermor 1972).

Soils covering the limestone are fairly well drained and moderately permeable (Vernon and Carroll 1965). Typically 1 m thick, they are made up of carbonate and silicate minerals, quartz, oxides, organic matter, seaspray salts, and fertilizer (Banner et al. 1996). While parent materials for the soil's carbonates are Pleistocene and Tertiary, origins of the silicates and oxides are a mixture of African dust, volcanic ash from St.Vincent, and Tertiary pelagic bedrock from the Scotland District. The dominant source for soil clays seems to be African dust transported by the trade winds (Muhs et al. 1987).

The Scotland district is covered by soils composed of clay, marls, and sand from the underlying geology. These soils are densely packed and thus impermeable and impervious. As a result, very little infiltration occurs in this area (Vernon and Carroll 1965).

2.2 Coral Reef Ecosystems

2.2.1 Natural Oligotrophic Conditions

Coral reef ecosystems exist in shallow coastal areas in tropical latitudes. They are characterized by clear, warm waters low in nutrients. Hard corals, the reef-builders, are sessile colonial invertebrates which have formed symbiotic relationships with single-celled algae, known as zooxanthellae, living within the tentacles of the coral polyps. In exchange for protection from herbivory, the algae create energy and nutrients for the polyps. It is this exchange which makes corals so successful in nutrient poor environments. These ecosystems are reliant on the structure of the reef for the protection of smaller organisms, and thus a continuous food source for larger organisms. This produces a large diversity of organisms contributing to fisheries and to tourism, while the reef structure also provides protection for coastal areas from wave action (Birkeland 1997).

2.2.2 Degradation Due To Land-Based Sources

The pollution of coastal waters has led to the degradation of coral reef ecosystems. Turbidity, the "cloudiness" of water, reduces the amount of light reaching the coral on the substrate, and is known to decrease coral growth (Carricart-Ganivet and Merino 2001). Various contaminants of water quality produce increased turbidity. Upstream erosion contributes suspended sediments in the water column while excess nutrients lead to algal blooms reducing the water's clarity (Boyd 2000). Sediments also have the added harm of smothering corals and creating soft substrate on which coral larvae cannot settle (Aller and Dodge 1974; Cortes and Risk 1985; Gilmour 1999). This has been shown to favour long branching corals which are not smothered, but these same corals are susceptible to being destroyed by the waves of large storms (Rogers 1990). Nutrients may also disrupt the symbiosis between the corals and the zooxanthellae, and reduce reproduction (Ferrier-Pages et al. 2001). One of the expected outcomes of sedimentation and eutrophication is the shift of an ecosystem towards macroalgal dominance. In nutrient enriched waters, these algae grow taller and faster than corals, shading and out-competing them for light. Macroalgae also have an advantage over corals in regions of high sedimentation as macroalgae do not require hard substrate to settle (Fabricius 2005).

2.3 Eutrophication

2.3.1 General Process

The process of eutrophication occurs with the input of nutrients into a water body enhancing the population of phytoplankton. These autotrophs are opportunistic and will consume nutrients released in excess of the ambient concentrations. Increased primary productivity in a water body has the effect of decreasing water transparency and depleting dissolved oxygen (Welch et al. 2004). The bloom of productivity limits the amount of sunlight reaching the substrate thus limiting benthic growth. In turn, this limits the production of oxygen by benthic vegetation. Once the nutrients are consumed there can be a mass mortality of the phytoplankton bloom, requiring decomposition and thus oxygen demand. These processes can lead to anoxic conditions and the death of aquatic organisms (Correll 1998). In lakes, this process is natural as gradual nutrient loading will eventually cause the aging of lakes, however, human presence has accelerated the process (Lamb 1985).

Nutrient enrichment of freshwater and marine environments has been directly linked to land-based sources such as urbanization, organic sewage, and application of fertilizers (Lapointe and Clark 1992; Lapointe and Matzie 1996; Cloern 2001; Lapointe et al. 2004). Therefore, controlling eutrophication requires management of both point-source and non-point-source pollution (Lamb 1985). One of the most important questions from a management point of view is: what is the critical loading of a receiving water body? This nutrient loading level is a threshold beyond which eutrophication will occur. To answer this question one needs not only an understanding of the nutrient supply of various inputs, but of a receiving water body's ambient nutrient concentrations, flushing rate, and sedimentation rate (i.e. the process of nutrients binding to sediments, thus becoming unavailable) (Perry and Vanderklein 1996).

Basically, the process of eutrophication begins when concentrations of the nutrient limiting algal production are increased. The algal cellular molar ratio of nitrogen to phosphorus, the two primary nutrients limiting production, is naturally 16:1. If ambient nutrient levels yield a molar ration of total nitrogen to total phosphorus of greater than 16:1, the water body is phosphorus limited. If this ratio is less than 16:1, nitrogen is limiting production (Downing 1997).

2.3.2 Phosphorus

Phosphorus (P) exists in many forms in water or soil. It may be classified as particulate (PP) or dissolved (DP, also called soluble (SP)). The distinction between the two is defined by the nutrient's ability to pass though a 0.45 µm filter (Brodie and Mitchell 2005). Each of these two forms may be further classified as organic (OP) or inorganic (IP). Another term, reactive P, describes P which can be detected in the laboratory without any prior processing. This class is generally of the dissolved inorganic form (DIP), such as orthophosphate ions ($H_2PO_4^-$ and HPO_4^{-2}), though it may also include particulate fractions less than 0.45 µm in size and various dissolved polyphosphates (Brodie and Mitchell 2005). The larger molecular structure of the dissolved organic form (DOP) makes it less reactive but may also be incorporated in this measure, along with particulate fractions smaller than 0.45 µm. That which is not reactive requires digestion before laboratory detection is possible (Delcan Consulting 1994b). The only form of P available for photosynthetic uptake is soluble reactive phosphorus (SRP), making this class of P most commonly measured in studies of eutrophication. However, PP may act as a long-term source of SRP to a water body as it is gradually dissolved and decomposed, and so measuring total phosphorus (TP) is preferable (Sharpley et al. 1999). For example, Quebec has set a surface water quality standard of 0.03 TP-mg/l as the threshold concentration for threats of eutrophication (Ministère de l'Environnement du Québec 2001).

The proportion of different forms of P in water or soil is site specific. In soil, the proportion of PP is usually quite high, but will depend on the characteristics of the soil (Sharpley et al. 1999). P's sorption potential onto soil particles is high, especially with finer sediments such as clay and reactive minerals such as aluminum, iron, and calcium (Schlesinger 1997). This results in the rapid fixation of DP upon entry to soil, thus becoming PP. In natural soils, OP is present in microbial tissue, plant residue, and humus while the inorganic forms are attached to soil particles. However, in agricultural soils, application of manure and commercial fertilizers contributes large amounts of OP and DIP, respectively, to the top layer of the soil (Brady and Weil 2002). The proportion of a soil's TP which is inorganic can vary between 10-90% though in most agricultural soils it varies between 50-75% (Sharpley and Rekolainen 1997).

Transport of P from the soil system can occur through plant uptake as SRP, surface runoff as PP and/or DP, percolation to the water table as DP, and subsurface drainage as PP and/or DP in agricultural fields (Brady and Weil 2002). P is most likely to be transported via runoff (Haygarth and Jarvis 1997) and associated with suspended particulate matter (Brodie and Mitchell 2005). This is due to P's high potential for sorption to soil particles and tendency to be in the top layer of agricultural soils. As a result, most P loss from the soil system occurs during large rainfall events which can represent a relatively short part of the year (Pionke et al. 1997).

The proportion of different forms of P in runoff widely varies depending on geology, soil type, hydrology, and the sources of P in the catchment (Dillon and Kirchner 1975). As P is commonly associated with particulate matter, the amount of TP in runoff will largely depend on the land's susceptibility to erosion. Therefore, soil management practices, such as tillage, will have an effect as well (Brady and Weil 2002). In agricultural runoff, TP may be composed of as much as 60-90% PP (Sharpley and Beegle 1999).

Losses of DP from agricultural areas are very dependent on the timing of fertilizer application with respect to storms. The DIP contained in commercial fertilizers is totally fixed within 2-4 weeks (Sharpley and Beegle 1999). Should runoff occur before the P is used by plants or adsorbed to soil particles, these dissolved forms will be transported to receiving water bodies where they are immediately available for photosynthetic growth. Therefore, fertilizer application will have a great impact on the amount of DP transported via runoff (Brookes et al. 1996). In addition to timing, the rate and method of fertilizer application as well as the type of fertilizer will all affect DP concentrations in runoff.

One can expect a very high proportion of P lost from a catchment to arrive at the outlet, especially with short event flows. There may be slight losses of PP due to settling of large sediments or desorption transforming PP to DP, but the proportions will generally remain constant during the transport process (Brodie and Mitchell 2005). Adsorption/desoprtion processes involve a quick step (minutes, hours) and a slow step (days, months). The amount of time required for desorption to occur is proportional to the time period over which adsorption had occurred (Froelich 1988). Therefore, when runoff washes away PP which has been in the soil for over a day will, it will take at least that long for the P to return to its dissolved state. However, in receiving water bodies, where particles may remain for long periods of time, one may expect significant desorption to occur and subsequent increases in concentrations of SRP. Globally, when suspended particulates contain 30-300 μg-P/g are flushed to the ocean, desorption of PP will eventually result in the total flux of SRP being 2-5 times higher than that of the original SRP flux alone (Froelich 1988). In anaerobic conditions, desorption will occur at a faster rate (Furumai and Ohgaki 1989).

2.3.3 Nitrogen

The reactive forms of nitrogen (N) immediately available for photosynthetic uptake are termed dissolved inorganic nitrogen (DIN) and include nitrate (NO_3), nitrite (NO_2), and ammonium (NH_4). The oxides of nitrogen, NO_3 and NO_2, are sometimes termed together as nitrate-nitrite (NO_x) if they were not separated during laboratory analyses. NH_4 is relatively immobile, held tightly by clays and organic matter. Thus, it would typically be transported via surface water rather than infiltration. In the soil, NH_4 is rapidly converted into NO_3 by soil microorganisms by the process of nitrification. NO_2 is the intermediary product of nitrification and is very reactive and toxic to aquatic life. It has a very short half-life so it poses little risk except under high temperature and poor aeration when NH_4 oxidation exceeds NO_2 oxidation, in which case leaching is an issue. NO_3 is highly soluble, doesn’t fix on clays or organic matter and is thus highly mobile (Boyd 2000). As a result, most of the N transported from a catchment will be in the form of NO_3 and little will be lost along the way (Brodie and Mitchell 2005). Under anaerobic conditions, NO_3 may be transformed into the gaseous form N_2 by the process of denitrification (Vitousek et al. 1997).

A major source of nitrogen are agricultural fertilizers, usually added to the soil in excess of its N requirements (Vitousek et al. 1997). Elevated NO_3 concentrations can often be observed in agricultural areas (Moody 1990). Manure contributes mostly organic nitrogen (ON) while N in commercial fertilizers is present in its inorganic forms. In the soil, ON undergoes microbial decomposition to create inorganic nitrogen, the process of ammonification (Boyd 2000).

Sources of DIN to a receiving water body include runoff, groundwater seepage, atmospheric deposition as well as N-fixation by aquatic microorganisms. Free-living heterotrophic microorganisms and blue-green algae have the ability to fix gaseous nitrogen, N_2, reducing it to NH_4^+, and can hence overcome N-deficiency (Perry and Vanderklein 1996).

A correlation between NO_3 in rivers and human population in the adjacent catchment is well established, making NO_3 a good indicator of catchment disturbance and development (Peierls et al. 1991). Eutrophication of marine environments has been well-documented and has been accepted as a consequence of anthropogenic influences on the nitrogen cycle (Howarth et al. 1996).

2.4 Streamflow Measurement

An important parameter in hydrological monitoring is streamflow, or discharge, commonly measured using the velocity-area method (Herschy 1995). By measuring the cross-sectional area of flowing water and the velocity at which the water flows, the volumetric rate of discharge can be calculated. These measurements are often taken for multiple discrete sections across the stream’s width and then summed to make a more accurate calculation of discharge.

Measurement of a stream's cross-sectional area requires the gauging of stage, or water level, along with an assessment of the streambed's shape. Stage may be measured directly via a staff gauge or indirectly with a pressure-transducer recording the pressure of water induced upon the sensor below the flow. If continuous monitoring of stream flow is not possible, the peak stage may be inferred from a residual high water mark such as vegetation wrapped around tree trunks or by means of a "Maximum Stage Recorder" as described below.

Surface velocity can be measured with the float method and then converted to mean velocity by a coefficient. This coefficient generally varies between 0.8-0.9 depending on the channel's vertical velocity distribution (Herschy 1995), with higher values being used for smoother beds. However, mean velocity is best measured with a current meter, taking measurements at multiple points across a stream. The number of points depends on the bed's size and uniformity while the spacing of points should divide the flow into sections of equal discharge. At each point, the current meter should be placed at 6 tenths of the total depth below the surface for shallow depths (< 1 m), or at 2 and 8 tenths of the total depth below the surface for deeper depths (> 1 m). A series of velocity measurements at various flow stages can be used to establish a stage-discharge relationship, or rating curve, used to calculate discharge from future measurements of stage alone. Rating curves are useful in calculating discharges over long periods of time when measurements of stage are made continuously, such as with a pressure transducer (Herschy 1995).

The slope-area method is the most commonly used method of indirect measurement of discharge. This method makes use of Manning's equation for uniform flow to calculate mean velocity from measurements of stage, slope, and surface roughness:

$$V = \frac{1}{n} R^{2/3} S_e^{1/2} \qquad \text{(Eq. 2.1)}$$

where:
V = mean velocity of flow (m/s)
R = hydraulic radius (m)
S_e = slope of energy grade line (m/m)
n = Manning's roughness coefficient

The Manning's roughness coefficient represents the waterway's resistance to flow and is determined by assessing the channel's bed material and factors which contribute to resistance. Selection of the roughness coefficient is subjective and can produce a large amount of error and so it should be verified with direct measurements of velocity (Herschy 1995).

There are many interdependent factors that affect the value of the roughness coefficient, *n*, which have been described by Chow (1959): Firstly, *n* depends on the roughness of the streambed and will decrease with smaller and smoother materials forming the surface. The height, density, distribution, and type of vegetation on the surface affects *n*, and so *n* may vary seasonally. This effect decreases with higher water velocities which can flatten the underlying vegetation. Any irregularities in the channel such as sharp turns or abrupt changes in the shape of the bottom will induce resistance and increase *n*, an effect which may carry downstream for several hundred meters. This effect depends primarily on the number of alternations of large and small sections and secondarily on the magnitude of the changes. Changes in the channel's surface may occur during flow such as scouring which uses energy, increasing *n*, or silting which makes the bottom more uniform, decreasing *n*. The transport of materials such as sediment, whether suspended or on the bed, requires energy, decreases water velocities and thus increases *n*. Any obstructions causing the flow to diverge will have a negative effect on velocity and thus require an increased *n*-value. The value of the roughness coefficient in a channel may also vary with stage as factors inducing resistance will become proportionately smaller compared to the cross-sectional area of higher water levels. Therefore, *n* may not be constant, and so a calibrated rating curve is a more accurate method of discharge calculation.

Cowan (1956) developed the following formula to incorporate the effects of these factors into *n*'s determination:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad \text{(Eq. 2.2)}$$

where:
n_b = a base value of n for a straight, uniform, smooth channel in natural materials
n_1 = a correction factor for the effect of surface irregularities
n_2 = a value for variations in shape and size of the channel cross section
n_3 = a value for obstructions
n_4 = a value for vegetation and flow conditions
m = a correction factor for meandering of the channel

Once water levels are above a channel's bank the *n* value will increase due to the surface roughness associated with the flood plain. For above bank conditions, the channel's cross-section may be partitioned into channel and flood-plain subsections. For such compound channels, the value of *n* should be weighted according to the wetted perimeter or area of the subsections. The basis for weighting *n* depends on the variability of depth between subsections: if depth is fairly uniform the wetted perimeter is used, and if depth varies considerably the area is used (Arcement and Schneider 1989). However, vegetation in the flood plain has a marked effect only up to a certain stage, and so the roughness coefficient may be considered constant for practical purposes in determining overbank flood discharges (Chow 1959).

III. ENVIRONMENTAL IMPACTS OF RUNOFF ON THE BELLAIRS FRINGING REEF, BARBADOS

3.1 Abstract

The fringing reefs of Barbados have been suffering the chronic disturbances of eutrophication and sedimentation for more than 25 years. These processes are driven by the addition of sediments and nutrients to the oligotrophic marine environment. The contributions of runoff to these processes were documented by event-based sampling of flow at an outlet through Holetown and the adjacent nearshore area including the Bellairs Reef. The following parameters were monitored and their contributions to coastal water quality degradation assessed: turbidity, total suspended solids (TSS), nitrate-nitrite nitrogen (NO_x-N), soluble reactive phosphorus (SRP), nearshore sedimentation, salinity, and terrestrial discharge. A significant northward dispersion trend was observed directing plumes towards the Bellairs Reef. All 4 flow events documented produced detrimental levels of turbidity, or TSS, or both above the reef. Water quality in the area of the outlet and above the reef significantly varied among events in correspondence to total TSS loads and discharges from the outlet, though temporal variation above the reef also depended on wind stress. While excessive turbidity levels lasted less than 2-3 days, excessive TSS levels reaching the reef lasted at least 3 days. Estimated suspended sediment loads ranged between 32-187 metric tonnes. Reef sedimentation rates were in excess of guidelines for 35 of the 118 days monitored, presenting a chronic stress in addition to that of reduced surface water clarity. Dissolved nutrient loads were estimated to range between 8.5-32.4 kg-SRP and 17.6-66.7 kg-NO_x-N. It is expected that these

loads make large contributions to coastal eutrophication, especially with respect to phosphorus.

3.2 Introduction

"A high incidence of sunshine, unbroken warm temperatures, brilliantly clear seas and white coral sand beaches provide the natural attractions which bring a quarter million tourists to the West Indian Island of Barbados every year." (Bird et al. 1979) Little has changed since 1979 with respect to the described natural attractions though they currently bring four times as many tourists (Ministry of Tourism 2003). In addition to the quarter million local Barbadians (Ministry of Labour 2002), this populace has prompted extensive development of the coastal area (Nurse 1986). On the west coast in the catchment area of Holetown, urban areas have doubled between 1964 and 1996 causing higher proportions of rainfall to be transported as surface runoff to the coast (Leitch and Harbor 1999). Runoff events in the coastal area can leave the seawater somewhat less than "brilliantly clear" impacting another natural attraction not described above: the coral reefs.

3.2.1 The Coral Reefs of Barbados

A series of fringing coral reefs extends along the western, leeward coast of Barbados (Lewis 1960). These ecosystems have undergone considerable changes over the past 25 years as the fringing reefs have degraded both structurally (Lewis 2002) and biologically (Bell and Tomascik 1993). While these systems have been affected by acute disturbances such as Hurricane Allen (Mah and Stearn 1986) and the mass mortality of the grazer *Diadema antillarum* (Hunte et al. 1986), an underlying cause of the demise has been eutrophication and associated suspended particulate matter (SPM, or total suspended solids, TSS) and sedimentation (Bell and Tomascik 1993). This chronic stress has been documented along the west coast as a gradient of water quality deteriorating towards the south (Tomascik and Sander 1985). Studies along this eutrophication gradient have shown it affects coral growth rates (Tomascik and Sander 1985; Davies 1990; Tomascik 1990), reproduction (Tomascik and Sander 1987a), settlement (Tomascik 1991; Hunte and Wittenberg 1992; Mann 1994), juvenile mortality (Wittenberg and Hunte 1992; Mann 1994), community structure (Tomascik and Sander 1987b; Wittenberg and Hunte 1992; Allard 1994; Mann 1994), associated crustacean fauna (Snelgrove and Lewis 1989) as well as *D. antillarum* densities (Wittenberg and Hunte 1992; Allard 1994; Mann 1994) and bioerosion (Holmes 1996). Similarly, coastal development along the west coast follows such a pattern with populations decreasing northwards away from the city of Bridgetown in the south.

3.2.2 Coastal Eutrophication

Coastal eutrophication is a process governed by excess nutrients causing increased productivity and associated decreases in water clarity. This process has been directly linked to land-based sources as urban, industrial, and agricultural effluents regularly have high nutrient concentrations (Cloern 2001). This process has been shown to harm coral, which naturally live in clear, nutrient-poor environments. Nutrient enrichment can disrupt coral symbiosis with its symbiont zooxanthellae, but will more commonly be rapidly utilized by phytoplankton, the expansion of which decreases water clarity, inhibiting growth of the light-dependent coral (Fabricius 2005). Sedimentation on reefs often results in reduced biodiversity as smothering can cause mortality. Certain morphologies, such as that of large branching corals, or the ability to remove settled particles make some corals more tolerant to sedimentation, however particle removal comes at a metabolic cost thus inhibiting growth (Rogers 1990).

3.2.3 Coastal Inputs

Inputs to the nearshore zone of Barbados affecting water quality include runoff, groundwater, coastal point-sources, and oceanic currents. Periodic runoff events during the rainy season (June-December) create plumes of nutrient-rich, sediment-laden freshwater which can extend over 1 km offshore to the island's bank reefs (Delcan Consulting 1994c). Transport of freshwater plumes can be variable as they rest above the denser seawater on the surface where currents are largely affected by wind stress (Devlin and Brodie 2005). Groundwater seepage along the west coast has been shown to make significant nutrient contributions (Lewis 1985, 1987), as have point source discharges such as rum refineries (Runnalls 1994). Ocean currents have the potential to bring productive waters from the South American rivers Amazon and Orinoco, and while these waters generally arrive in the months of July and August, the passing of North Brazil Current rings bringing Amazon waters is unpredictable (Fratantoni and Glickson 2002).

3.2.4 The Study

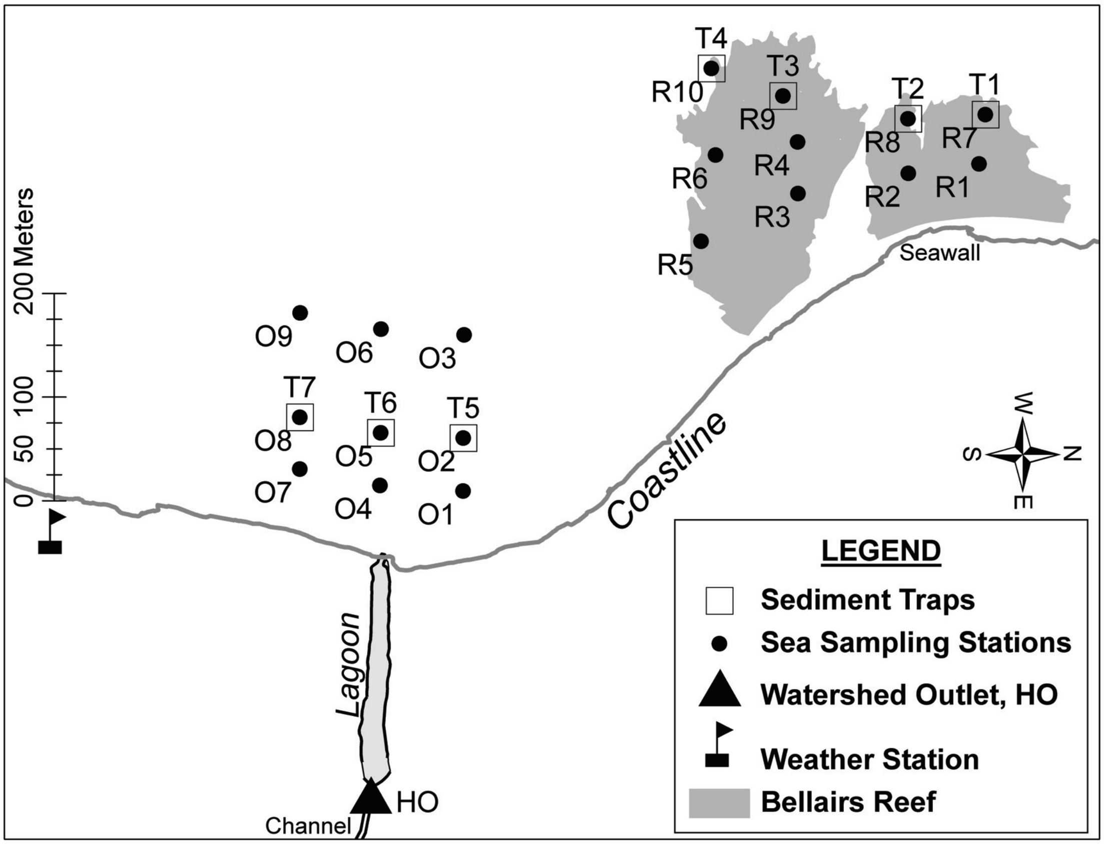
This study aims to assess the specific contributions of runoff to the nearshore area of Holetown, situated on the central west coast of Barbados. A 9.9 km^2 watershed drains into the Holetown Lagoon, a body of surface water separated from the sea by a 9 m length of beach. The occurrence of ephemeral runoff events quickly washes away this beach, flushing runoff and lagoon water out to sea. About 600 m north-west of this outlet lies the Bellairs Reef, which is separated into a northern and southern lobe. Flow events were monitored from May-December 2006. Sampling of the runoff and subsequently the nearshore surface water allowed for an event-based assessment of water quality processes. Additionally, sedimentation rates were recorded between July-December 2006.

3.3 Methods

3.3.1 Field Methods

At the coastal outlet of the Holetown watershed, site HO (Fig. 3.1), a rating curve was established in the rectangular concrete channel (2.5 m width, 0.6 m depth) 25 m upstream of the Holetown lagoon. Velocity was measured at 6 tenths of the total depth below the surface at five points equally spaced across the channel's width using a model 1210 Price Type AA Current Meter (Herschy 1995). Stage and velocity were recorded simultaneously during 4 flow events producing a data set with a range of stages from 9.1 – 56.4 cm. Discharge values were calculated and a 4th order polynomial curve was fit to the stage-discharge relationship ($R^2 = 0.9885$). A pressure transducer in the channel operated by Baird & Associates Ltd. for the Barbados Coastal Zone Management Unit (CZMU) recorded continuous measurements of stage which were later converted to discharge using the rating curve. For above bank conditions, the channel's cross-section was partitioned into channel and flood-plain subsections and Manning's equation was used to calculate flow with a roughness coefficient weighted by each subsection's area (Arcement and Schneider 1989). A Manning's *n* value was calibrated for the channel subsection using the rating curve while another *n* value was selected for the floodplain subsection.

Figure 3.1: Marine sampling scheme. Labels identify sea sampling stations (Outlet Area: O1-O9, Reef Area: R1-R10) and sediment traps (T1-T7).



Samples (300 ml) were taken from the runoff's surface water and analyzed for total suspended solids (TSS) by standard methods (American Public Health Association et al. 2005). Single samples were taken every 5 minutes for at least the first 3 hours of each of 3 flow events (Oct.16, Oct.27, Nov.14). A high frequency of sampling is important due to rapid changes in concentrations during events (Brodie and Mitchell 2005). Triplicate samples were taken every 30 minutes to verify the precision of measurement. The concentrations plotted over time were fitted with curves ($R^2_{\text{Oct.16}}$ = 0.9332, $R^2_{\text{Oct.27}}$ = 0.9911, $R^2_{\text{Nov.14}}$ = 0.9857) used to calculate the total load of TSS for each event. For 1 event (Aug.24), a set of 7 grab samples were taken over 10 minutes following the first 2 hours of flow. For this event, the total TSS load was estimated by fitting the average concentration curve established during the other 3 events, all of which produced very similar curves, to the TSS concentrations measured on Aug.24. Nutrients were analyzed with a DR/2000 Hach Spectrophotometer by the Ascorbic Acid Method (range: 0-0.82 mg/l) for soluble reactive phosphorus (SRP) on Oct.16, Oct.27, and Nov.14, and the Cadmium Reduction Method (range: 0-30.0 mg/l) for nitrate-nitrite-nitrogen (NO_x-N) on Nov.14.

Seawater surface samples were collected at depths of 0.5 m (Devlin and Brodie 2005) from a sea kayak. Tidal level can affect seawater nutrient concentrations (Sander 1981; Lewis 1987), and so sampling was always done just after low-tide for consistency. Sampling began immediately following low-tide such that tidal currents did not change during sampling. For each of 4 events, seawater sampling was done following the conclusion of flow in the channel, and one tidal cycle, such that the rising tide had rebuilt the beach. This corresponded to a period of 17 hours following the onset of flow which coincidently always occurred within 1 hour of the same time of day (16:00 local time). A second set of samples was collected for the events of Aug.24, Oct.16, and Nov.14 following periods of 67, 41, and 67 hours, respectively, after the onset of the flow event. Baseline data were collected on 4 occasions between Sept.30-Oct.14, at which point no flow event had occurred for at least 1 month. Sampling was done at 19 stations (Fig. 3.1): 10 stations in the area of the Bellairs Reef (R1-R10) and 9 stations in the area of the terrestrial outlet (O1-O9). However, for 1 event (Aug.24) only the reef area was sampled. In each area, sampling was done along offshore transects (Devlin and Brodie 2005) with 80 m between each transect and stations located at approximately 50, 100, and 200 m offshore. These offshore distances were selected in order to sample both the crest zone and the spur and groove zone of both North and South Bellairs. Stations R7-R10 were located in the spur and groove zone of the Bellairs Reef (depth = 5 m), while stations R1-R6 were located in the reef's crest zone (depth = 2 m). At each station, triplicate 1 L samples were taken and analyzed for turbidity using a Scientific model Micro 100 Turbidimeter and for TSS by standard methods (American Public Health Association et al. 2005). Salinity was also measured in samples taken 17 hours after the onset of 2 flow events (Oct.16, Oct.27) and on 1 baseline sampling occasion using a YSI model 33 S-C-T meter.

Seven sediment traps were placed in the area and monitored from July 31 to Dec.5 (Fig. 3.1). Four traps were placed in the spur and groove zones of the Bellairs reefs (T1-T4) and three were placed directly offshore of the terrestrial outlet (T5-T7). Traps were placed 100 m offshore with the exception of two traps on South Bellairs, traps T3 and T4, for which offshore distances were adjusted to 175 and 225 m, respectively, such that all traps on the reefs were at equal depths of 5.4m. The opening of each trap was positioned at a height of 60 cm off the seabed (Delcan Consulting 1994c). Each trap was composed of three PVC tubes (3.8 cm diameter, 25 cm length) spaced 20 cm apart on a single cement block. These dimensions yield an aspect ratio (height:mouth diameter) of 6.6, characteristic of an efficient sediment trap (Hargrave and Burns 1979). Traps were retrieved periodically, with sampling periods ranging between 3-30 days. Once transported to the lab, the traps were allowed to settle for one hour, after which seawater was decanted, and sediments were rinsed with freshwater to remove salts (Tomascik and Sander 1985). Sediments were then dried at a temperature of 100°C to a constant weight (Delcan Consulting 1994c).

Wind data were obtained from a weather station operated by the Barbados CZMU. The weather station was located on the roof of a building on the coastline 300 m south of the terrestrial outlet (Fig. 3.1). Hourly data were used to calculate the average wind speed during the 17 hours between the onset of flow and seawater sampling. The wind direction for this period was described by calculating a mean direction weighted by speed. Significant wave heights were obtained from a sensor stationed approximately 1km south of station O8 operated by the Barbados CZMU. Wave heights at this location may not be representative of that in the study area due to spatial variation, and so the data are only used for analyses of temporal variation, to identify periods of higher wave action.

3.3.2 Statistical Analyses

Statistical analyses were performed with seawater quality data after subtraction of baseline levels. Spatial trends were analyzed for the 9 sampling stations in the outlet area as well as for the 10 sampling stations in the reef area. Temporal trends were analyzed across 3 flow events in the outlet area and 4 flow events in the reef area. Spatio-temporal effects of seawater quality change in the nearshore area following a flow event were first analyzed using classical unmodified ANOVA. The basic ANOVA model was a fixed two-way factorial model with replicates, the sampling station and flow event being the two crossed factors.

However, the spatial and temporal data exhibited signs of autocorrelation and heteroscedasticity in violation of the circularity condition required for unmodified ANOVA F-tests (Huynh and Feldt 1970; Rouanet and Lepine 1970). Thus, a modified univariate testing procedure was performed, using estimates of Box's epsilon (Box 1954a, b) to correct the numbers of degrees of freedom in a given F-test statistic and adjust the probability of significance. A doubly multivariate model, called the matrix normal model, was used to compute estimates of Box's epsilon and adjust probabilities of significance of the modified ANOVA F-tests for space, time, and space-time effects (Dutilleul and Pinel-Alloul 1996). When main effects of sampling station or flow event were declared significant ($P < 0.05$) by the modified ANOVA F-test, multiple comparisons of means were performed with a modified Student-Newman-Keuls procedure. In this procedure, the error number of degrees of freedom was multiplied by the corresponding Box's estimate.

3.4 Results

3.4.1 Event Characteristics

Inputs of runoff to the nearshore area and wind data for each event are summarized in Table 3.1. Total discharge, peak discharge, and TSS load were positively related. The single exception is the TSS load of Aug.24, estimated to be much higher than the load of Nov.14 which had a higher total discharge and peak discharge. This may be expected as the Aug.24 event was the year's first flow which can contain much higher concentrations (Lee et al. 2004). The concentrations of TSS in the channel ranged from 500 – 3500 mg/l. Wind speed showed strong variation and although wind direction varied, it was consistently offshore with a northward component.

Table 3.1: Summary of flow event data. Includes estimates of total discharge of water, total suspended solids (TSS), soluble reactive phosphorus (SRP), and nitrate-nitrite-nitrogen (NO_x-N), as well as wind data for each flow event. Hyphens (-) indicate a lack of data necessary for making estimates. Estimates of potential error are presented in parentheses. Wind direction is given in degrees where zero represents north and angles are measured clockwise.

Event Date	Total Discharge (10^6 L)	Peak Rate of Discharge (m^3/s)	TSS Load (tonnes)	SRP Load (kg)	NO_x-N Load (kg)	Wind Speed (m/s)	Wind Direction (degrees)
Aug.24	68.2 (9.2)	10.9 (0.4)	~187 (25)	-	-	13.2	168.2
Oct.16	66.2 (6.5)	12.1 (0.5)	97.5 (13.2)	22.5 (6.2)	46.4 (24.6)	4.0	123.2
Oct.27	25.1 (6.5)	3.0 (0.3)	32.0 (4.1)	8.6 (4.0)	17.6 (13.7)	7.1	135.0
Nov.14	95.3 (13.6)	17.8 (0.6)	117.6 (20.4)	32.4 (10.4)	66.7 (38.5)	8.8	118.1

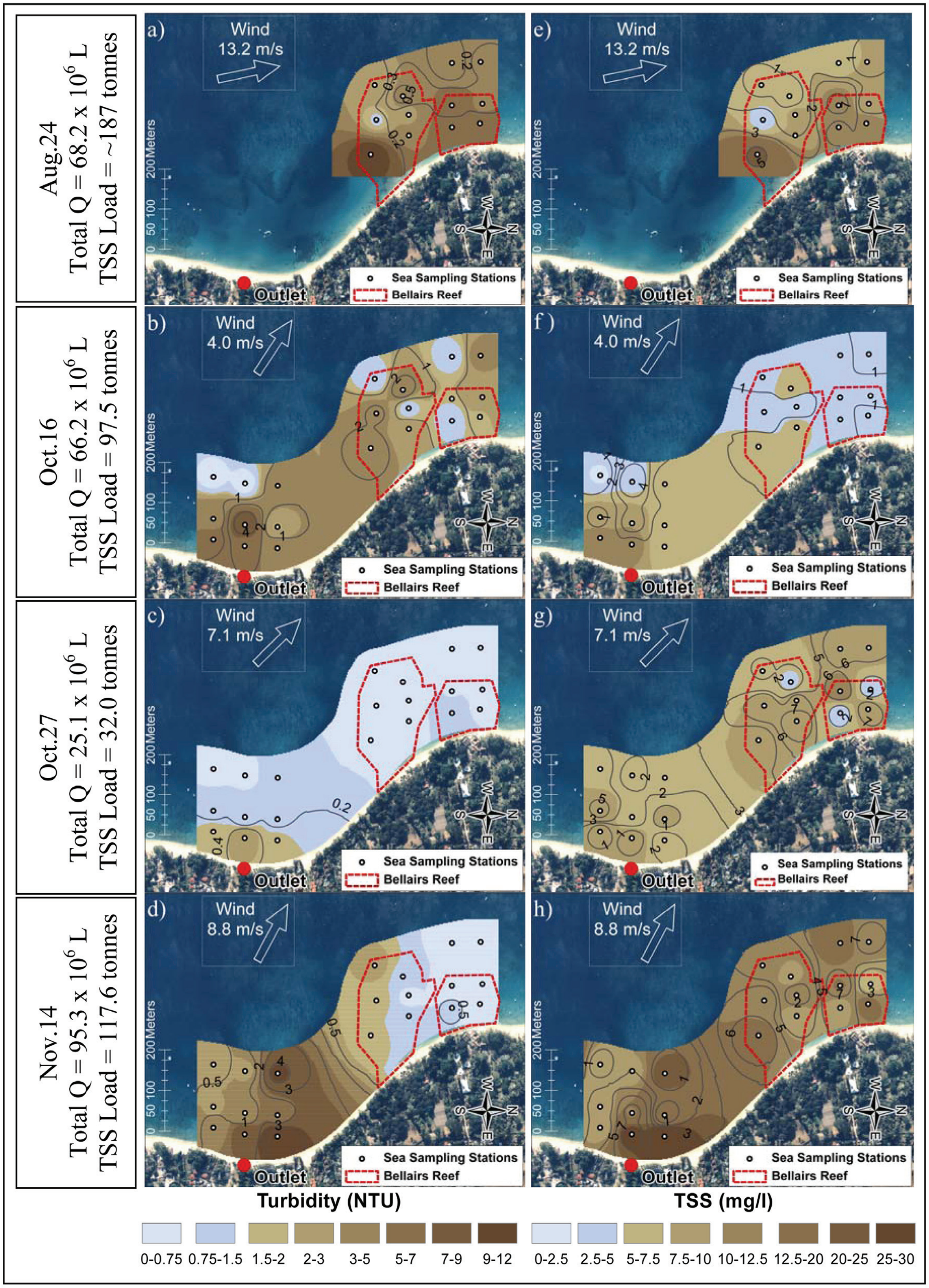
Nutrient concentrations in the channel averaged 0.34 +/- 0.06 mg SRP/l and 0.7 +/- 0.3 mg NO_x-N/l which are generally high for runoff (Meybeck 1982; Brodie and Mitchell 2005). These concentrations were used to estimate nutrient loads presented in

Table 3.1. While these effluents would be expected to enrich the nearshore seawater it is difficult to assess the impact these loads would have on ambient nearshore concentrations without concurrent measurements of seawater nutrients during the events. Loads can be used to predict the potential for eutrophication, however, this would require knowledge of the nearshore flushing rate (Valiela et al. 2004).

3.4.2 Seawater Quality

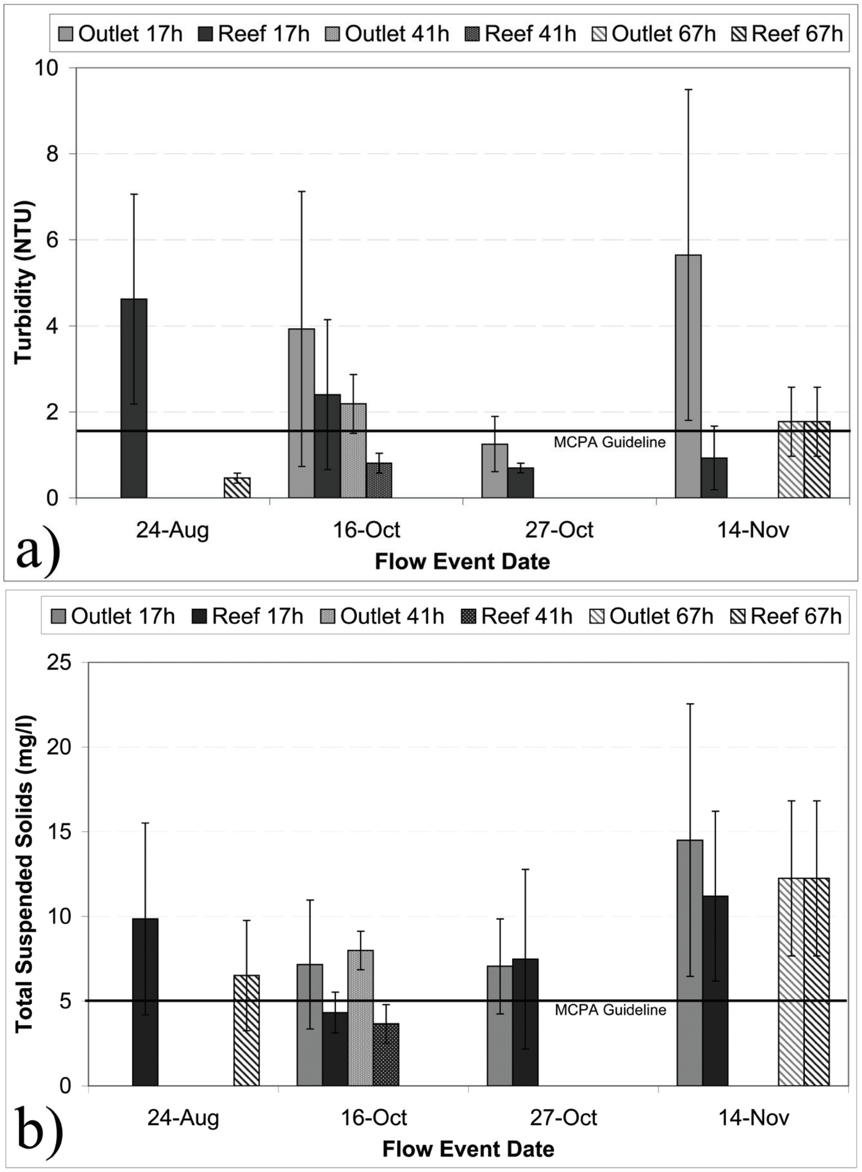
Salinity analyses of the seawater showed no difference between baseline values and post-event values (34.6 +/- 0.4 ppt) meaning that surface waters were well-mixed by the time of sampling, 17 hours after the onset of flow. Baseline TSS values averaged 2.24 +/- 0.26 mg/l and baseline turbidity averaged 0.47 +/- 0.07 NTU. The results of post-event seawater turbidity and TSS analyses are shown in Figure 3.2 for the 4 events documented in this study. Turbidity and TSS values from each sampling station were used for interpolation using the IDW method to the power of 3. Standard deviations at sampling stations were similarly interpolated and are displayed as contours (Antonic et al. 2001). Guidelines for the protection of marine health have been set by the Barbados Government's Marine Pollution Control Act (MPCA) for turbidity and TSS at 1.5 NTU and 5.0 mg/l, respectively (Government of Barbados 1998). On all occasions, the Bellairs Reef was affected by excessive levels of turbidity, or TSS, or both, with respect to these guidelines.

Figure 3.2: Seawater turbidity (a-d) and TSS (e-h) following flow events on Aug.24 (a,e), Oct.16 (b,f), Oct.27 (c,g), and Nov.14 (d,h). Contours indicate standard deviations. Indicated on the left are each event's total discharge of water (Total Q) and TSS.



Second sets of seawater samples taken 41 and 67 hours after the onset of flow showed that above-guideline turbidity levels did not remain in the surface water for long (Fig. 3.3a). On the other hand, TSS levels did not recede showing little, if any change (Fig. 3.3b). As a result, this study shows that when plumes reach the reef, it is subject to harmful TSS conditions due to runoff for a minimum of 3 days following an event.

Figure 3.3: Overall averages of a) turbidity and b) TSS of post-event seawater samples. Error bars show standard deviations. Samples were taken 17, 41, and 67 hours after the onset of flow.



3.4.3 Statistical Analyses

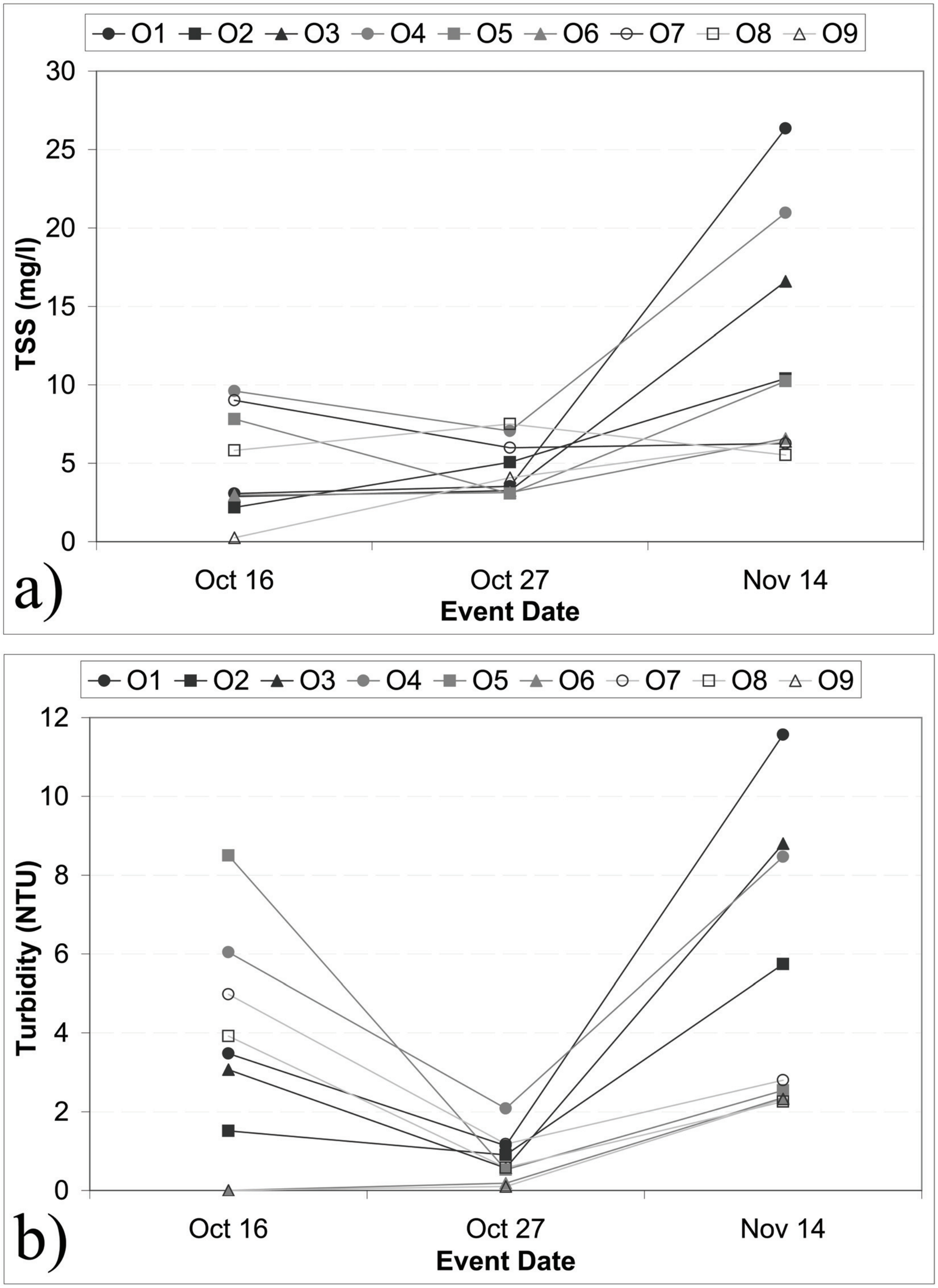
Statistical analyses of spatio-temporal variance in seawater quality showed that all effects exhibited a departure from the circularity condition with exception to TSS in the outlet area which was close to satisfying the condition on the temporal scale (Table 3.2). Adjustments to P-values had a slight effect with exception to TSS in the reef area, where station effects were highly significant before correction (P=0.0080) and no longer significant at the 5% level after correction (P=0.0773). The station*time effects of TSS in the reef area were neither significant before nor after adjustment. All other effects were found to be significant after correction, while time effects were highly significant in all cases.

Table 3.2: Results of statistical analyses.

Parameter	Main effects and interactions	Outlet				Reef		
		Epsilon	Unadjusted *P*	Adjusted *P*		Epsilon	Unadjusted *P*	Adjusted *P*
Turbidity (NTU)	station	0.313	<0.0001	0.0038		0.149	<0.0001	0.0251
	time	0.630	<0.0001	<0.0001		0.413	<0.0001	0.0003
	station*time	0.185	<0.0001	0.0118		0.047	<0.0001	0.0304
TSS (mg/l)	station	0.314	<0.0001	0.0025		0.384	0.0080	0.0773
	time	0.927	<0.0001	<0.0001		0.770	<0.0001	0.0004
	station*time	0.278	<0.0001	0.0016		0.179	0.2790	0.3656

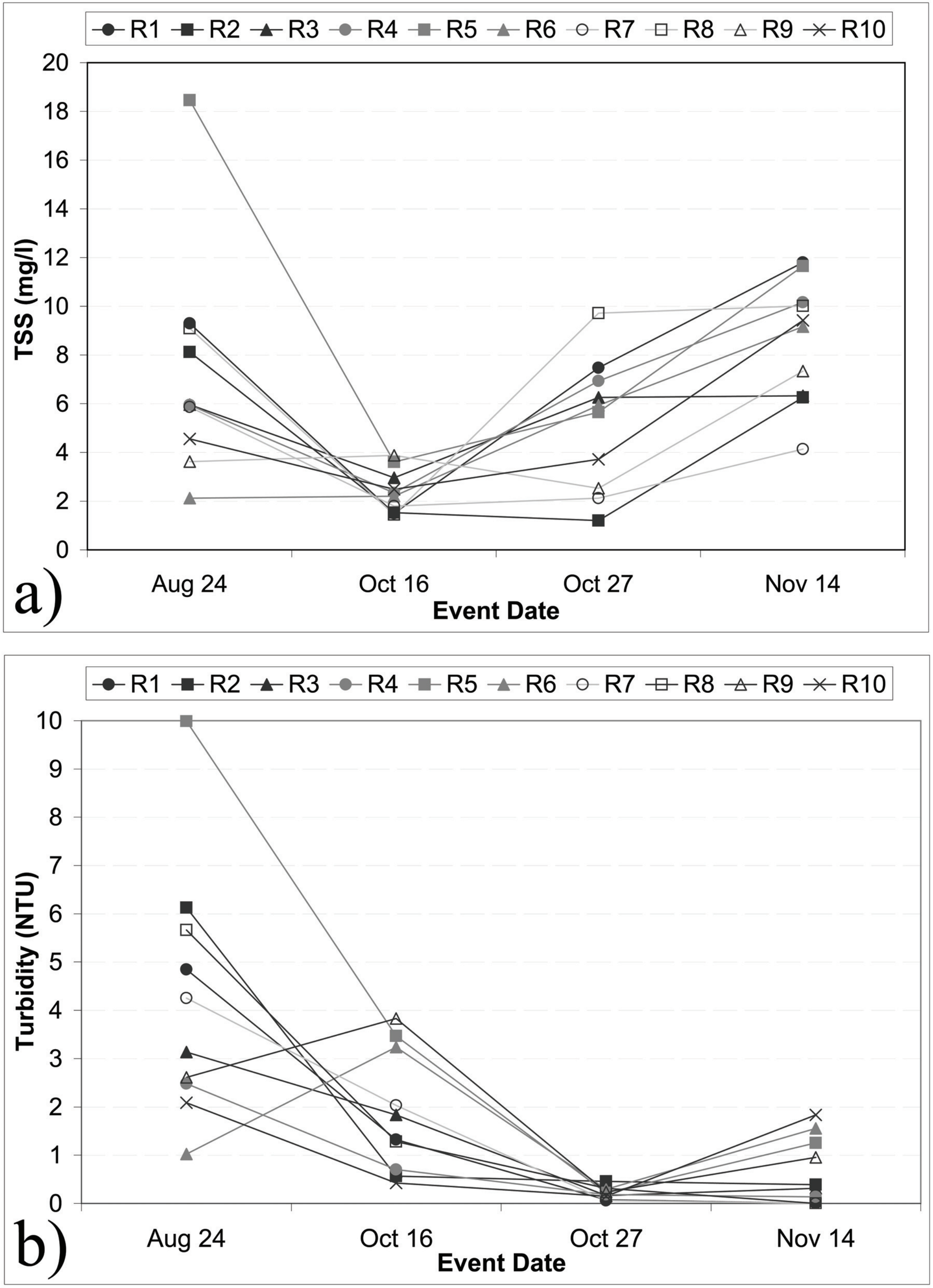
The significant station effects in the outlet area show high spatial variation of water quality (Fig. 3.4). In terms of both turbidity and TSS, the station directly in front of the outlet, O4, had the poorest water quality overall, followed by the station O1 to the north. Station O9, 200 m offshore and to the south, was least affected by the flow events, followed by station O6, 200 m directly offshore of the outlet. This indicates a northward trend for the fate of runoff as the stations to the north yielded significantly higher values than those to the south for turbidity at 50 m and 200 m offshore, and for TSS at 50 m offshore.

Figure 3.4: a) TSS and b) turbidity at sea sampling stations (O1-O9) in the outlet area.



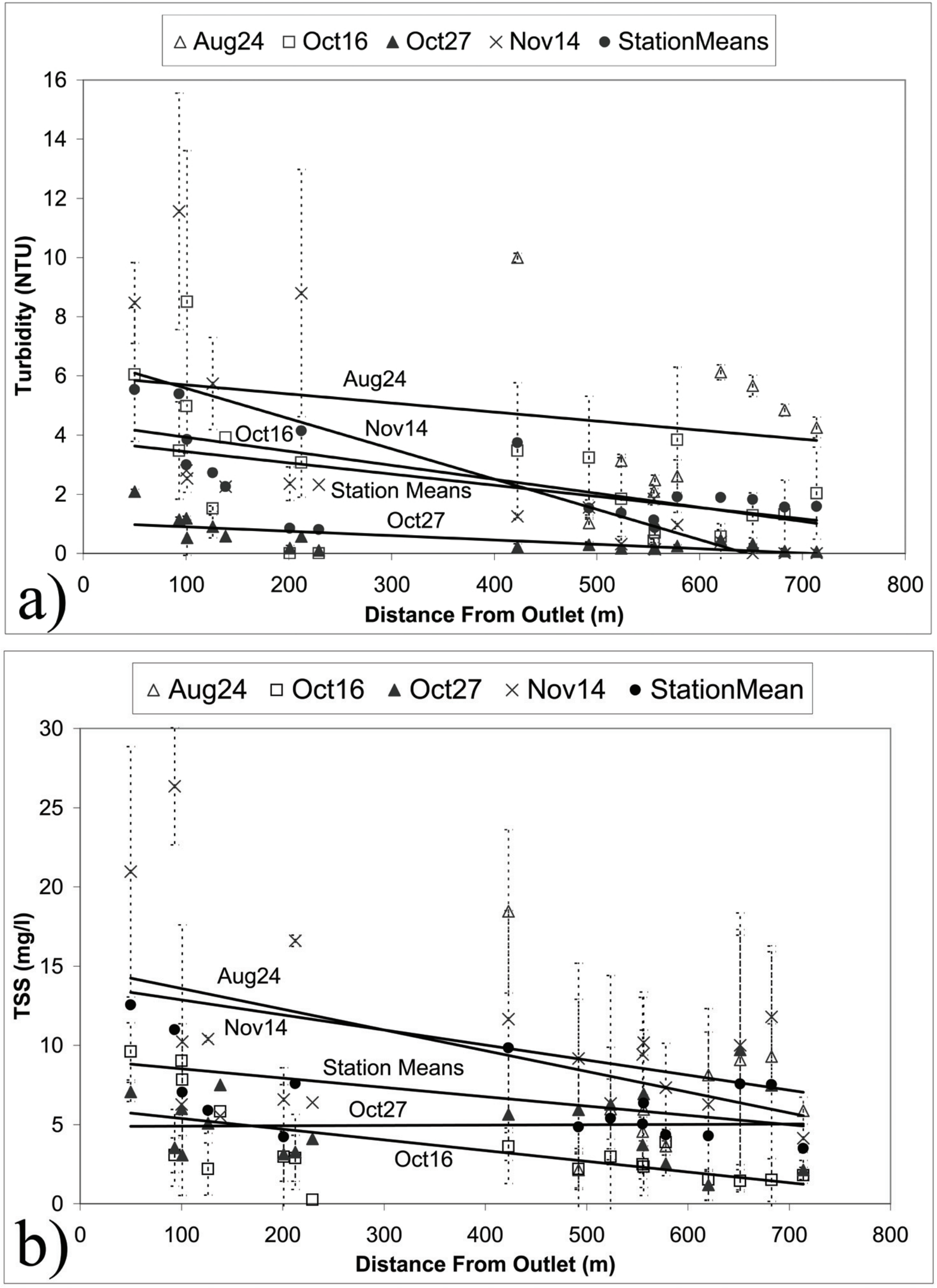
On the reef, the lack of statistically significant station effects for TSS following correction indicates that there is no consistent spatial variation in the area (Fig. 3.5a). Therefore, most of the variation observed among stations before correction was due to the data's autocorrelation and heteroscedasticity. Spatial trends for turbidity on the reef were limited to the station closest to the outlet, R5, having significantly higher values than the rest (Fig. 3.5b). There were no differences in turbidity or TSS between the reef's spur and groove zone and crest zone, nor between the north and south lobes of the reef.

Figure 3.5: a) TSS and b) turbidity at sea sampling stations (R1-R10) in the reef area.



Considering all sampling stations in the reef and outlet areas together, negative relationships were observed between turbidity and distance from the outlet and between TSS and distance from the outlet (Fig. 3.6). The single exception is TSS on Oct.27 in which stations at further distances are no lower than those directly in front of the outlet.

Figure 3.6: Water quality vs. distance to outlet. a) Turbidity and b) TSS at all stations displayed with error bars of standard deviations and trend lines labelled by event date.



Significant station*time interactions indicate that differences between stations were not constant from one event to the next, as was the case for turbidity and TSS in the outlet area and turbidity in the reef area. In particular, the station with the highest turbidity or TSS value in each area varied among the events. These interaction effects are evident in the differing slopes of the straight lines fitted for each event in Figure 3.6. For example, both turbidity and TSS decreased rapidly with distance from the outlet on Nov.14 while the event of Oct.27 produced lines with much flatter slopes. In the outlet area, station*time effects were much stronger for TSS than for turbidity.

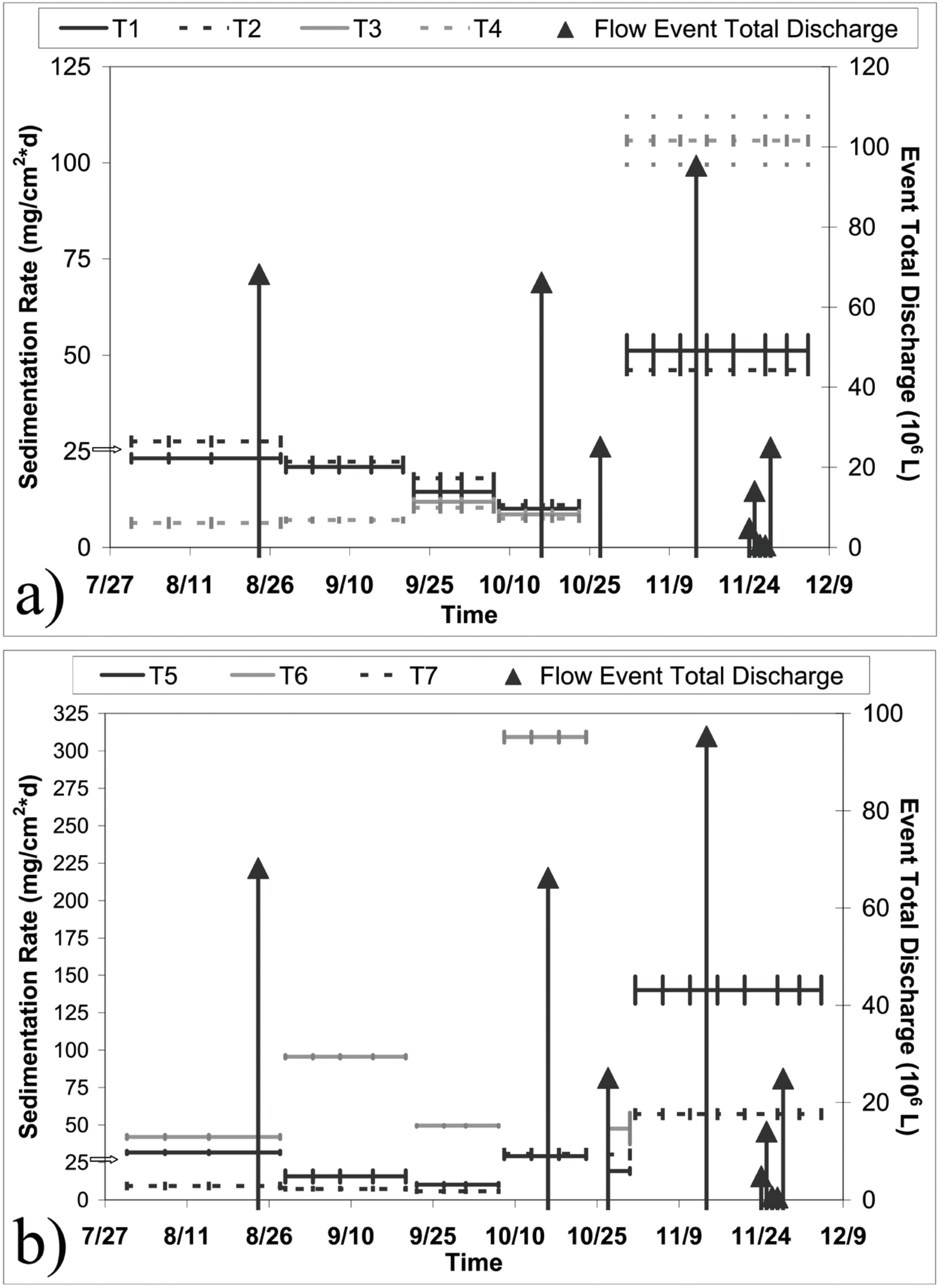
The most important effects were those due to temporal variation which were highly statistically significant in all cases. This variation may be associated with the differences between the individual events (Table 3.1, Fig. 3.2). In the outlet area, all three events produced significantly different turbidity levels. The event of Nov.14 produced the highest turbidity values followed by the events of Oct.16, and then Oct.27. This ranking is in accordance to differences in the total discharge, peak discharge, and TSS load of the three events sampled. TSS levels yielded the same ranking; however, there was no significant difference between the events of Oct.16 and Oct.27.

In the reef area, changes in turbidity due to the four events sampled were once again all significantly different. The events of Aug.24 and Oct.27 respectively produced the highest and lowest seawater turbidity values as well as TSS loads in the runoff (Table 3.1, Fig. 3.2). However, the event of Nov.14 had less of an effect on turbidity in the reef area than the event of Oct.16 which yielded a lower discharge, TSS load, and much weaker wind speeds. A possible explanation could be that the strong winds of Nov.14 were directed more westward causing the plume to disperse offshore quickly enough to avoid the nearby reef to the north (Table 3.1). Seawater TSS levels in the reef area were significantly higher for the two events with the greatest discharges and loads, Aug.24 and Nov.14. The event with the lowest discharge and load, Oct.27, created greater changes in the reef's seawater TSS levels than that of the Oct.16 event. Again, this could be explained by wind direction, as the winds on Oct.27 were much stronger and more northward than those of Oct.16 (Table 3.1).

3.4.4 Sedimentation

Time-averages from the sediment traps are displayed in Figure 3.7, though on occasion some traps were not set or found knocked over, resulting in missing data. Sedimentation rates were above MPCA guidelines (25 mg/cm^2*d) for the last 35 days of sampling on both lobes of the reef (Fig. 3.7a). On North Bellairs, traps T1 and T2, sedimentation rates were above or near the guidelines for the first 52 days of sampling. However, it is most likely that the average rate of the first sampling set was elevated by the first flow event (Aug.24) occurring at the end of the sampling period, and that the period during which rates were near MCPA guidelines was approximately 26 days.

Figure 3.7: Time-averaged sedimentation rates (mg/cm^2*d) in a) the reef area and b) the outlet area, and flow event total discharge volumes (10^6 L). Vertical error bars show standard deviations. Guidelines from the Barbados Marine Pollution Control Act (25 mg/cm^2*d) are indicated on the left vertical axes with an arrow.



In the outlet area, temporal variation of sedimentation rates appears to be regulated by inputs of terrigenous sediment. For example, rates increased following the event of Aug.24 and then gradually decreased until the next event (Fig. 3.7b). Sedimentation rates at trap T6, directly in front of the outlet, are extremely high following the event of Oct.16. While this event was not the largest in magnitude, its resulting plume did not disperse widely due to the low wind speeds, as seen in the TSS values (Fig. 3.2f), which may have resulted in the considerably large mass of accumulated sediment at T6. Spatial variation was similar to that of the surface water with the trap to the north of the outlet, trap T5, collecting larger quantities than the trap to the south, trap T7.

In the reef area, it appears that temporal variation was also regulated by the input of terrigenous sediment. However, in this case the input is not only dependent on the occurrence of flow events but on the presence of substantial wind speeds capable of transporting plumes to the reef; wind speeds were weak during the event of Oct.16 resulting in a lack of input to the reef area, as was the result for surface water TSS. Wave heights gradually increased during the season but the sedimentation rates gradually decreased for the first 3 months of sampling, thus weakening hypotheses of temporal variation depending on wave heights. Spatial variation of sedimentation may depend on differential levels of sediment resuspension. Wave action, for example, can control resuspension of sediments and thus recorded sedimentation rates (Bothner et al. 2006). Though wave data were not recorded over the spatial scale of the sediment traps, observations of sea conditions were made daily. During times of low wave action, significant resuspension may still occur in the spur and groove zone of North Bellairs due to its close proximity to the coastline. This coastline is bordered by a seawall (Fig. 3.1) against which waves are regularly crashing. This may be the reason sedimentation rates were higher on the reef's northern lobe, traps T1 and T2, for the first 3 months of sampling. At the end of the season, wave heights increased and substantially greater surf took place upon South Bellairs, traps T3 and T4. This likely caused increases in resuspension and sedimentation rates on South Bellairs to be higher than on North Bellairs. Taking averages over the entire sampling season, overall sedimentation rates on the two lobes of the reef were equal.

3.5 Discussion

3.5.1 Nutrient Loading

Estimates of nutrient loads can be compared to other primary nutrient inputs to the nearshore area of Holetown such as the water of the Holetown Lagoon and groundwater seeping through the beach. Sampling the Holetown lagoon over space and time, Braithwaite (2004) reported nutrient concentrations averaging 0.7+/-0.3 mg/l NO_3-N (converted from original) and 24.0+/-13.9 mg/l PO_4-P. A hotel acts as a point-source input to this water body discharging its laundry effluent directly (Braithwaite 2004) and treated wastewater (secondary treatment) (Stanley International Group Inc. 1998). The reported nitrogen concentrations in the lagoon are similar to that of wastewater which typically has nutrient concentrations of about 0.7 mg/l NO_3-N and 5.0 mg/l PO_4-P (Stanley International Group Inc. 1998). The higher concentrations of phosphorus in the lagoon indicate another source which could likely be the laundry effluent as detergents are typically rich in phosphates. Another plausible source of phosphorus could be sediment from previous runoff events settled in the lagoon slowly releasing dissolved phosphorus by the process of desorption (Froelich 1988). With an approximate volume of $3x10^6$ L, lagoon water represents estimated nutrient loads of 2.1+/-1.3 kg-NO_3-N and 72+/-54 kg-PO_4-P. While this nitrate load is less than even the smallest estimate of that for runoff (Oct.27 = 17.6+/-13.7 kg-NO_x-N), the load of reactive phosphorus in the lagoon is more than twice the estimate of that due to runoff during the year's largest flow event (Nov.14 = 32.4+/-10.4 kg-SRP).

This combined load of dissolved phosphorus is of great importance as phosphorus may be the nutrient limiting algal growth in the nearshore area. The molar ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus has been reported as 28.1:1 (Sander and Moore 1979) greater than the average cellular ratio of 16:1 (Hecky and Kilham 1988). Current research shows that estimates of this ratio are more accurately described by total nutrient levels (Downing 1997). Wellington (1999) measured total nutrients in the coastal waters of Holetown in both the wet and dry season, and reported values yielding N:P molar ratios of no less than 69:1. However, others have reported a much lower average TN:TP molar ratio of 14:1 (Bellairs Research Institute 1997), and so further research is needed.

Based on groundwater and offshore sources, Wellington (1999) estimated nutrient loading rates of approximately 1 kg NO_3-N/day and 0.009 kg PO_4-P/day entering a 1200 m^2 area along 100 m of Holetown's coast. Such quantifications are subject to large error, especially since the estimated groundwater contribution is based on nearshore tap-water quality and seepage rates from a single location, and thus may not have yielded a realistic representation of the groundwater's contribution to coastal nutrient loading. However, the magnitudes of these estimates suggest that runoff makes substantial dissolved nutrient contributions to the coastal system, especially with respect to phosphorus. Extending Wellington's estimates over the entire 2 km coastline of Holetown (i.e. multiplying by 20), dissolved nitrogen loading due to runoff is apparently comparable to that which naturally enters the coastal water daily. However, the combined dissolved phosphorus load of runoff and the lagoon is still 2 orders of magnitude greater than natural daily loading. Under these assumptions, a single runoff event contributes a dissolved phosphorus load equal to the annual load estimated by Wellington (1999). Of course, the total nutrient loads due to runoff compared here are only minimum estimates, as only reactive nutrients were measured.

3.5.2 Northward Trend

A trend of northward flow from the outlet for turbidity was confirmed by stations to the north yielding significantly higher values than those to the south at 50 m and 200 m offshore. The fact that this trend was not observed at 100 m offshore may be explained by the irregular bathymetry of the northern transect. The three stations O1, O2, and O3 located 50 m, 100 m, and 200 m along this transect have depths of 4.4, 6.1, and 4.2 m, respectively. According to Fick's Law, the concentration at any location will be inversely proportional to the location's depth during dispersion of a given flux. Thus, the greater depth of station O2 could explain its turbidity levels being lower than that of the further station, O3.

3.5.3 Implications for Coral Health

The lack of spatial effects in the distribution of plume waters over the reef indicated that if an event's plume reaches the reef, it will affect the entire reef similarly. While this suggests that different zones of the reef will be affected equally by poor surface water quality, the implications may be greater for the reef crest. This zone takes the brunt of the wave action and has far poorer coral species diversity than that of the spur and groove zone (Lewis and Oxenford 1996). Wave action may be considered a chronic stress upon coastal ecosystems (Grigg 1998; Tewfik et al. 2007). Perhaps the added stresses of eutrophication and sedimentation restricting coral growth in the crest zone are thus inhibiting the coral's resistance to the zone's naturally turbulent environment.

In addition to the potential effects caused by the estimated nutrient loads, event-water plumes with detrimental levels of turbidity and TSS could be termed a chronic stress to the Bellairs Reef as flow events occur every year and all of the events sampled produced detrimental water quality levels above the reef making this a predictable seasonal disturbance. Of the 3 events for which second sets of seawater samples were taken, the two largest events both caused initially high TSS levels that did not recede within 67 hours from the onset of flow. It thus appears that large events can cause poor water quality to linger above the reef but further sampling is needed to confirm this and establish the full duration of influence. Few flow events occurred this year until late November when more frequent flows from the outlet restricted reformation of the beach separating the lagoon from the sea. Residents of Holetown state that this flow regime usually dominates much more of the rainy season, and rainfall in the adjacent watershed was below average for the year (unpublished data, Caribbean Institute for Meteorology and Hydrology), suggesting that more than the observed 9 flow events would normally occur. In fact, adjacent watersheds to the north and south atypically did not generate runoff at all in 2006, minimizing stress incurred by the Bellairs Reef due to additional sources of runoff. During the final stages of the study period, when the lagoon flowed continuously and wave heights were highest, sedimentation rates on the reef were far above the recommended guidelines. Such heavy surf continues for months into the dry season potentially sustaining high sediment resuspension rates. While the complexities of coastal sediment transport exceed the scope of this study, the documented terrestrial sediment loads represent a significant contribution to the nearshore zone and thus the excessive levels of sedimentation observed on the reef.

Excessive sedimentation commonly decreases coral diversity as few species are resilient to such conditions (Cortes and Risk 1985). Large branching corals can typically survive the stress of sedimentation as their morphology limits the accumulation of sediment on their surfaces (Rogers 1990). However, the proliferation of such corals may impede the resilience of a reef's coral community as their tolerance to sedimentation is counterbalanced by their susceptibility to large waves (Blanchon and Jones 1997). For example, the southern part of South Bellairs was once densely covered by the branching coral *Porites porites* (James et al. 1977) until the passing of Hurricane Allen in 1981 destroyed 96% of this species (Mah and Stearn 1986).

3.6 Conclusions

Runoff into the nearshore zone of Holetown causes plumes in excess of the MPCA guidelines for turbidity (1.5 NTU) and TSS (5 mg/l), and delivers large loads of sediments and nutrients contributing to the chronic effects of eutrophication and sedimentation. Plumes around the outlet revealed a trend of northward flow towards the Bellairs Reef. This study's data show that the magnitude of post-discharge changes in the seawater depends on a flow event's TSS load and total discharge, which were proportional for the 3 events monitored in the outlet area. In the reef area, factors controlling seawater quality changes included TSS load and total discharge, as well as the strength and direction of prevailing winds. Turbidity levels were above the MPCA guidelines for less than 2-3 days following events but TSS levels showed the potential to remain high for at least 3 days following the sampled events. Sedimentation represents a definite chronic disturbance as accumulation rates on the reef were far above the recommended guidelines for 35 of the 118 days monitored, and were near the threshold on North Bellairs for an added 26 days.

Runoff quickly delivers large loads of dissolved nutrients along with that of the lagoon through which it flushes, though it appears that water from the lagoon itself presents a greater dissolved phosphorus load than that delivered by runoff. This lagoon has a volume equal to 10% of an average flow event's total discharge, meaning that regardless of all the upstream nutrient sources, the most efficient means for reducing phosphorus loading would be to control this lagoon's point-sources. These sources are known to have been discharging large quantities of phosphorus for a long time (Brewster 1990; Braithwaite 2004). As phosphorus may be the nutrient limiting algal growth in the coastal area, these land-based sources are doubtlessly making a substantial contribution to coastal eutrophication.

The fringing reefs of Barbados are still recovering from the acute disturbances which occurred over 20 years ago as their recovery is impeded by the chronic disturbances of eutrophication and sedimentation resulting from land-based sources (Bell and Tomascik 1993). Remediation of the degrading seawater is critical to the health of the reefs (Bellairs Research Institute 1997). If measures are taken to improve water quality, there is potential for the reef's subsequent improvement. A recent study on the island's south coast documenting local improvements in seawater quality due to enhanced flushing rates in a coastal lagoon, revealed ecosystem recovery with increased abundances of coral, fish, and *Diadema antillarum* as well as an increase in number of coral species, coral diversity, and percent coral cover (Risk et al. 2007).

CONNECTING TEXT

In the previous chapter it was concluded that runoff is contributing to the deterioration of coastal zone water quality. These contributions came in the form of sediment and nutrient loads, creating plumes of sustained poor water quality, and causing chronic levels of sedimentation and presumably eutrophication. While it appears that coastal point-sources may be discharging the largest loads of dissolved phosphorus, and thus a clear priority for management control measures, the sediment loads can be almost entirely attributed to runoff. Therefore, upstream sources should be investigated to develop further remediation strategies.

The watershed draining to Holetown has already been studied by various researchers. Soils (Vernon and Carroll 1965), hydrogeology (Jones and Banner 2003), and landuses are well-known (Leitch and Harbor 1999), though the latter have shown a tendency for change. Few studies of hydrology and water quality using empirical data have been done (Hunte 1989; Brewster 1990; Delcan Consulting 1994a). The following study presents hydrological and water quality data unique to Barbados. Firstly, an accumulation of data from high-intensity rain gauges resulted in a data set with the highest spatio-temporal sampling density recorded on the island, to the best of the author's knowledge. Collected by Baird & Associates Ltd., the Barbados Coastal Zone Management Unit, the Barbados Drainage Unit, and Sandy Lane Golf Course, these data are crucial to making accurate measurements of rainfall distribution patterns which can be highly localized. Secondly, intensive event-sampling of runoff allowed for a characterization of temporal patterns in water quality. Water quality can change rapidly during the early phases of flow and thus high-frequency sampling during the onset of an event is necessary to accurately assess concentrations and loads. These and other data are used to perform a watershed diagnostic in an attempt to characterize the watershed's processes of runoff and water quality, which are inevitably linked. An understanding of water quality and landuse distribution can then be incorporated towards identifying sources contributing to water quality degradation.

IV. CHARACTERISTICS OF WATER QUANTITY AND QUALITY IN A TROPICAL KARST WATERSHED

4.1 Abstract

A watershed diagnostic was performed on the 9.9 km^2 area draining to Holetown on the west coast of Barbados. The following parameters were monitored during the rainy season of 2006: rainfall, discharge, total suspended solids (TSS), turbidity, soluble reactive phosphorus (SRP), and nitrate-nitrite-nitrogen (NO_x-N). Observed hydrological characteristics included spatially heterogeneous rainfall, flash floods, internal drainage of runoff into the karstic aquifer, and a correlation between event total runoff volumes and event runoff coefficients ($r = 0.89$). Intensive water quality sampling during the early stages of flow revealed a first flush phenomenon for TSS. High mean nutrient concentrations (0.34 mg SRP/l, 0.7 mg NO_x-N/l) despite the watershed's high proportion of natural land (69%) imply overfertilization of agricultural lands and enrichment from urban sources. The subbasin with the highest proportions of developed landuse (combined agriculture, urban, and industrial) produced significantly higher levels of TSS, turbidity, and SRP than the other 3 subbasins, and significantly higher levels of turbidity and SRP than the watershed as a whole. Potential solutions to the poor water quality observed are presented and discussed.

4.2 Introduction

4.2.1 Karst Hydrology

A watershed is a unit of land within which all of its inhabitants are interconnected by the passage of water, and is thus a preferential unit of study for water research and ensuing policy (Chesters and Schierow 1985). The boundary of this unit is commonly derived from elevation information defining ridges which partition the pathways of incoming rainwater. However, such delineations may be complicated in a karst aquifer, one containing dissolution-generated conduits (White 2002). Karst features such as sinkholes and conduits present openings in the surface permitting much faster water infiltration rates than that of percolation through a matrix soil system. While surface water naturally drains to a watershed's outlet, runoff through a karstic area may be drained internally should it encounter a sinkhole, a localized land surface depression (Milanovic 2004). Internal drainage of runoff can also occur without the presence of a sinkhole but simply through cracks, or fissures, along a waterway's reach in which water is lost gradually (White 1988). Runoff will pass through such a reach only if it exceeds the carrying capacity for the area's conduit drainage system (White 2002). These forms of rapid infiltration create a close relationship between the surface water and groundwater systems connected by unpredictable flow paths. Subterranean transport follows through conduits representing paths of least resistance, or maximum erodibility, which may not correspond with surface gradient topology. Therefore, groundwater resurfacing through springs could potentially have originated from outside the topographically defined watershed. As a result, a groundwater catchment area may not correspond to a surface watershed's boundary (White 2002).

4.2.2 Landuse

As the areas within a watershed are related by the passage of water, so are the various landuses within the watershed due to their inherent effect on water quality. Landuses influence the quality of water which passes through them as runoff is chemically altered by surface materials, as is subsurface drainage water by the composition of soils and substratum. Agricultural land can be uniquely characterized by the addition of commercial fertilizers and manure to the soil, cultivation of the soil, and the presence of animal waste in animal farms or pastures. Without control of land management practices and fertilizer application, runoff has the potential to transport large quantities of sediments and nutrients from these areas (Moody 1990; Brookes et al. 1996). High-density grazing lands can also be a problem, especially if the animals have access to waterways (Brodie and Mitchell 2005). Urban areas make their own contributions to runoff with litter or dirt upon the streets which easily wash away along the many impermeable surfaces (Sansalone and Buchberger 1997). Proper disposal and treatment of wastewater from these areas is pertinent to the management of water quality as they often carry the risks of harmful bacteria and nutrients. Globally, high nitrogen levels in rivers are related to high population densities within the watersheds they drain (Peierls et al. 1991; Howarth et al. 1996). The influence of industries on water quality can be largely dependent on the effluents produced. One of the most common problems to a watershed's water quality is landuse development. In addition to increasing the amount of runoff (Leitch and Harbor 1999), the conversion of land from natural areas uproots vegetation, loosens and exposes soil along with any contained nutrients which are then very susceptible to transport via runoff (Fredriksen 1971). Construction sites, for example, are a common source of sediments and heavy metals to waterways (Kayhanian et al. 2001). Natural areas, on the other hand, don't commonly degrade water quality (Meybeck 1982) but can act as buffers in trapping nutrients and sediments.

4.2.3 The Study

The aim of this study is to assess the hydrological characteristics and water quality of runoff in a karst, tropical watershed in Barbados. From the previous study, it is known that the downstream coral reef ecosystem is occasionally exposed to detrimental levels of TSS, turbidity, and sedimentation following flow events. Surface water from this watershed has also been reported to have high TSS concentrations relative to other parts of the island (Delcan Consulting 1994a). Thus, this watershed diagnostic focuses on the dynamics and sources of turbidity and total suspended solids (TSS). In addition to these parameters, reactive nutrients were monitored for their contributions to eutrophication, a process known to affect the coast's nearshore zone (Tomascik and Sander 1985). Parallels will be made between water quality and upstream landuses in an attempt to identify potential sources.

4.3 Methods

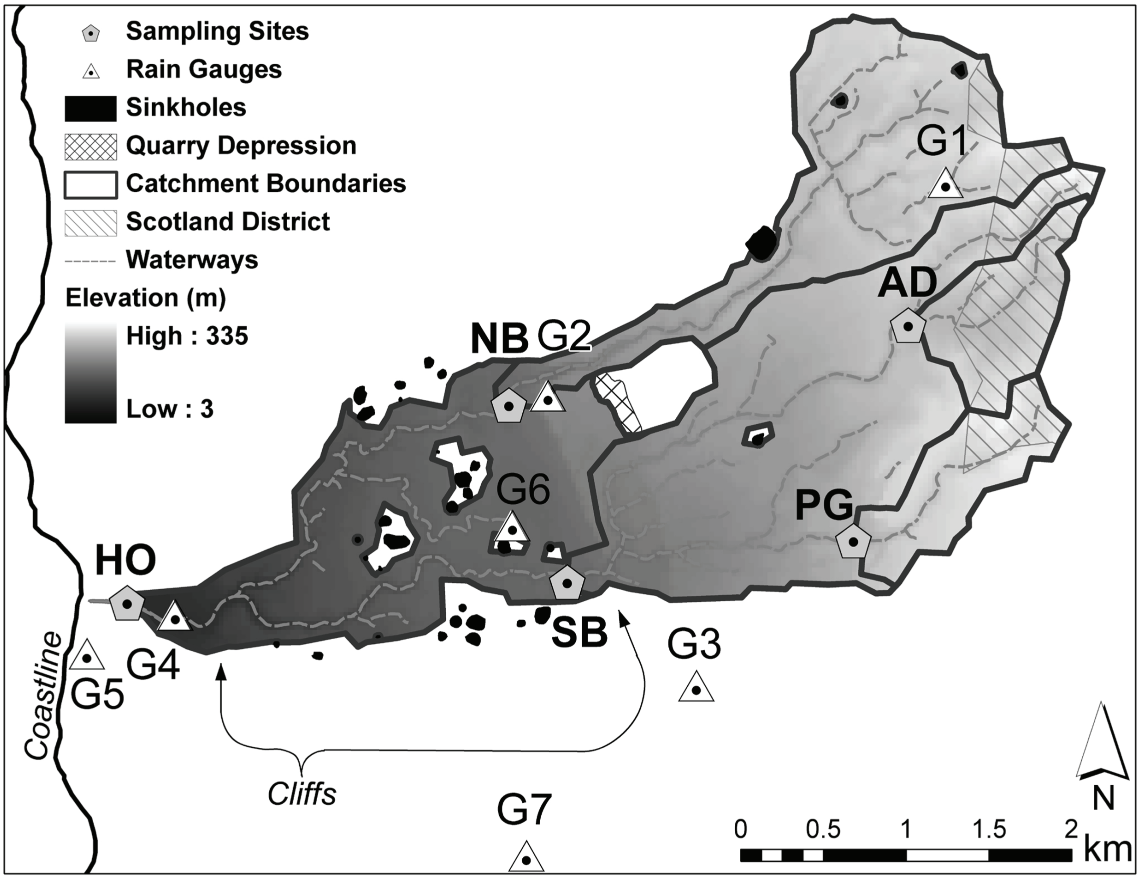
4.3.1 Water Quality Sampling

Weather patterns were tracked and flow events were monitored from May-December 2006. Samples (300 ml) were taken from the runoff's surface water and analyzed for TSS, turbidity, soluble reactive phosphorus (SRP), and nitrate-nitrite-nitrogen (NO_x-N). TSS was analyzed by standard methods (American Public Health Association et al. 2005) and turbidity was measured using a Scientific Inc, Micro 100 Turbidimeter. Nutrients were analyzed with a DR/2000 Hach Spectrophotometer by the Ascorbic Acid Method (range: 0-0.82 mg/l) for SRP and the Cadmium Reduction Method (range: 0-30.0 mg/l) for NO_x-N.

At the coastal outlet of the Holetown watershed, HO, (Fig. 4.1) single samples were taken every 5 minutes for at least the first 3 hours of each of 4 flow events (Oct.16, Oct.27, Nov.14, Nov.24). A high intensity of sampling is important due to rapid changes in concentrations during events (Brodie and Mitchell 2005). Triplicate samples were taken every 30 minutes to verify the precision of measurement. In addition, a set of 7 grab samples were taken at HO 2 hours after the initial flow of an event on Aug.24. These 5 flow events comprise the first 5 of the year. TSS and turbidity were analyzed for all events, SRP was analyzed for the events of Oct.16, Oct.27, Nov.14, Nov.24, and NO_x-N was analyzed for the events of Nov.14 and Nov.24.

Upstream sites for water quality sampling and gauging of peak discharges were selected based on accessibility (Fig. 4.1). For two events (Nov.14, Nov.24), triplicate sets of grab samples were taken from upstream sites in the following order: SB, NB, AD, and PG. Upstream sampling on Nov.14 and Nov.24 began 50 and 40 minutes after the initial flow at HO, respectively, and was complete within 55 and 45 minutes, respectively. The catchments draining to these sampling sites (Fig. 4.1) will hereafter be referred to by the names of their outlets. Statistical comparisons of water quality parameters at these sites were done using classical unmodified ANOVA models.

Figure 4.1: Watershed sampling scheme and physical characteristics. Labels identify sampling sites (HO, SB, NB, AD, PG) and rain gauges (G1-G7). Sampling site abbreviations: HO – Holetown Outlet; SB – South Branch; NB – North Branch; AD – Ape's Hill Dam; PG – Porey Spring Gully.



4.3.2 Hydrological Data

Rain data recorded by 7 gauges, G1-G7 (Fig.1), were contributed by various sources (Table 4.1). Additional historical data were also provided by the Caribbean Institute for Meteorology and Hydrology. Theissen polygons were computed from available rain gauges for each event and used to calculate average and total rainfall depths within the watershed. A pressure transducer in the channel operated by Baird & Associates Ltd. for the Barbados Coastal Zone Management Unit (CZMU) recorded continuous measurements of stage which were later converted to discharge using a rating curve.

Table 4.1: Sources of rain data. See reference list for detailed citations. Gauge locations are shown in Fig. 4.1.

Gauge ID	Recording Interval	Operated by
G1-G4	1mm	Baird & Associates Ltd.
G5	1h	Coastal Zone Management Unit, Barbados
G6	0.2mm	Drainage Unit, Barbados
G7	1h	Sandy Lane Golf Course

A rating curve was established at site HO (Fig. 4.1) in the rectangular concrete channel (2.5 m width, 0.6 m depth) 25 m upstream of the Holetown lagoon. Velocity was measured at 6 tenths of the total depth below the surface at five points equally spaced across the channel's width using a model 1210 Price Type AA Current Meter (Herschy 1995). Stage and velocity were recorded simultaneously during 4 flow events producing a data set with a range of stages from 9.1 – 56.4 cm. Discharge values were calculated and a 4th order polynomial curve was fit to the stage-discharge relationship ($R^2 = 0.9885$). For above bank conditions, the channel's cross-section was partitioned into channel and flood-plain subsections and Manning's equation was used to calculate flow with a roughness coefficient weighted by each subsection's area (Arcement and Schneider 1989). A Manning's n value was calibrated for the channel subsection using the rating curve while another n value was selected for the floodplain subsection.

At sites NB, SB, PG, and AD, peak discharges of 3-5 flow events occurring between Nov.25 – Dec.19 were calculated using the slope-area method and Manning's equation (Herschy 1995). At each outlet, reaches were characterized according to bed materials, factors affecting flow uniformity, and slopes. Selection of Manning's roughness coefficients was done according to the methods of Acrement and Schneider (1989). Due to the broad range of values given for each class of channel, this method yields a potential error of about 30%. The cross-sectional area of peak flow was measured according to the peak stage.

The highest water level due to an event was measured with Maximum Stage Recorders set in the waterway of each outlet. Each recorder consisted of a wooden dowel (122 cm length, 1.57 cm diameter) placed within perforated PVC tubing (122 cm length, 5.08 cm inner diameter) with caps at both ends and ground cork board placed within the tubing. As rising water levels infiltrate the gauge, the cork board floats to the highest water level and adheres to the wooden dowel before the flow recedes, thus marking the peak stage during a flow event.

4.3.3 GIS Data

Landuse, soil, and waterway information was obtained from McGill University's Geographic Information Center, Montreal, and verified in the field. Waterways required minor updates though landuse had largely changed requiring the digitization of a new layer. Sinkholes, landuses, and waterways were mapped using a Thales ProMark 3 GPS unit. GPS data were post-processed with data from the Continuously Operated Reference Station at the Barbados CZMU. A DEM was interpolated using ArcGIS 9.1 from 3.05 m contours digitized by Baird & Associates Ltd. ArcHydro was used to delineate the watershed with the utilization of stream-burning (Maidment 2002). Sinkholes, as well as a large quarry, represent areas of internal drainage which do not contribute to runoff at the watershed's outlet and so their catchment areas were delineated and removed to define an effective contributing area (Fig. 4.1) (Wallace Evans and Partners 1973; Leitch and Harbor 1999).

4.4 Watershed Characteristics

4.4.1 Physical Characteristics

This study's site is a tropical karst watershed draining an area of 9.9 km^2 to Holetown on the west coast of Barbados (13°11' N, 59°38' W). However, following the removal of areas draining to sinkholes and the quarry the watershed's effective contributing area is 9.2 km^2. Elevations range from 3-335 m with an overall slope of 4.0% over a longest flow length of 8314 m (Fig. 4.1). Surface water flows ephemerally through a system of gullies, sometimes called dry valleys (Fermor 1972). Gully beds are extremely eroded, can be up to 50 m deep, and are bordered by steep banks covered in dense forest (Stantec Consulting 2003). The watershed's time of concentration, the time needed for water to travel from the watershed's furthest point to the outlet, has been estimated at 145.8 minutes (Cumming Cockburn Ltd. 1996). At the watershed's outlet, HO (Fig. 4.1), a channel links the gully to the Holetown lagoon (approx.capacity = 3x10^6 L). This lagoon is separated from the sea by 9 m of beach which is occasionally breached by large inputs of water.

The watershed's aquifer is mostly composed of coral limestone (89%). Up to 100 m thick, the limestone has an average porosity of 45%, ranging between 20-60% (Jones and Banner 2003). A set of cliffs near coast has an approximate height and slope of 18 m and 33%, respectively, while a second set further inland has an approximate height and slope of 24 m and 51%, respectively (Fig. 4.1). These cliffs run parallel to the coastline and separate the watershed into three distinct terraces, the middle of which is highly karstified (Huang 2006). Many karstic features can be found in this area such as sinkholes in the interfluvial zone as well as caves and fissures in the gullies (Day 1983). Above the first terrace the water table is generally 30 m below the beds of the gullies but in some areas, gully beds approach the water table and intermittent springs may be found to flow for short distances (Fermor 1972). For example, a spring is located near site PG (Fig. 4.1) and there are probably others near the bases of the rugged and heavily vegetated cliffs.

Approximately 1 km^2 (11%) of the watershed lies within the Scotland District of Barbados (Fig. 4.1). In this area, the limestone has been breached exposing the underlying Tertiary oceanics (Fermor 1972). Soils in this region are composed of densely packed sand and clay. They are both impermeable and impervious resulting in a high proportion of rainfall lost to runoff. Soils in the limestone part of the watershed are fairly well drained and moderately permeable (Vernon and Carroll 1965). Typically 1 m thick, they are made up of carbonate and silicate minerals, quartz, oxides, organic matter, seaspray salts, and fertilizer (Banner et al. 1996).

4.4.2 Rainfall

Barbados has a sub-humid to humid maritime, tropical climate with monthly temperatures ranging between 28-31°C. The rainy season lasts from June-December, peaks during the months of August-October, and accounts for 60% of the total annual rainfall (Jones and Banner 2003). Average annual precipitations spatially vary from 1300-2000 mm with values increasing towards higher elevations (Fig. 4.1). However, spatial precipitation patterns vary seasonally as well with totals increasing towards the western leeward side of the island during the rainy season (Jones and Banner 2003). Large rainfall events are typically modulated by the passing of tropical waves (Riehl 1954). Moving westward across the Atlantic, these waves cause heavy localized storms and act as precursors to tropical cyclone development (Avila et al. 2000).

4.4.3 Landuse

Landuse around the watershed has changed a great deal over the past 40 years. From 1964 to 1996, there has been extensive development in the area due to the economy's growth and shift towards tourism (Leitch and Harbor 1999). Urban areas doubled during this period resulting in a predicted 5.5% increase in runoff depth. The effects of developing urban areas on hydrological response were somewhat counterbalanced by the demise of the sugar cane industry. Sugar cane plantations covered 50% of the area in 1964, a proportion that was halved by 1996 as many plantations were converted to pastures.

Currently, less than 1% of the watershed is still used for sugar cane, with all agricultural areas combining for only 6% (HO, Fig. 4.2). Some of the plantations have been converted into pasture while others have been left idle and overgrown with brush. Landuse is now dominated by natural lands (69%) including the forested gullies, grasslands, and brush. Animal husbandry accounts for 12% of the land, nearly all of which is in pasture except for one small (0.6 ha) animal farm. Urban areas and industries are utilizing 10% and 3% of the land, respectively. The watershed's industries include a sugar factory, a cement factory, a small catering service, construction of a golf course and a reservoir, and a quarry though half of it is excluded from the watershed's effective drainage area as it acts as a sink.

Figures 4.2 and 4.3 show the proportions and spatial distributions, respectively, of each of the major landuse categories found in the watershed and its upstream subbasins. NB has the highest percentages of urban (16%) and industrial (6%) land, as well as the second highest percentage of agricultural (11%). Mostly draining the village of Hillaby, the subbasin is also experiencing a small part of a large-scale golf course development. During the period of study, the construction site's land within the watershed (11.5 ha) was left as exposed earth. Just upstream of site NB is a small catering service though its methods of waste disposal are unknown. Industrial activity draining to SB consists of a small cement factory in the village of Rock Hall, through which a small tributary flows, construction on the highway above the sampled waterway, and a source from site AD. Directly upstream of site AD there is another large-scale development, the construction of a reservoir. During this study, construction was still in progress and the dam was continually open. The subbasin drained by AD is unique in that most of its area is devoted to a pasture. The watershed's pastures were observed to have moderate densities of horses or tethered cattle (about 25/km^2). The area upstream of PG has a relatively high proportion of agricultural land, little urban landuse, and no industries. Downstream of sites NB and SB lies the porous middle terrace, a small area of agriculture, and a large sugar factory. By-products of this factory are composed of fly ash, bagasse, and filter press mud (Dunfield 1991) and were observed to be left as big, loose, exposed piles in large plots on the property. Also draining through this area is the large quarry, half of which drains to the gully system.

Figure 4.2: Proportions of landuse in the watershed (HO) and in upstream subbasins (SB, NB, AD, PG). Distribution of landuses and locations of subbasins can be seen in Fig. 4.3

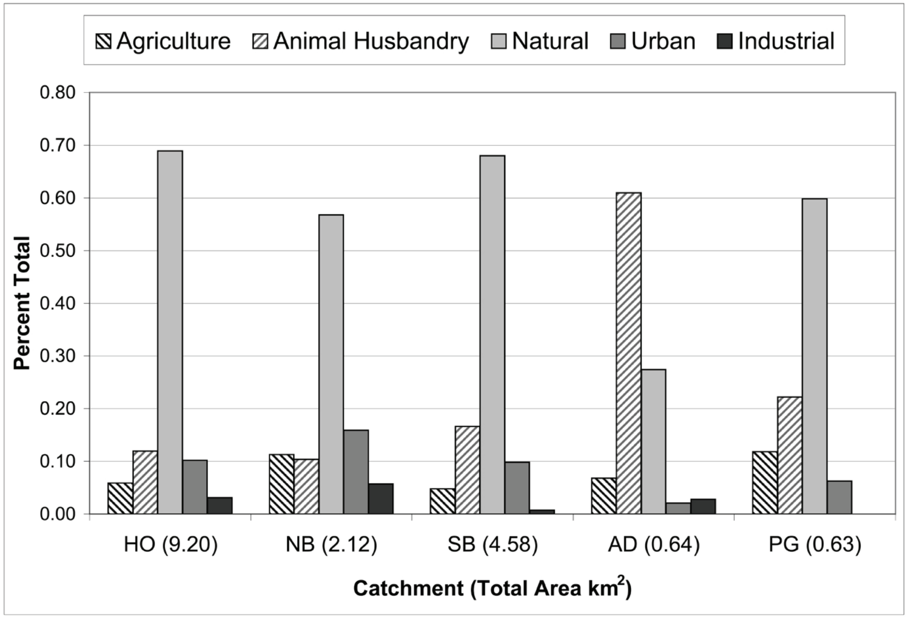
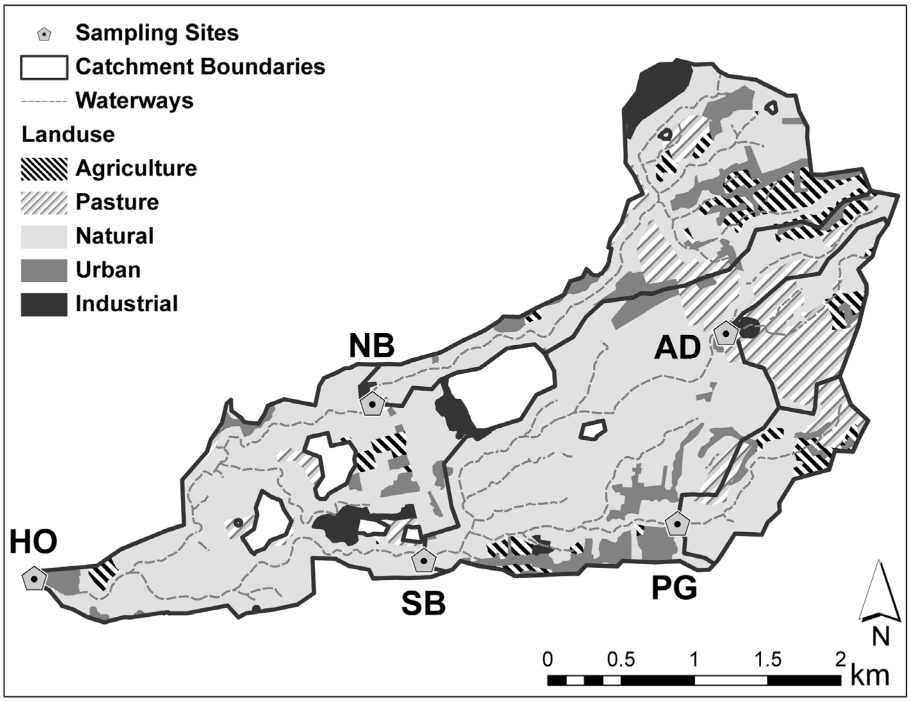


Figure 4.3: Landuse distribution in the watershed. Labels identify sampling sites and the catchments draining to them.



Urban areas in Barbados are distinctive in their wastewater disposal methods and their widespread utilization of garden plots. The west coast of Barbados is not yet serviced by a sewerage system. Most houses are equipped with suckwells, or soakaways, for sewage disposal (73%). This consists of a 1.2-1.8 m^2 hole in the ground, usually to the depth of the limestone, to which a house's water closet is connected. While one would not expect wastewater to be of great concern to surface water quality as it is disposed of into the ground, there is always the possibility of groundwater resurfacing through springs or in the nearby gullies, and 11.2% of surveyed residences reported system malfunctions such as overflows (Stanley International Group Inc. 1998). Therefore, during flooding events, there is a higher potential risk of residential areas contributing to nutrients in the runoff.

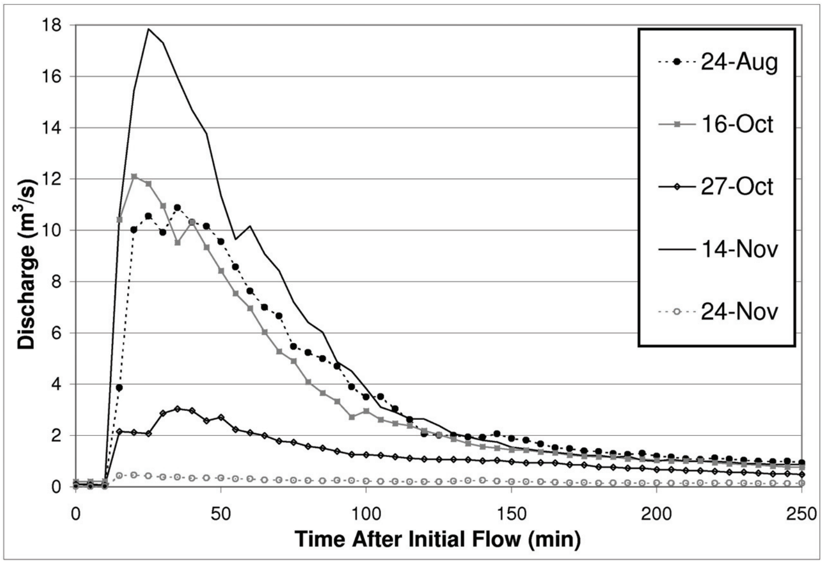
Garden plots of food crops or fruit trees are quite common to residential areas in Barbados. While these small plots should truly be categorized as agricultural, they were not distinguished in the field. Thus, the effects of agriculture on surface water quality may also be expected from residential areas to some extent. Lastly, much of the island lacks a proper waste collection system which has resulted in some of the gullies near urban areas being used as clandestine dumpsites (Stantec Consulting 2003). Observed materials in the gullies include clothing, food waste, garden debris, automotive parts, electronics, mattresses, domestic appliances as well as a kitchen sink.

4.5 Results and Discussion

4.5.1 Water Quantity

The flow regime of the watershed's gully system is dominated by the characteristics of flash floods (Gaume et al. 2004). Discharges at the watershed's outlet, site HO, rise from zero to peak flow within the first 15 minutes of flow and then gradually decrease (Fig. 4.4). A second peak discharge was visible for 5 of the events 10-20 minutes after the first peak, indicating the arrival of another tributary's runoff. Most flow events resulted from rainfall intensities between 30-45 mm/h, though values of 94 and 78 mm/h were recorded on Oct.16 and Nov.28, respectively, at the gauge furthest upstream, G1. The period of time between peak rainfall at G1 and peak discharge at HO varied between 1-1.5 hours for high-flow events and 2.5-3 hours for low-flow events. During the study period 9 flow events occurred at HO, all of which breached the beach and flowed directly to sea.

Figure 4.4: Discharge at the Holetown watershed outlet (HO) for the first 5 of 9 flow events that occurred in 2006.



Total annual rainfall was average in the watershed's upper terrace, G1, and below average near the coast, G4, compared to the past 25 years (unpublished data, Caribbean Institute for Meteorology and Hydrology). During this rainy season's peak, Aug.-Nov., all monthly totals were below average at all stations except G1 where monthly rainfall was below average only in September and above average in November. September was an unusually dry month yielding no flow events and creating public concern over the upcoming year's groundwater reserve (Price 2006).

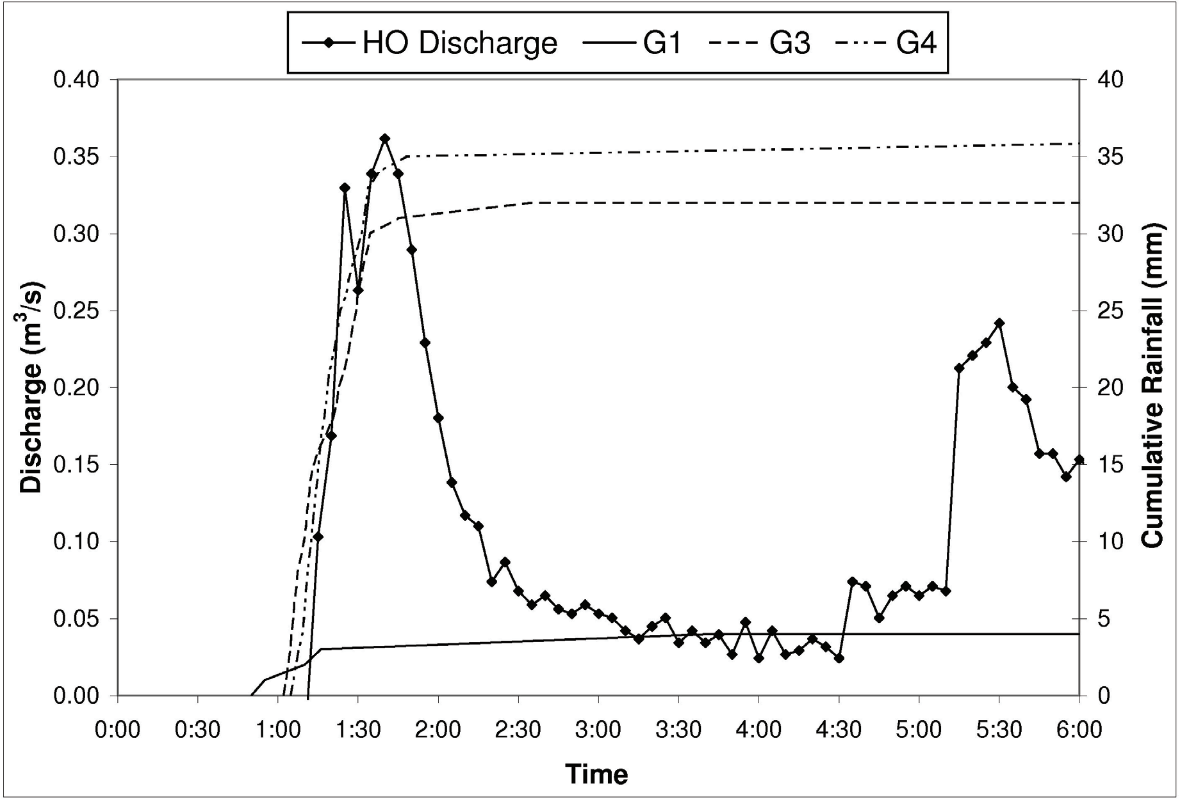
The spatial distribution of rainfall within the watershed showed high heterogeneity (Table 4.2). During some storms, parts of the watershed received almost no rain while the vast majority of rainfall was localized in the upper terrace (e.g. Oct.16). For most flow events rainfall was highest at gauge G1, though later in the season the proportion of event rainfall near the coastal area increased, typical of distribution patterns in the rainy season (Jones and Banner 2003). Rainfall at G5 and its common discrepancy from nearby gauge G4 is a good example of how sharply contrasting these distributions can be. The data show that rainfall from a single station cannot be used as an indicator for runoff, as used in past research (Sander 1981).

Table 4.2: Event rainfall totals (mm) for 2006. Hyphens (-) indicate a lack of data.

ID	Aug.24	Oct.16	Oct.27	Nov.14	Nov.24	Nov.25	Nov.28	Dec.6	Dec.10	Dec.19
G1	97	58	40	54	18	11	37	4	12	12
G2	-	-	-	55	-	0	53	-	-	-
G3	-	3	22	14	3	0	9	32	19	2
G4	-	7	31	32	4	7	11	36	15	1
G5	69.4	1.8	24.6	0	0	0	0.2	33.4	10.6	0.2
G6	55.7	18	16.8	39	3.7	6.3	9.5	-	-	-
G7	46.7	1.8	6.3	25	4.1	6.6	2	25	8.6	-

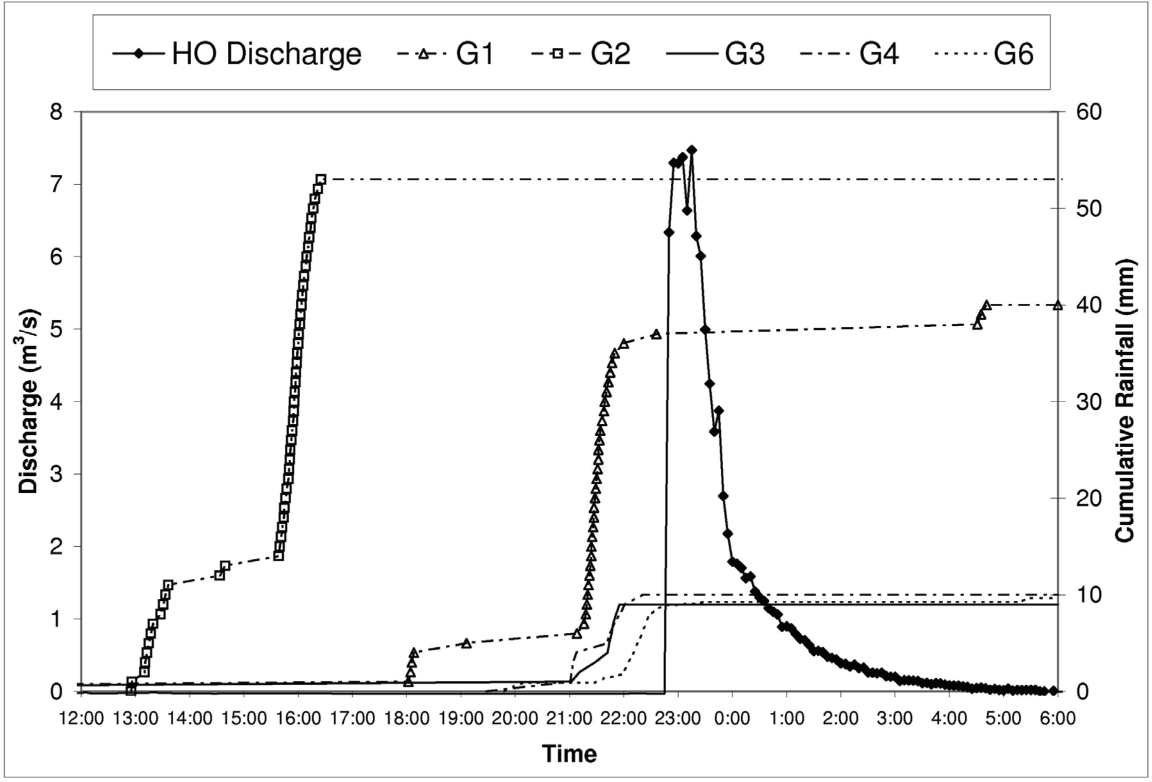
The number of rain gauges used to characterize portions of the watershed for each event varied between 3 and 5, and so the planimetric areas characterized by each gauge varied accordingly. For one event, a rise in discharge 4 hours after the initial flash flow was not accompanied by any rainfall from the 3 monitored gauges within this 4 hour period (Fig. 4.5). As this period exceeds the watershed's time of concentration, there must have been another input of water not recorded, indicating an insufficient sampling density of rain for this event. This illustrates the difficulties involved in measuring spatially heterogeneous tropical rainfall and the necessity for higher sample densities. However, since the event's discharge was very low, this observation may not have any implications for larger events. Another possibility is that the 2nd rise is just the result of a point source discharge from one of the upstream industries.

Figure 4.5: Hydrograph Dec.6, 2006.



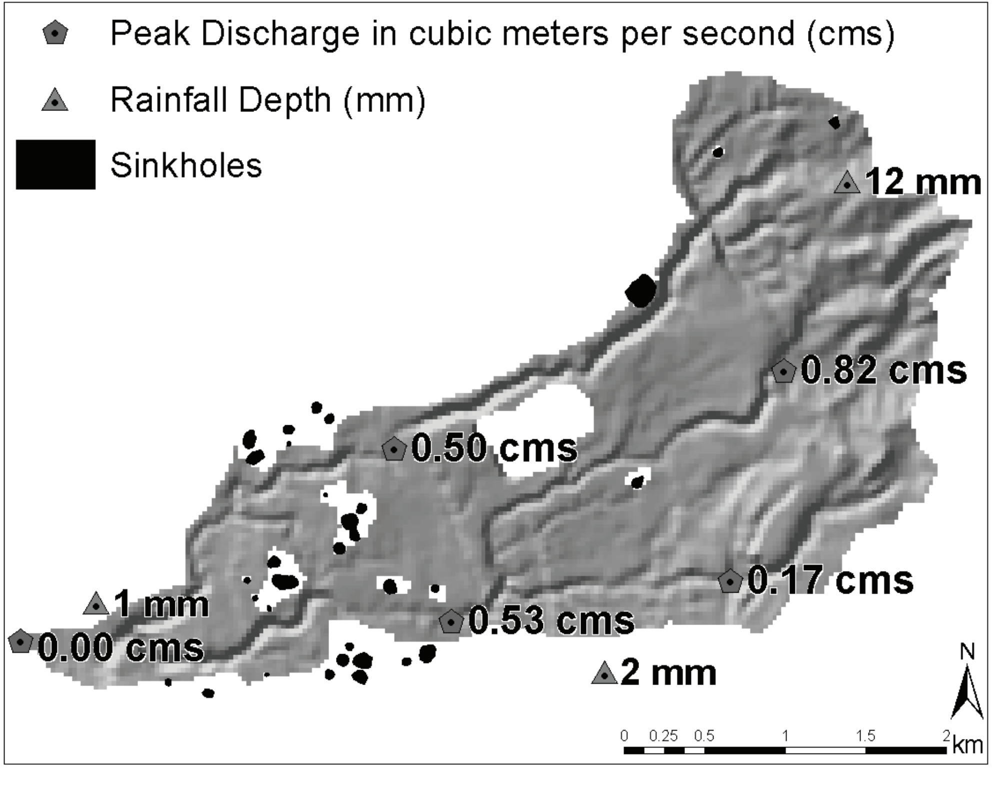
In contrast, high levels of rainfall were occasionally recorded within the watershed without any discharge occurring at the outlet, HO. On Nov.28, 40 mm of rain was recorded within 50 minutes at G2, though no runoff occurred at HO until the onset of another rain event 7 hours later (Fig. 4.6). This period exceeds the watershed's time of concentration and rainfall of this magnitude and intensity was observed to generate runoff during other events. Therefore, this must be evidence of internal drainage. G2 is located in a porous area densely covered with sinkholes. While sinkholes were mapped and their catchment areas removed from the watershed boundary, G2 still accounts for 1.6 km^2 of land theoretically contributing to the watershed's outlet. Therefore, a substantial amount of internal drainage must not only be occurring through sinkholes but also through fissures in the interfluvial zone and within the gullies themselves.

Figure 4.6: Hydrograph Nov.28-29, 2006.



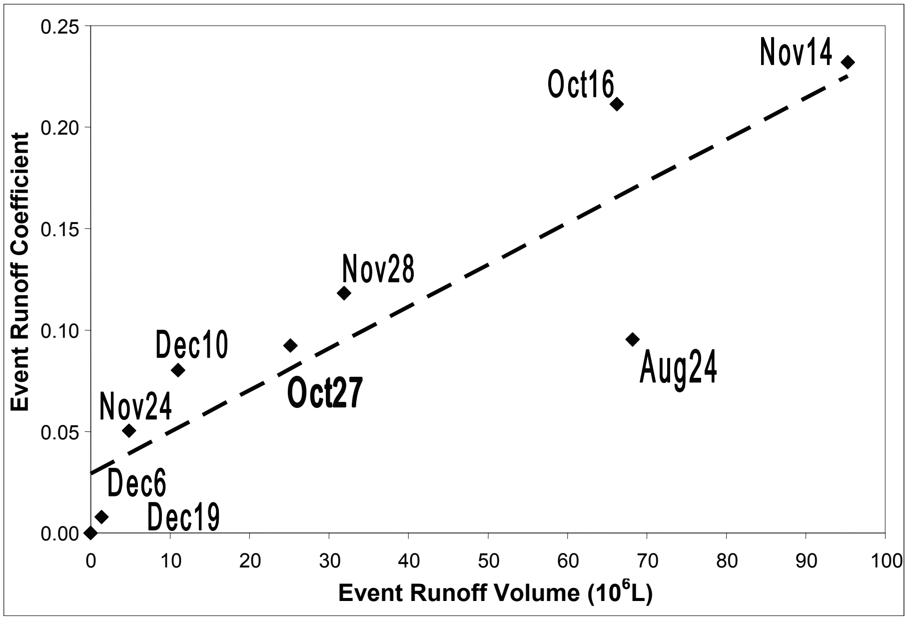
Further evidence of internal drainage was shown by measurements of peak discharge at upstream sampling stations. The event of Dec.19 illustrates the potential for water loss in the gully system (Fig. 4.7). The combination of low flow and isolated rainfall in the upper terrace, G1, made this event unique. The result was measurable water levels at upstream sites with absolutely no runoff arriving downstream of the porous middle terrace to HO. For this event, peak discharges of 0.58 m^3/s and 0.50 m^3/s at SB and NB, respectively, were the lowest measured this season. The total discharges generated by this event at SB and NB represent a minimum estimate of the carrying capacity for the downstream gully drainage system (White 2002). A maximum may be represented by the flows of Nov.24, with a similar rainfall distribution pattern to Dec.19 but a higher total rainfall at G1 (Table 4.2), resulting in the arrival of runoff at HO at a peak rate of 0.45 m^3/s.

Figure 4.7: Peak discharges Dec.19, 2006. Hillshaded watershed.



While internal drainage of storm water diminishes runoff to the coast, this effect was shown to be inversely related to the size of the event. The proportion of storm water arriving at HO as runoff is quantified by an event runoff coefficient, estimated as the ratio of event runoff volume to event rainfall volume (Merz et al. 2006). Though this ratio is sometimes thought to be constant for a watershed, this watershed's event runoff coefficients showed strong variation between events and were positively correlated with event runoff volume ($r = 0.89$, Fig. 4.8). This result may be explained by the internal drainage system having a maximum carrying capacity which, once exceeded, will have less of a diminishing effect in proportion to the total volume of runoff. Previous research has observed smaller event rainfall volumes yielding smaller event runoff coefficients within a given watershed (Merz et al. 2006) but in the present study rainfall volume had less of an effect ($r = 0.48$). Other factors can also cause variability in runoff coefficients such as antecedent moisture conditions and rainfall distribution patterns (Sen and Altunkaynak 2006). For example, the rainfall of Oct.16 was fairly localized in the watershed's upper terrace which is partly composed of the Scotland District's impermeable soils. Compared to the rest of the watershed, the lower infiltration rate of these soils would cause a higher proportion of rainwater to be transported as runoff, augmenting the event runoff coefficient. The monitored events had similar antecedent moisture conditions with little to no precipitation in the days prior. However, there may be seasonal effects on the observed event runoff coefficients as seasonality of rainfall can strongly affect a catchment's moisture conditions (Merz et al. 2006). The flow event on Aug.24 was the first in nearly 8 months, and while its runoff volume was one of the year's highest it was a relatively low proportion of the total rainfall compared to the other similarly sized events. Omission of this event from the relationship in Figure 4.8 yields a much stronger correlation between event runoff coefficients and event runoff volumes (r = 0.97) and between event runoff coefficients and event rainfall volumes (r = 0.89). Confirmation of this last result would require further research across multiple seasons. Regardless of the quantity and proportion of water lost to internal drainage, runoff from all of the monitored events arriving at the coast was enough to breach the beach, impacting receiving environments by the materials transported.

Figure 4.8: Runoff coefficients for the flow events of 2006.



4.5.2 Water Quality

Concentration curves for TSS and turbidity during the events monitored at HO are displayed in Figures 4.9 and 4.10, respectively. The temporal variation of TSS during the high-flow events (Oct.16, Oct.27, Nov.14) exhibits the characteristics of the first flush phenomenon: a disproportionately high delivery of a substance's mass during the initial portions of a flow event (Sansalone and Cristina 2004). On Oct.16, Oct.27, and Nov.14, 80% of the total TSS load was delivered within the first 59%, 38%, and 46% of total runoff volume, respectively. This phenomenon has commonly been seen in runoff from urban areas, highways, and construction zones (Sansalone and Buchberger 1997; Deletic 1998; Lee et al. 2002; Kayhanian and Stenstrom 2005) as well as agricultural fields (Klaine et al. 1988). It is likely that these landuses made considerable contributions to the observed first flush of solids, especially the industries observed to leave large quantities of solids exposed to rainfall and susceptible to runoff. TSS concentrations 2 hours into the year's first flow event, Aug.24, were much higher than those 2 hours into any other event (Fig. 4.9), and so it appears that there may also be a seasonal first flush phenomenon (Lee et al. 2004). Correspondingly, TSS in the residual discharge of the year's second event, Oct.16, was higher than that of the events to follow. Such a phenomenon can naturally be expected as a result of sediment accumulation during the year's 8 month dry season proceeded by sediment exhaustion by the season's first flow.

Figure 4.9: TSS concentrations at the Holetown watershed outlet, HO.

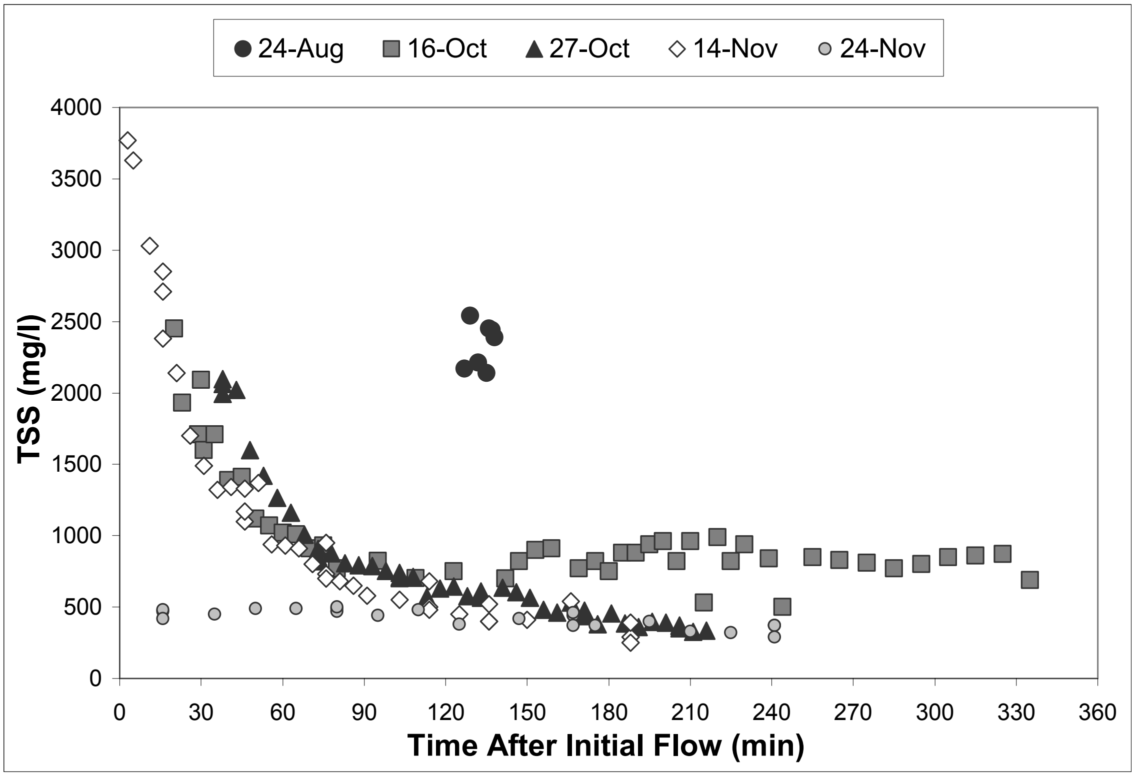
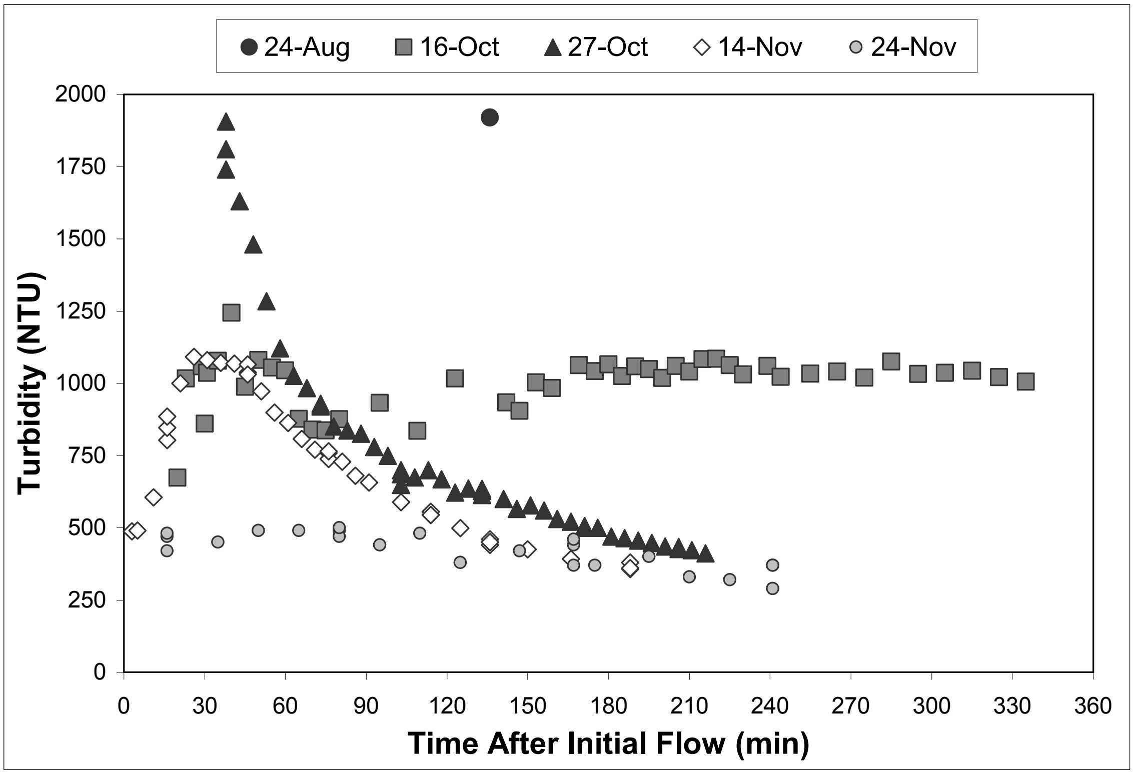


Figure 4.10: Turbidity at the Holetown watershed outlet, HO.



Similarly, turbidity values in the events' residual discharge decreased with each successive event (Fig. 4.10). Temporal variation of turbidity within a given event was different from TSS. The 2 high-flow events during which samples were taken within the first 30 minutes (Oct.16, Nov.14) showed that turbidity gradually increased during the initial period of flow. Turbidity and TSS are sometimes thought to be interchangeable and have been shown to correlate well with one another (Dodds and Whiles 2004; Stubblefield et al. 2007). However, particle size distributions in a sample could skew this relationship. For instance, the turbidity reported by a turbidimeter will result from the water's median clarity and a single disproportionately large particle will not affect the outcome but this same particle would be incorporated into the TSS mass. A conceivable example would be the presence of sizable organic matter adding to TSS mass but not accounted for in the turbidity measurement. It is possible that the observed differences between the two parameters in the first 30 minutes are due to the presence of high amounts of organic matter flushed out of the gullies (where illicit dumping is common). Higher turbidity may be related to discharge with a short lag or, alternatively, originate from a further location.

Nutrient concentrations showed no discernable temporal patterns and so total loads were calculated using event mean concentrations (EMC). EMC of soluble reactive phosphorus were equal to 0.34+/-0.06 mg SRP/l while EMC of nitrate-nitrite-nitrogen were equal to 0.7+/-0.3 mg NO_x-N/l. A previous study sampling just 300 m upstream of HO on multiple occasions during the wet season reported similar nitrogen concentrations (0.610 mg NO_3-N/l) though lower phosphorus concentrations (0.096 mg PO_4-P/l) (data converted from original, Hunte 1989). A reduction in agriculture and expansion of urban areas over the time period between these two studies suggests SRP increases could be the result of greater amounts of urban wastewater, though increased fertilizer availability and use are also possibilities. These concentrations are similar to those in some of the world's large contaminated rivers (Meybeck 1982). Brodie and Mitchell (2005) report dissolved inorganic nitrogen (DIN = NH_4-N + NO_x-N) concentrations of 0.14-1.40 mg/l in northern Australian catchments dominated by agriculture. High nutrient concentrations in agricultural watersheds are expected due to widespread fertilizer use, however, with only 6% of the present watershed's land devoted to agriculture (HO, Fig. 4.2) these values are quite high. Whereas natural areas in this watershed account for 69% of the land, natural catchments around the world typically have nitrate-nitrogen and phosphate-phosphorus concentrations of 0.1 mg/l and 0.01 mg/l, respectively (Meybeck 1982).

One tenth of the watershed is covered by urban areas which have the potential to contribute high nutrient concentrations as well. Wastewater nutrient levels are typically about 0.7 mg/l NO_3-N and 5.0 mg/l PO_4-P (Stanley International Group Inc. 1998), similar to the NO_x-N levels observed in the watershed's runoff but much higher in phosphorus. While wastewater is generally disposed of into the ground there is potential for resurfacing groundwater in a karst aquifer via springs and the potential for suckwells to overflow. For example, a spring located near PG had concentrations of 4.8 mg NO_x-N/l and 0.01 mg SRP/l, though it runs into a pool of surface water and does not feed the nearby tributary. These concentrations are consistent with those seen at many other springs and government monitored wells in Barbados (Klohn-Crippen Consultants Ltd. 1997). While the groundwater nitrogen concentrations are high, the low concentrations of SRP coming from the groundwater indicate that the high SRP concentrations in the surface water come from another source. Therefore, it is quite likely that fertilizer use is making a large contribution to surface SRP levels in addition to urban wastewater that did not infiltrate through the ground.

Means of water quality results from various sites in the watershed during the events of Nov.14 (high-flow) and Nov.24 (low-flow) are displayed in Figures 4.11 and 4.12. Values at HO used for comparison are values obtained 30 minutes after sampling at sites NB and SB, to allow for travel time between the two terraces. Overall, turbidity and TSS were significantly higher among all sites for the high-flow event ($p<0.001$), which is expected as a result of higher water velocities capable of eroding and transporting more sediments. Differences in nutrient concentrations between the events were insignificant, showing the potential for nutrient transport even by low-flow events.

Figure 4.11: Upstream water quality sampling Nov.14, 2006. Values given at each site are event means.

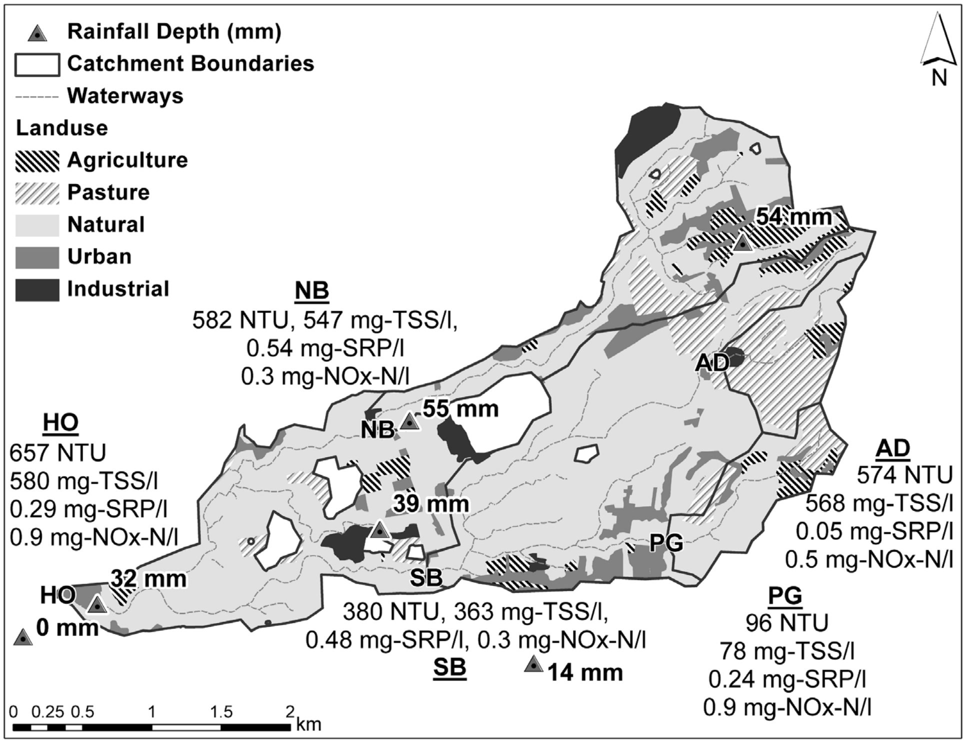
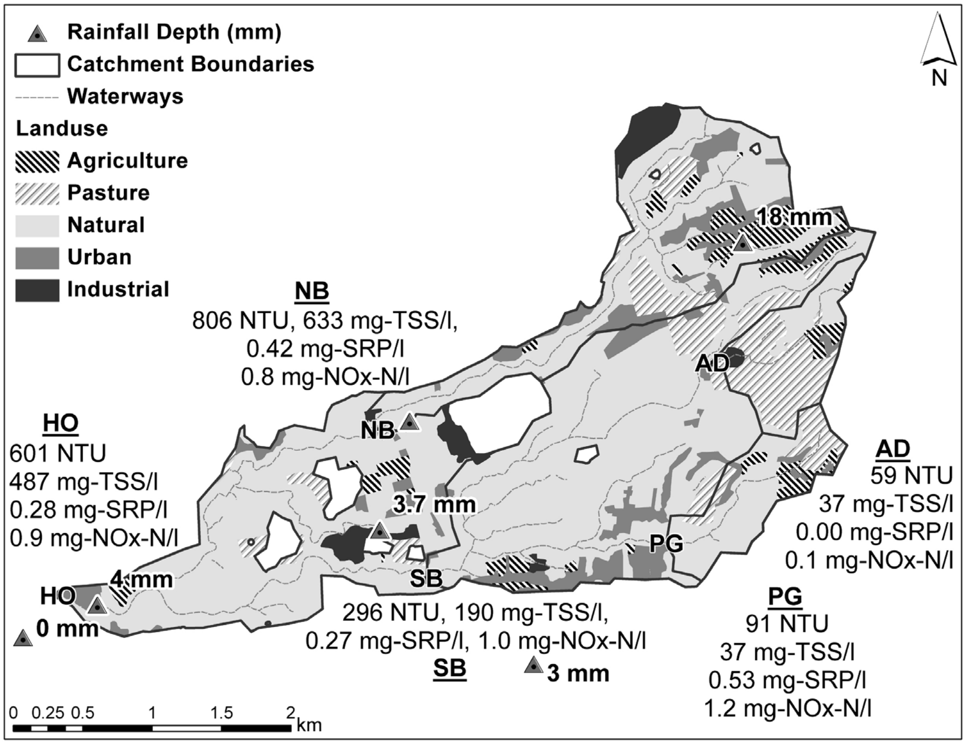


Figure 4.12: Upstream water quality sampling Nov.24, 2006. Values given at each site are event means.

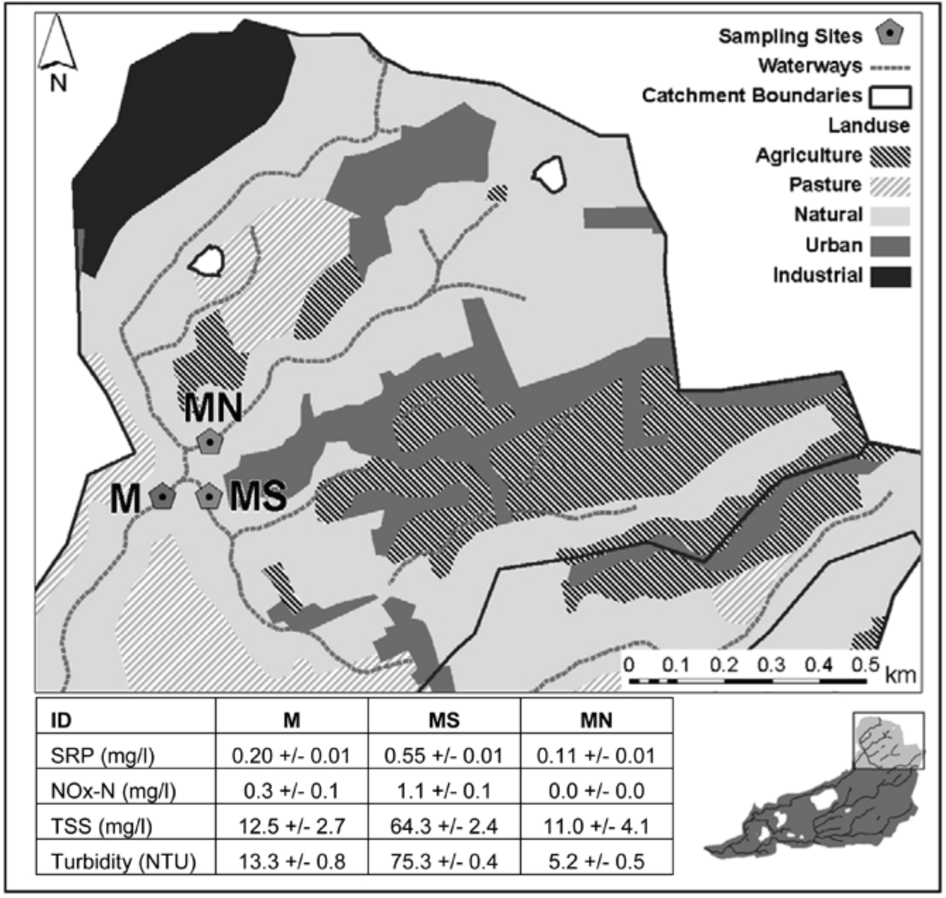


On Nov.14, the surface water's turbidity, TSS, and NO_x-N increased as it traveled from sites NB and SB to site HO, indicating sources in the area between the sites. These increases could very possibly be caused by the sugar factory which has large fields of loose piles of the factory's particulate by-products. An accumulation of fine sediments was also observed at the base of a clearing through the bank of the gully adjacent to the factory's property. Hunte (1989) sampled this gully directly downstream of the factory and reported high nitrate levels (0.843 mg NO_3-N/l) which were much higher than concurrent samples taken downstream, near HO, on 3 of 4 occasions. Another source with the potential for increasing downstream turbidity is the industrialized land contributing runoff from the quarry. Increases in NO_x-N could also be contributed by the small proportions of agricultural and urban landuses in the area or resurfacing groundwater through springs in the karstic gullies. On Nov.24, the lower terrace received very low amounts of rainfall, suggesting that surface runoff was not generated in the area, and that values at HO simply resulted from mixing of the upstream tributaries.

Turbidity, TSS, and SRP were significantly higher at the upstream site NB than at all other sites ($p<0.0001$), with the exception of there being no significant difference between TSS at NB and HO. Urban, agricultural, and industrial landuses combine for 33% of subbasin NB's area, a much higher proportion than in catchments HO (19%), SB (15%), AD (12%), and PG (18%) (Fig. 4.2). A spatial comparison of this sort may be questionable due to temporal variations of TSS and turbidity in the time between sampling each of the sites and due to differential rainfall patterns. However, the following reasons justify this result. Firstly, all sites were sampled at least 50 minutes after the onset of flow at HO at which point the rate of change in these parameters has decreased (Figs. 4.9 and 4.10). Secondly, neither of the events exhibited 2nd peak discharges in the downstream hydrographs (Fig. 4.4) indicating that runoff in upstream tributaries was generated at approximately the same time. Thirdly, overall means of TSS and turbidity at NB were twice those of the other upstream sites, differences that are far too large to result from temporal variation within the maximum time period between sampling NB and any other site, 30 minutes (Figs. 4.9 and 4.10). Finally, subbasin NB received the highest average rainfall depths for both of these events and so concentrations resulting from a given square area of land could only be diluted relative to the other subbasins. Therefore, the landuses in subbasin NB are contributing much higher turbidity, TSS, and SRP per unit area of land than the landuses in the other subbasins. However, subbasins NB and AD incurred higher average rainfall intensities than the other catchments during both events, which could cause greater amounts of erosion, weakening the hypothesis that the observed spatial differences in water quality are purely a result of differential landuse. The impact of these upstream tributaries on downstream water quality would best be assessed by their total loads but these cannot be calculated accurately as the shapes of their hydrographs are unknown and may be different.

Subbasin NB was further examined with samples taken at locations further upstream (Fig. 4.13). These samples were taken during the late stages of a low-flow event which did not arrive downstream to NB. Water levels were low enough that the 2 tributaries sampled (MS & MN which flow to M) were the only ones flowing. Low water levels and the fact that the tributary running from the nearby construction site ("Industrial" Fig. 4.13) wasn't flowing are the likely reasons turbidity and TSS were low compared to levels at NB during other events. However, it is clear that the tributary draining the urban and agricultural areas of Hillaby, MS, is contributing much higher levels of all the tested parameters than the tributary draining the less developed area to the north, MN. Water quality levels at site M are closer to those at MN, showing a larger contribution of water from MN than MS, though this may not necessarily be the case during the onset of an event.

Figure 4.13: Upstream water quality in subbasin NB, Nov.23, 2006.



ID	M	MS	MN
SRP (mg/l)	0.20 +/- 0.01	0.55 +/- 0.01	0.11 +/- 0.01
NOx-N (mg/l)	0.3 +/- 0.1	1.1 +/- 0.1	0.0 +/- 0.0
TSS (mg/l)	12.5 +/- 2.7	64.3 +/- 2.4	11.0 +/- 4.1
Turbidity (NTU)	13.3 +/- 0.8	75.3 +/- 0.4	5.2 +/- 0.5

A pasture covers much of the area draining to site AD (61%). Nutrient concentrations at this site were the lowest among all sites showing how little pastures contribute to nutrients in this watershed's runoff. The higher TSS and turbidity levels seen on Nov.14 are surely flushed from the large scale construction site immediately upstream, yet they were very low on Nov.24. These inconsistent results may be due to differences in flow levels between the two events, or may also be specific to the state of the construction site during the events.

Subbasin PG had the 2nd highest SRP concentrations and the highest NO_x-N concentrations among sites, though the lowest levels of turbidity and TSS. This subbasin is similar to NB in its high nutrient concentrations and high proportion of agricultural landuse (12%) relative to SB, AD, and HO. However, PG and NB differ in that PG has no industries and a smaller amount of urban area (5%) than NB. The low levels of TSS and turbidity at PG support the notion that sources of sediment and turbidity are more likely to be industrial and urban rather than agricultural areas. Of course, this may just be specific to the agricultural practices in this subbasin. Meanwhile the high nutrient concentrations further support the identification of agriculture as a source of nutrients in the runoff.

4.6 Recommendations

The first flush phenomenon observed in TSS at the watershed's outlet shows that if any efforts were made to reduce sediment fluxes to the sea, this could efficiently be done by retarding as much of the initial discharge as possible to allow for settling. In this regard, it has been suggested to divert the tributary upstream of site NB into the nearby quarry (Cumming Cockburn Ltd. 1996). The present study supports that this venture would not only be a viable solution for reducing runoff peak flows but turbidity, TSS, and SRP concentrations as well. Capturing only half of the runoff would capture 80% of the TSS, and the tributary to the north has been shown to be contributing the highest concentrations per unit area of land. Once operational, the reservoir at site AD will only slightly reduce the entire watershed's total runoff as this subbasin represents but a small proportion of the area draining to HO. Completing construction at this site and others would theoretically improve water quality but only until the onset of future construction which is inevitable to this developing coastal area.

Nutrient concentrations are high considering the large proportion of natural land in the watershed. Due to the low concentrations of SRP in the groundwater and the unlikeliness of such high SRP values in the runoff resulting from wastewater on the surface, agricultural sources must be making large contributions. Given the low proportions of agricultural and urban landuses, it thus appears that excessive application of fertilizers is occurring. A recent survey of farmers in a nearby watershed revealed that none were aware of the fertilizer quantities being applied (Denis and Hughes 2003). Though not an immediate solution, it is likely that agricultural practices will eventually require improvement and control as ongoing development and population growth will only expand agricultural demand.

Increases in the island's local and tourist populations will also enhance the potential for wastewater contamination of runoff. Remediation of this problem has been addressed and awaits the progress of the West Coast Sewerage Project (Stanley International Group Inc. 1998). An additional solution would be to phase out the use, or importation, of soaps and detergents containing phosphates. This last solution would be beneficial to conservation of the nearshore marine environment in which phosphorus has been suggested to be the nutrient limiting algal growth (Sander and Moore 1979; Wellington 1999).

4.7 Conclusions

This study revealed information imperative to conducting similar future research. Spatial rainfall patterns varied drastically showing that high sampling densities are required to attain accurate measurements. The strong temporal variations of discharge, TSS, and turbidity during events confirm the necessity for intensive sampling within the initial period of flow to accurately assess these parameters. Documentation of the time at which a sample was taken with respect to the onset of runoff is essential to comparing events by their levels of TSS and turbidity.

It was shown that the occurrence of runoff or rainfall sufficient for generating runoff upstream of the watershed's porous middle terrace may not lead to flow at the downstream outlet. These results constitute direct evidence of internal drainage within the gullies and show that the gully system has a carrying capacity which must be exceeded for runoff to reach the coast. This carrying capacity could help to explain the correlation observed between event runoff coefficients and event runoff volumes: the set volume of water lost to internal drainage represents a smaller proportion of the total runoff volume for larger events. Thus, the proportion of an event's rainfall volume discharged at the watershed's outlet increases with larger events.

Water quality in the watershed is much poorer than it ought to be with such a high proportion of natural land. While high-flow events have a much higher potential for transporting solids, similar nutrient concentrations were observed in high- and low-flow events alike. The high levels of TSS, turbidity, and SRP in the most developed subbasin support the hypothesis of sources being agricultural, urban, and industrial areas.

The first-flush phenomenon observed for TSS and turbidity show that most of the runoff's sediment content is transported rapidly. Sources are most likely those where solids are abundant and unstable such as the various construction sites and the fields of by-product at the sugar factory. This hypothesis is supported firstly by elevated TSS and turbidity levels drained from the areas with large industries, and secondly by lower levels coming from a subbasin containing no industries, a small urban area, and greater agricultural landcover relative to the rest of the watershed.

The reported nutrient concentrations are quite high considering what little agricultural land remains. An increase in surface water SRP since a past study (Hunte 1989) may reflect urban expansion and an increased contribution of wastewater which typically contains large amounts of SRP (Stanley International Group Inc. 1998). Though wastewater is commonly disposed of into the ground, it has the potential to resurface due to suckwell overflows and via springs which are common in such aquifers. However, low levels of SRP previously reported in the groundwater (Klohn-Crippen Consultants Ltd. 1997) and the improbability of overflows being prevalent throughout the entire watershed indicate that agriculture must still be making a significant nutrient contribution. Therefore, expected reductions in nutrient contamination due to the demise of agriculture in the watershed's recent history may have been offset by increased fertilizer application in the remaining areas. Identification of agricultural areas as sources of nutrients is supported by high nutrient concentrations found draining from a subbasin with relatively larger agricultural and smaller urban landcover. Pastures, on the other hand, yielded much smaller concentrations of nutrients.

The interconnectedness of a watershed's inhabitants requires responsible management of landuses as their influence on water quality will inevitably be realized by the degradation of receiving water bodies. In this case, the recipients are the groundwater and nearshore seawater. The former comprises the island's chief source of freshwater, a scarce and deteriorating commodity (Government of Barbados 2000). Degradation of the latter has been documented, associated with increased tourist and industrial development, and led to the demise of the fringing coral reef ecosystem (Bell and Tomascik 1993). Remediation of these problems is critical, though this has been suggested before (Nurse 1986; Bellairs Research Institute 1997).

V. SUMMARY & CONCLUSIONS

The effects of runoff on the environment of the Bellairs fringing reef can be summarized as follows: 1) Flow events create northward drifting plumes across the reef with turbidity and TSS levels in excess of guidelines for marine health set by the Marine Pollution Control Act (Government of Barbados 1998). While excessive surface water turbidity levels are short-lived (< 3 days), surface water TSS levels remain above guidelines for at least 3 days making their full impact unknown. 2) Flow events discharge large sediment loads to the nearshore system contributing to the chronic stress of sedimentation observed on the reef. 3) Flow events discharge large loads of dissolved nutrients presumably causing coastal eutrophication. The effects of runoff on marine eutrophication are augmented by the flushing of the Holetown lagoon linking the watershed and the coast. Past research (Braithwaite 2004) reports data that suggest a similarly large source of dissolved nutrients is stored in the relatively small lagoon.

Upstream sources of sediments and nutrients were identified as industries, urban areas, and agriculture. Rapid transport of sediment suggests sources are likely those where solids are abundant and unstable such as the various construction sites and the fields of by-product at the sugar factory. Urban areas probably enrich runoff with nutrients as wastewater disposed into a karst aquifer will undoubtedly resurface, whether upstream or in the sea, and degrade surface water quality. However, data also confirm the role of agriculture in enhancing dissolved nutrient content. As the area of agricultural land represents such a small portion of the overall watershed, it is likely that fertilizers are being over-applied to some degree.

The identification of sources is simply the necessary first step towards remediation of the problems observed downstream. Once identified, recommendations for remediation can be made and their feasibilities assessed. Recommendations for solving these problems include controlling point-sources in the coastal area, excluding phosphate-based detergents and soaps from the island, retarding runoff to increase settling, and improving the management of agricultural practices. Clearly, improvements to the watershed's wastewater disposal system are also needed but such projects are already underway (Stanley International Group Inc. 1998). Far more research would be needed to follow through with the next step in assessing the socio-economic feasibilities of such solutions.

VI. APPENDIX: Calculations for Potential Error of Load Estimates

This section is included to explain the methods and calculations used in determining the potential error involved in estimating total loads of nutrients and sediments previously presented in Table 3.1 of Section 3.4.1. Potential error in these estimates includes a contribution from measuring streamflow as well as nutrient and sediment concentrations. The water quality data's variability is presented as standard deviations incorporated in the text of Sections 3.4.1 and 4.5.2 as well as in Figure 4.9. The other contribution to this potential error is due to measurements of stage and multiple calculations required in order to obtain values of discharge. Table 6.1 below summarizes the estimated loads and potential errors while discussion of the latter's calculations may be found to follow.

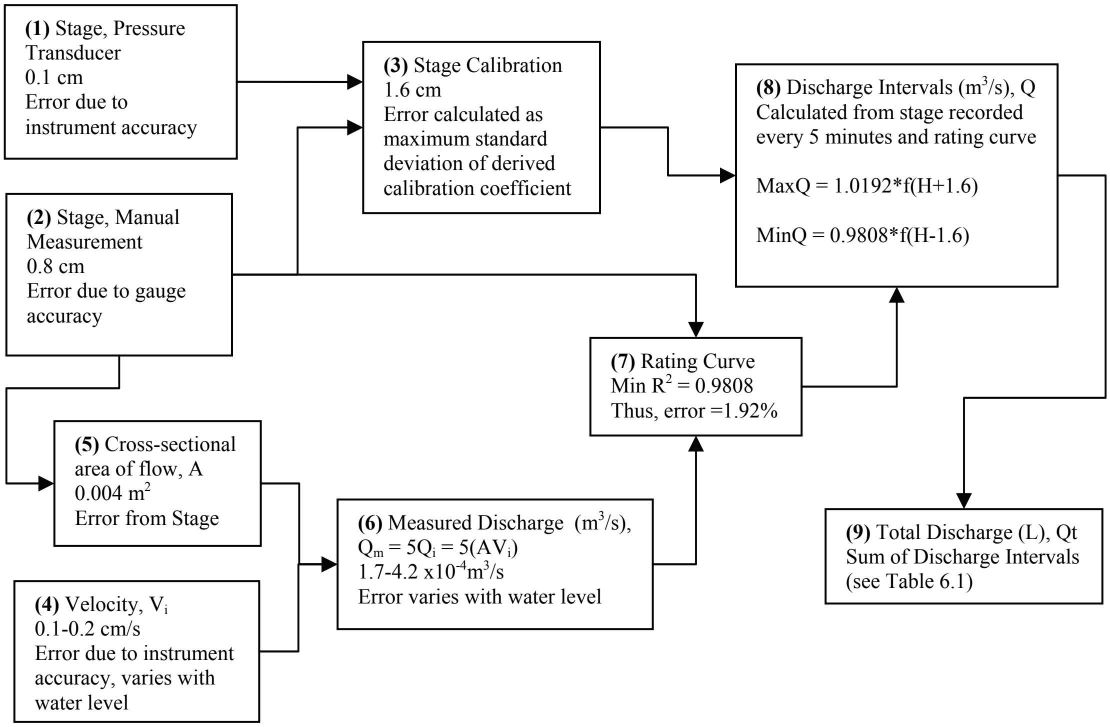
Table 6.1: Summary of flow event loading. Includes estimates of total discharge of water, total suspended solids (TSS), soluble reactive phosphorus (SRP), and nitrate-nitrite-nitrogen (NO_x-N), as well as wind data for each flow event. Estimates of potential error are presented in parentheses.

Event Date	Total Discharge (10^6 L)	TSS Load (tonnes)	SRP Load (kg)	NO_x-N Load (kg)
Aug.24	68.2 (9.2)	~187 (25)	-	-
Oct.16	66.2 (6.5)	97.5 (13.2)	22.5 (6.2)	46.4 (24.6)
Oct.27	25.1 (6.5)	32.0 (4.1)	8.6 (4.0)	17.6 (13.7)
Nov.14	95.3 (13.6)	117.6 (20.4)	32.4 (10.4)	66.7 (38.5)

6.1 Calculations for Potential Error of Discharge

The methods for calculating the potential errors of discharge values are illustrated in Figure 6.1 below. Steps in the calculation procedure (numbered **1-9**) are contained in boxes while discussions of steps may be found to follow.

Figure 6.1: Flow chart for potential error of discharge calculation



<u>(1) Stage, Pressure Transducer</u>

The pressure transducer in the channel recorded measurements of stage accurate to 1 mm. Potential error for this instrument is thus assumed to be equal to 0.5 mm, half of the instrument's finest measurement. Measurements of stage also required subtraction of measurements taken by another pressure transducer recording atmospheric pressure. In making this subtraction, the potential error of the two pressure transducers is accumulated making the potential error 1 mm, following this calculation.

(2) Stage, Manual Measurements

Manual measurements of stage have a potential error of 0.8 cm, as they were recorded to an accuracy of 0.05 feet (1.6 cm).

(3) Stage Calibration

Further error potentially accumulated due to a calibration required for measurements of stage. A calibration was required because of a fairly constant discrepancy between recordings of stage made by the pressure transducer and those taken manually. Since measurements were taken manually and by the pressure transducer were rarely taken simultaneously, regression equations were used to estimate stage for both data sets concurrently. Twenty-nine values of stage calculated by these regressions were then subtracted. The average difference was used as the calibration coefficient, while the standard deviation of this set of differences, 1.2 cm, may be assumed to be the potential error incurred due to calibration.

However, both measurements of stage required for this calibration (**(1)** pressure transducer and **(2)** manual) have a potential error. As previously described, error due to the pressure transducer and manual measurements of stage may be up to 0.1 cm and 0.8 cm, respectively, and so potential error from these two measurements accumulates to 0.9 cm for each of the 29 values of stage calculated for calibration. To test the effect of a 0.9 cm potential error on the standard deviation of the set of differences used for calibration, 0.9 cm was randomly added or subtracted to each of the 29 differences. This was repeated 10 times and revealed a maximum standard deviation of 1.6 cm. Therefore, the potential error incurred due to calibration may be up to 1.6 cm.

4) Velocity, V_i

Velocity measurements have the potential for 1% error due to the instrument, equal to 0.01-0.02 m/s, depending on the velocity.

(5) Cross-sectional Area, A

Cross-sectional area of each of 5 channel segments was calculated as the segment's width (0.504 m) multiplied by stage measured manually. Due to the potential error of the latter (0.8 cm, previously described **(2)**) the potential error of each segment's cross-sectional area is calculated as 50.4 cm multiplied by 0.8 cm, equal to 0.004 m^2.

(6) Measured Discharge, Q_m

Error for each channel segment's calculated discharge, Q_i, is equal to the velocity error multiplied by each segment's error in area. The potential error for each measurement of discharge for the entire channel, Q_m, is found by summing the error due to the 5 segments. This value varies with water level, with a range of 1.7-4.2 $\times 10^{-4}$ m^3/s.

(7) Rating Curve

A rating curve was used to convert calibrated stage measurements made by the pressure transducer **(3)** into measurements of discharge (m^3/s). This rating curve was established using a regression equation (4th order polynomial) that fit 98.85% of the data ($R^2 = 0.9885$). Therefore, the potential error due to the use of this curve may be up to 1.15%. However, the two parameters used to calculate this curve, stage **(2)** and discharge **(6)**, have potential error which could have augmented the error involved in the rating curve. The potential error due to discharge **(6)** is two orders of magnitude less than the values of discharge recorded and used for the rating curve, and can thus be considered negligible. Manual measurements of stage have a potential error of 0.8 cm **(2)**. To test the effect of a 0.8 cm potential error on the rating curve's r-squared value, 0.8 cm was randomly added or subtracted to each value of stage used in the relationship, and a new regression curve was created. This was repeated 10 times and revealed a minimum r-square value of 0.9808. Therefore, the potential error due to the use of this curve may be estimated to be up to 1.92%.

(8) Discharge Intervals, Q

Intervals of discharge (m^3/s) were calculated using the rating curve for each calibrated value of stage **(3)** recorded by the pressure transducer every 5 minutes. This was done using the following equation:

$$Q = f(H) \qquad \text{(Eq. 6.1)}$$

where:
Q = discharge interval (m^3/s)
H = stage (cm)
f = a function of H, defined by the rating curve

The potential error incurred in these calculations include that due to the values of stage (1.6 cm following calibration **(3)**) and that due to the rating curve (1.92%, **(7)**). As the amount of potential error varies with stage, it was necessary to calculate the potential error for each interval of discharge. This was done using 2 equations, the first to define a maximum potential error, and the second to define a minimum:

$$Q = 1.0192 \bullet f(H + 1.6) \quad \text{(Eq. 6.2)} \qquad \text{and} \qquad Q = 0.9808 \bullet f(H - 1.6) \quad \text{(Eq. 6.3)}$$

The factors 1.0192 and 0.9808 are used to increase and decrease, respectively, the discharge values calculated from the rating curve **(7)** by 1.92%. Calculated errors for the event of Oct.16, for example, ranged between 0.04 – 0.32 m^3/s.

(9) Total Discharge, Qt

Total discharge of a flow event was calculated by multiplying each discharge interval **(8)** by 300 s (= 5 min), summing the values produced, and then converting to litres (1000 L/m^3). The following equation was used:

$$Qt = 1000 \bullet \sum (Q \bullet 300) \qquad \text{(Eq. 6.4)}$$

where:
Qt = total discharge (L)
Q = discharge interval (m^3/s)

As both a maximum and minimum potential error was calculated for discharge intervals **(8)**, the above equation was similarly used to calculate both a minimum and maximum potential error for total discharge. Reported in Table 6.1 is the average of these two potential errors.

6.2 Calculations for Potential Error of TSS Load

Variability in TSS data is represented using the standard deviation of the analyzed triplicate samples, shown in Figure 4.9 of Section 4.5.2. In order to calculate an event's total TSS load, discharge intervals were converted to litres per second (1000 L/m^3) and each multiplied by the TSS concentration (mg/l) corresponding to the same time, yielding intervals of TSS load in mg/s (Fig. 6.2). Total TSS load of a flow event was then calculated by multiplying each TSS load interval by 300 s (= 5 min), summing the values produced, and then converting to metric tonnes (1 tonne /10^9 mg, Fig. 6.2). The following equation was used:

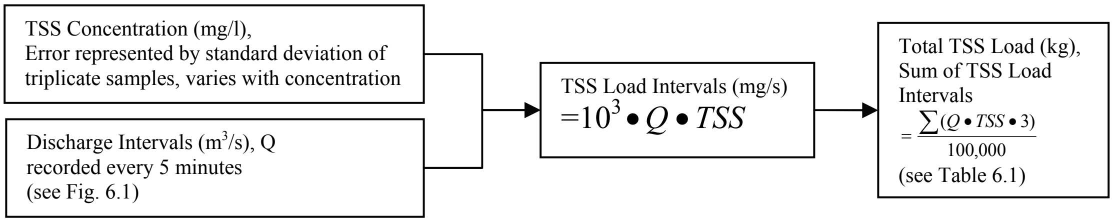
$$TSSL = \frac{\sum(Q \bullet TSS \bullet 300 \bullet 1000)}{1{,}000{,}000{,}000} \qquad \text{(Eq. 6.5)}$$

where:
TSSL = total TSS load (tonnes)
TSS = TSS concentration (mg/l)
Q = discharge interval (m^3/s)

Potential error in total TSS load was derived by calculating maximum and minimum values. This was done by increasing TSS concentrations by their standard deviations and increasing discharge intervals by their respective maximum potential values, as previously described, and then repeating the procedure using minimum values. Reported in Table 6.1 is the average of these two potential errors.

As triplicate samples were only taken every 30 minutes, standard deviations for single samples required estimation. Also, as samples were only taken for at least the first 3 hours of a flow event, TSS concentration curves required extrapolation for the rest of each event. However, the TSS load for this period of flow only represents about 7% of an event's total load, and so this extrapolation should not be considered critical to the results. Estimates of standard deviations, for single samples and extrapolated values, were derived by establishing a linear relationship between TSS concentrations and standard deviations obtained from triplicate samples for each event.

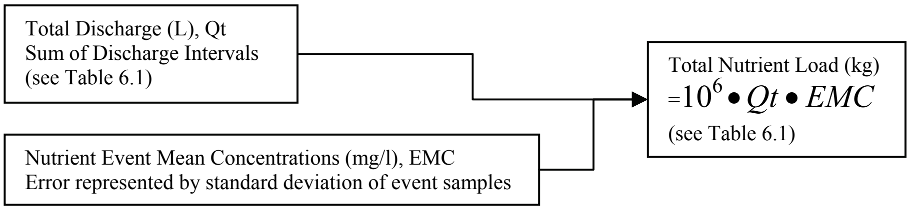
Figure 6.2: Flow chart for potential error of TSS load calculation



6.3 Calculations for Potential Error of Nutrient Load

Nutrient loads were estimated simply by multiplying the event mean concentration, EMC, of nutrients by the event's total discharge, Qt. Variability in nutrient concentration is represented using the standard deviation of the event's analyzed samples, presented in Sections 3.4.1 and 4.5.2, while the potential error of total discharge calculations was previously described **(9)**. The potential error of nutrient load estimates was derived by calculating maximum and minimum values. This was done by increasing nutrient concentrations by their standard deviations and increasing total discharge values by their respective maximum potential values, as previously described, and then repeating the procedure using minimum values. Reported in Table 6.1 is the average of these two potential errors.

Figure 6.3: Flow chart for potential error of nutrient load calculation



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