IMPLEMENTATION OF A SPATIAL DECISION SUPPORT SYSTEM FOR WATER QUALITY PROTECTION AND MANAGEMENT IN THE HOLETOWN WATERSHED, BARBADOS: A CASE FOR THE ESTABLISHMENT OF A NSDI FOR ENVIRONMENTAL MANAGEMENT

By

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Dedication

I would like to dedicate the work here presented to my mother Maria Del Carmen Arriola, for her exemplary resilience and perseverance in surviving a critical cancer. Her strength and determination then, and throughout her life have proven to me that good intentioned accomplishments can only be attained by strong self determination, and self confidence. I hope this message and inspiration can be translated to formal initiatives concerned with environmental management in Barbados and throughout the World.

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ABSTRACT

Water quality protection in Barbados is provided by means of a zoning policy defined on bacteriological travel-times, based on matrix groundwater flow; and without consideration of neither: surface/subsurface water karstic-hydrology-dynamics (which characterise the island of Barbados), nor chemical pollution-transport and -fate in surface water, which is the main source of groundwater recharge for the island. This thesis explores the institutional frameworks, as well as the physical data necessary to implement the use of a spatial, tightly-coupled Decision Support System for water quality protection and management in Barbados. While a technical DSS application is provided for demonstration purposes, focus is placed on the imminent importance of establishing a National Spatial Data Infrastructure, and on the necessary enhancement of institutional frameworks to meet the requirements for a DSS implementation at the national level. It is concluded that under current institutional and data quality, availability/accessibility conditions such an endeavour will not be possible.

Keywords: Spatial Decision Support System, IWRM, WARMF, Barbados, Hydrological modeling of Karst Terrain, NSDI, data accessibility, DEM

Mise en place d'un système spatiale d'Aide à la Décision Multicritère pour la protection de la qualité et la gestion de l'eau dans le bassin hydrographique de Holetown, à la Barbade, Petites Antilles: Un cas pour la création d'une Infrastructure Nationale de Données Géographiques

RÉSUMÉ

La protection de la qualité de l'eau sur l'île de la Barbade est assurée par une politique de règlement de zonage définie par la mesure du temps de propagation bactériologique basée sur une matrice d'écoulement des eaux souterraines. Cette politique ne tient ni compte des dynamiques du système hydrologique-karstique des eaux souterraines/de surface (qui caractérisent la Barbade), ni du transport des polluants chimiques aboutissant en eaux de surface qui représentent la principale source de réalimentation des réserves d'eaux souterraines de l'île. Cette thèse explore les cadres institutionnels ainsi que les données physiques nécessaires pour mettre en application un système spatiale d'Appui à la prise de décision pour la protection de la qualité et la gestion de l'eau avec un système complexe de logiciels associés à l'aménagement du territoire de l'île de la Barbade. Tandis qu'une application technique SDD est fourni à des fins de démonstration, l'accent est mis sur l'importance imminente d'établir une Infrastructure Nationale de Données Géographiques, ainsi que la nécessité de renforcer le cadre institutionnel pour répondre aux exigences de le mise en pratique d'un SDD au niveau national. Il est conclu que due à la qualité des données et l'état actuel des cadres institutionnels que les conditions de disponibilité/accessibilité d'une telle entreprise ne sera pas possible.

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Foreword

The system in Barbados as it relates to water quality protection and management through the use of DSS can be divided into two major realms: 1. the biophysical realm, which defines the dynamics governing water occurrence, water movement, water quantities, as well as pollutant loading, transport, and attenuation potentials. And 2. the institutional realm, which governs: land use activities, policies, and structural measures, affecting or protecting water quality; as well as the production and dissemination of data and tools used for water management. This data pertains to the representation, intersection and interaction of key elements affecting water quality from both the biophysical and institutional realms.

While the detailed exploration and technical discussions about modeling a Karstic system such as that of Barbados is worthy, and in need of the entire focus of an entire postgraduate thesis; in this thesis they are limited to only two chapters. This approach has been chosen under the premise that: in the context of a pragmatic approach for implementing a DSS for water quality protection and management in a national setting; the importance of attaining the necessary institutional frameworks, and provision of necessary "data bases" [not databases] for achieving modeling efforts efficiently, take precedence over the in-depth conceptual and practical technicalities associated with hydrological modeling and decision support. However, these practical and conceptual technicalities cannot be left out of sight, as they in turn shape the nature of the "data bases" and, to a certain degree, the institutional characteristics required for a meaningful and successful DSS application as this thesis aims to demonstrate.

By providing an example of a practical implementation of the Watershed Analysis Risk Management Framework (WARMF), and by adopting a systems analysis approach, this thesis aims to build the case for the importance and necessity of establishing a National Spatial Data Infrastructure in Barbados to make such an application as the one presented here a possible reality in the Barbadian context.

Explicitly this thesis aims to achieve the above mentioned goal by fulfilling the following objectives:

1. To provide a comprehensive literature review on the development, application and adoption of DSS for the management of water resources
2. To provide an overall review of the physical makeup of the island of Barbados and how it relates to the water resources regime with a specific focus on water quality
3. To provide an overview of the current institutional arrangements in place for the management of water resources in Barbados
4. To rationalize, the main factors/components to be considered by the DSS

5. To provide an inventory, and an assessment of the state of, as well as the functionality of data needed for a DSS application for water quality protection and management
6. To identify which institutions / individuals are custodians of presently available datasets, and which would be the most suitable custodians for proposed future data collection/production initiatives.
7. To suggest a technical and conceptual design for possible applications of a spatial decision support system achieved by tight or loose coupling of hydrologic models and GIS for the purposes of water resource management.
8. To emphasize the importance of the crucial establishment of a NSDI to best achieve a sustainable DSS implementation.
9. To provide an implementation of a DSS for water quality protection and management protection, demonstrative of the potential it offers within the Barbadian context.

To these ends this thesis has been organized in 7 chapters in the following manner. Chapter 1 presents an extensive literature review, taking particular focus on aspects of environmental management and the use of information systems within it, DSS definitions, the use of hydrologic models, and the definition of NSDIs and what it usually takes to build one.

Chapter 2 describes the physical and biophysical makeup of the island and describes the dynamics that govern and affect water occurrence and quality in Barbados. Chapter 3 focuses on the institutional dimensions of water resource management in Barbados, introducing the key players involved and the legal and policy frameworks employed. Chapter 4 explores institutional arrangement in place for data collection and dissemination, and describes data gathering programs related to water resource management; ultimately providing an inventory listing of available datasets, relevant to the implementation of a DSS for water quality management and protection. Chapter 5 focuses on the considerations needed for the implementation of a DSS; providing an overview of WARMF and its main requirements together with an assessment of available data to meet them, presents an overview of the “water system” in Barbados, discuss the reality of data inaccessibility in Barbados, discuses previous NSDI establishment attempts in Barbados, and finally recommends further data gathering.

Chapter 6 presents the demonstration implementation of WARMF as a DSS for water quality protection management. The implementation exercise of both base and alternative scenarios is thoroughly documented highlighting, by demonstration, the importance and potential offered by the use of good data to meet the requirements for modeling the Karst terrain characteristic of Barbados.

Chapter 7 provides a summary of key points presented throughout the thesis, resumes discussion of the presented pilot implementation, and provides a recapitulation of the main recommendations for achieving a successful implementation of such a DSS at a larger scale. Recommendations are relevant both the physical and institutional realms of the Barbados system. A clear summary of the potential benefits the use of a DSS can offer in the Barbadian context is presented together with a discussion of WARMF limitations.

Through the preparation of this thesis, numerous important datasets and government documents previously inaccessible have been recovered and made available in digital format

By the need for reading accessibility, and the support of digital data storage and dissemination the following documents have been scanned and converted to PDF file format.

- The WRLS (Klohn and Crippen Consultants, 1997) reports and EMLUP documents (Wilm and Sheir *et al.* 1998)

- The Cumming and Cockburn (1996) Report and GIS files prepared for that study.

These files have been made available to the government agencies that initially provided them

Why Barbados?

The island of Barbados serves as an interesting case study for the topic of the work presented for various reasons:

- The island ranks amongst the most water-stressed countries in the world, and the long-term importance of sustainable water resources management is vital for the future prosperity of this country.
- Pressure on water resources is big, while the spatial extent of their occurrence (the territory) small; simultaneously facilitating and complicating their management.
- Barbados' high HDI ranking places it in the borderline of "developing" countries, which could indicate that institutional frameworks and infrastructure required could be easily facilitated.
- The Karstic makeup of the island presents challenges in the hydrologic modeling realm. The importance of modeling for management of Karstic systems in the global context is high due to their vast occurrence and high vulnerability.
- Given the small size of the island and its catchments it would be theoretically easy to collect most necessary data to gain a deep understanding of the system at ease and low cost.

Lessons from this case study can provide interesting material for application in other cases where characteristics assimilate.

List of Acronyms Used

BADMC	Barbados Agricultural Development and Marketing Corporation
BASINS	Better Assessment Science Integrating Point & Nonpoint Sources (DSS software)
BMPs	Best Management Practices
BOD	Biological Oxygen Demand
BWA	Barbados Water Authority
CEDERA	Caribbean Disaster Emergency Response Agency
CIMH	Caribbean Institute of Meteorology and Hydrology
CZMU	Costal Zone Management Unit
DB	Database
DBMS	Database Management System
DEM	Digital Elevation Model
DMP	Digital Mapping Project
DPFWRDM	Draft Policy Framework For Water Resource Development & Management
DSS	Decision Support System
DTM	Digital Terrain Model
DU	Drainage Unit
EIA	Environmental Impact Assessment
EMLUP	Environmental Management and Land Use Planning Project
EMP	Draft Environmental Management Plan
EPD	Environmental Protection Unit
EPRI	Electric Power Research Institute
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
GIS	Geographic Information System
GPP	Ground Protection Plan
GPZs	Ground Protection Zones
GUI	Graphical User Interface
IWRM	Integrated Water Resource Management
L&SD	Lands And Surveys Department
MARD	Ministry of Agriculture and Rural Development
MIS	Management Information Systems
MOHE	Ministry of Health and Environment
NCSDP	National Commission for Sustainable Development
NRDB	Natural Resources Database
NRGIS	Natural Resources Geographic Information System
NSDI	National Spatial Data Infrastructure
PDP	Physical Development Plan
PE	Potential Evaporation
PSW	Public Supply Well
SDI	Spatial Data Infrastructure
SDSS	Spatial Decision Support System

SW(x)	Subwatershed (x)
T&CPO	Town and Country Planning Office
TDS	Total dissolved solids
TMDLs	Total Maximum Daily Loads
TSS	Total suspended solids
URISA	Urban and Regional Information Systems Association
USEPA	United States Environmental Protection Agency
WARMF	Watershed Analysis Risk Management Framework (DSS software)
WCSP	West Coast Sewage Project
W-DSS	DSS for water quality management and protection
WRB	[proposed] Water Resources Board
WRM	Water Resources Management
WRMP	Water Resources Management Plan
WRU	[proposed] Water Resources Unit (part of the WRB)
WRWLS	Water Resources and Water Loss Study (Klohn and Crippen Consultants 1997d)

Units

ºC	Degrees Celsius
S.U.	Standard Units
m^3/s	Cubic Meters per second
m^3	Cubic Meters
m/s	Meters per second
cms	Cubic Meters per second
mg/l	Milligrams per litre
ug/ m^3	Micrograms per litre
m	Meters
hr	Hour
Ha	Hectare
h	Hour
mole/l	Moles per Liter
ºF	Degrees Fahrenheit
Ft	Feet
Kg/ha	Kilograms per hectare

Chapter 1: Literature Review

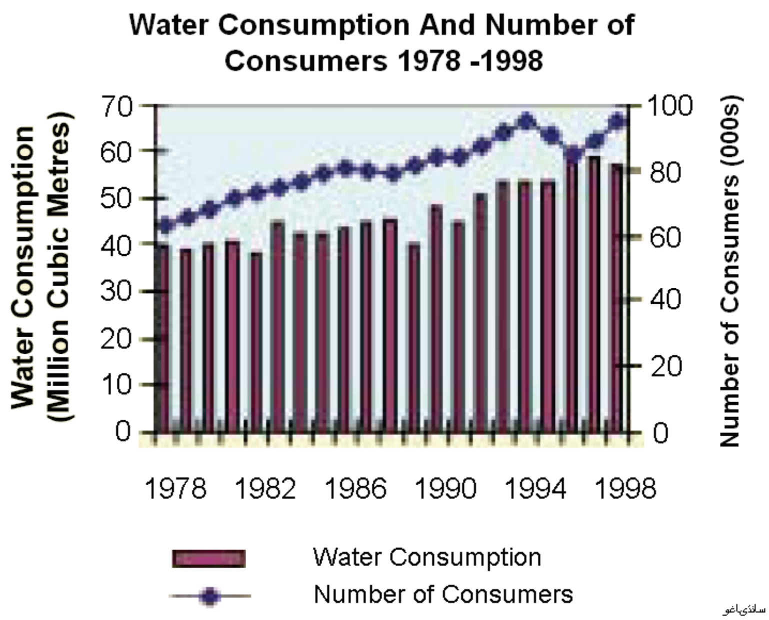
This Chapter provides a general review of the literature of the main topics that form the basis of the work to follow. In the first section, a general overview of *Environmental Management in Barbados* is presented with a specific focus on the *frameworks and legislations* that have been established to achieve sustainable development. One of the main recommendations towards this end has been the creation of *information systems* for environmental management. The next section discusses the achievement of effective information systems through the establishment of *Spatial Data Infrastructures*, which address the technical and institutional structures, as well as the appropriate policies required for *Building SDIs* to aid sustainable development. The third section looks at the use of *Decision Support Systems* as an avenue, paved by an effectively established SDI, to tackle *environmental management* problems through the use of *GIS*. *GIS and model coupling for the creation of spatial-DSS* is then discussed taking focus on water resource management. Particular attention is brought to the importance of modeling *recharge dynamics and pollutant transport* to set the stage for the final section which takes a more in depth discussion about *hydrologic models and Karst systems*. *Groundwater flow models* and *pollutant transport models* are presented and examined in the light of their problematic application in Karst systems.

1.1 Environmental Management in Barbados

Barbadians inhabit a small island (431 km^2). This island has finite land space and natural resources, and a population (654/km^2) that exerts a high and growing (as the island becomes more affluent) demand for products, goods and services the island can provide. Increasing demands are being made on the natural environment, as water usage increases (see Fig 1), and urban expansion takes place to accommodate a growing local and tourist population of an increasing affluence (Leitch and Harbor, 1999; UNEP, 2001). The small land and coastal area of Barbados predisposes the island to environmental vulnerability .As with all small island nations Barbados is particularly vulnerable to climate change impacts and to rapid environmental degradation (Ministry of Physical Development and Environment, 2001).

Negative impacts are difficult to partition, hide or trade-off. It has become evident, that in Barbados, land-based anthropogenic activities have resulted in degradation of biotic components of coastal and marine systems (Leitch and Harbor, 1999). Over time several factors have had a substantial impact on the marine and costal environments of Barbados, including and primarily the complete change to the terrestrial landscape through the clearance of forest cover from much of Barbados, intensive agriculture, and the infrastructure by-products (i.e. sewage and solid wastes) (UNEP, 2001). Consequently, approaches to environmental management require a conservative stance that minimises or eradicates both risk and impact. For these purposes, a strong system of governance, including its structure, infrastructure, frameworks and legislation, with appropriate policies for implementation is essential. Digital databases, GIS and DSS can play an important supportive role for these purposes. The governmental structure as it relates to water resource management is presented and discussed in detail in Chapter 3 in the "Barbados Institutional Section". The infrastructural aspects as they relate to data collection, analysis and dissemination as well as digital databases and GIS are discussed in detail in Chapter 4.

Figure 1.1 Adapted from Ministry of Physical Development and Environment



1.2 Frameworks and Legislation

In Barbados, the current legal framework, as it relates to environmental management, is a patchwork of statutory provisions created in an era when comprehensive environmental management was not an objective of government. Since then, concepts of environmental science, engineering and planning have undergone revolutionary change (Willms & Shier *et al.*, 1998d). Most legislation currently in use is not relevant or applicable to modern environmental management. While specificity and focus in the governance system are essential to avoid overlap and wastage of human and financial resources, there needs to be flexibility in arrangements for environmental management. This approach recognizes that management of environmental issues more often than not requires cross-sectoral, cross-disciplinary efforts.

The Government of Barbados has been preparing new environmental and natural resources management legislation (Willms & Shier *et al.*, 1998d). Such plans include the Proposed Environmental Management Act. This legislation will have provisions dealing with the following environmental and natural resources management issues:

- environmental planning
- coastal zone management
- environmental protection, including:
    - pollution control (sewage, industrial discharges)
    - waste management
    - regulation of nuisances
    - hazardous substance management
- water resources management

Furthermore, Barbados is signatory to various multilateral environmental agreements (MEAs) which have further enhanced or burdened the responsibilities government must pursue in relation to environmental management and sustainable development. One example of the manifestations of such MEAs has been the formation of the National Commission for Sustainable Development (NCSD) after the Johannesburg Plan of Implementation agreed upon during the World Summit for Sustainable development in 2002. The Johannesburg Plan of Implementation urges States to take immediate steps to make progress in the formulation and elaboration of national strategies for sustainable development (NSDS) and begin their implementation as of 2005. In Barbados, The NSDS policy has been laid in Parliament and the NCSD has committed to the development of comprehensive implementation strategies. The policy has called for the NCSD to "formulate appropriate criteria for the evaluation, assessment and review of the implementation of this policy at the sectoral, corporate and individual levels, including the formulation of a plan of action and incorporation of the use of indicators of Sustainable Development in measuring [Barbados'] progress towards achieving Sustainable Development" (UNESA, 2003 p3). In short, the NSDS policy recommends the creation of information systems, development of a legal framework, institutional changes, capacity building, expanding and procuring resources and improving access to information. (UNESA, 2003) Some of these points are discussed in some detail below.

1.3 Information and Information Systems

Effective natural resources conservation and management is a likely outcome only if there is sufficient information on which to base decisions and formulate policy. Furthermore, information (data and the analyses of that data) is the foundation for defensible decision-making (Willms & Shier *et al.*, 1998a). If long-term monitoring data of sufficient quality and quantity, obtained from field sampling and measurements as well as from remote sensing technologies, are not available, it is difficult to assess the extent of potential (or actual) environmental change (good or bad) that may arise from some decisions (Kolarit *et al.*, 2006). In the case of remote sensing data, it is possible to refer to historical archived datasets to asses various, but limited, changes; while in the case of field data (i.e. streamflows, water quality parameters) data collection and archiving efforts are essentially relied upon. The compilation of existing monitoring data, and the establishment of programs for its collection, where lacking, are the fundamental elements for creating and feeding information systems. The establishment of [National] Spatial Data Infrastructures (SDIs) offer a means of consolidating the creation of information systems, institutional frameworks, infrastructures, access to information, capacity building and access to information recommended by the NSDS policy.

1.4 [National] Spatial Data Infrastructures

The issue of sustainable development demands complex decision-making that weighs up economic, social and environmental consequences of the choices that are made about how resources will be used. Such complex decision-making requires ready access by decision makers and stakeholders to "current, relevant and accurate spatial information" (Fernandez Delgado, and Crompvoets, 2004, p 2). "Reliable information infrastructures are needed to accurately, and consistently record environmental, social and economic rights, restrictions and responsibilities as well as provide spatial data to facilitate appropriate decision-making and support conflict resolution in the realm of sustainable development" (Rajaafard *et al.*, 2002, p 12). Advanced spatial information and visualization technologies, including geographic information systems (GIS), remote sensing (RS), global positioning systems (GPS), image processing, among others, have enhanced the methods and tools for collecting, disseminating, sharing, integrating, and using spatial information. Access to such information as a primary input to the planning and implementation of various projects, policies, and programs is the key prerequisite for its effective use (Nedovic-Budic *et al.*, 2004)

To address the need for easy access to up-to-date spatial information, spatial data infrastructures (SDIs) are created globally and by many countries, international regions, and localities (Rajaafard, *et al.*, 2002). SDIs facilitate the collection, maintenance, dissemination, and use of spatial information. An SDI encompasses **policies, institutional frameworks, fundamental data sets, technical standards, access network technologies, and human resources** (including users, providers, and value adding sectors) necessary for the effective collection, management, access, delivery, and utilization of spatial data at different political/administrative levels (Chan, *et al.*, 2001; Coleman & McLaughlin, 1998; McLaughlin & Nichols, 1992; Rajaafard, *et al.*, 2000; Nedovic-Budic *et al.*, 2004; Kok and van Loenen, 2005; Rajaafard *et al.*, 2002). By reducing duplication, facilitating integration and developing new and innovative applications, and respecting user needs, SDIs can produce significant human and resource savings and returns (Chan, *et al.*, 2001; Kok and van Loenen, 2005).

SDI developments range from local to state/provincial, national, and international regional levels, to a global level. The design and implementation of an SDI is not only a matter of technology but also one of designing **institutions, the legislative and regulatory frameworks to facilitate its implementation, and acquiring new types of skills** (Feeney & Williamson, 2000; Remkes, 2000). "An SDI is fundamentally about facilitation and coordination of the exchange and sharing of spatial data between stakeholders in the spatial data community. SDI constitutes dynamic partnerships between inter- and intra-jurisdictional stakeholders" (Rajaafard *et al.*, 2002, p 12). The ultimate objectives of SDI's, are to promote economic development to stimulate better government, and to foster environmental sustainability through improved economic, social and environmental decision-making (Masser 1998; Rajaafard *et al.* 1999, 2000; Nedovic-Budic *et al.*, 2004).

There has been a significant evolution in the approach taken to implement and support spatial data frameworks over the last decade, especially in developed countries. There is increasing recognition that the benefits being returned to communities by investing in spatial information systems include development of a spatial information marketplace, economic development, social stability, reduced resource disputes, improved environmental management, and improvement of the land administration systems (UNRCC-Americas, 2001; Bathurst Declaration, 1999; UNRCC-AP, 1997). Meanwhile, in many developing countries some have achieved little beyond their initial good intentions, whilst others have built-up considerable experience in formulating and implementing SDI initiatives (Rajaafard *et al.*, 2002).

1.5 Building SDI's

According to Nedovic-Budic *et al.* (2004), to be effective, the SDIs may need to be built within or from existing organizational relationships and institutional setups, or, alternatively, new institutions and organizational restructuring may need to accompany SDI developments. They highlight that there has been a trend for countries to expand their effort in developing SDIs through partnerships to pool and integrate data assets and datasets (Rajaafard *et al.*, 2002).

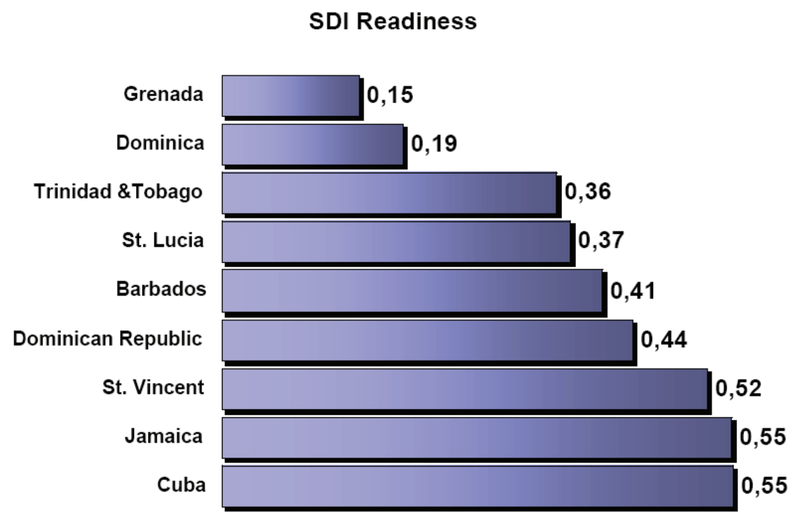
Two fundamental issues with greatest effect on the success of an SDI are **data availability and data accessibility**. Even if available, a spatial dataset may or may not be obtainable. Accessibility depends on various factors, including privacy, security, revenue expectations, power relationships, and enabling technologies. Furthermore, in addition to access, "**horizontal and vertical integration**, flexibility, suitability, and movement of spatial information resources are important for effective planning and policy-making" (Nedovic-Budic *et al.*, 2004, p 2).

All decisions require data and as data becomes more changeable, "human issues of data sharing, security, accuracy and access encourage the need for more defined relationships between people and data. The rights, restrictions and responsibilities influencing the relationship of people to data become increasingly complex, through compelling and often competing issues of social, environmental and economic management. Facilitating the role of people and data in governance that appropriately supports decision-making and sustainable development objectives is central to the concept of SDI" (Rajaafard *et al.*, 2002, p 13).

1.6 SDI's In the Caribbean

Presently, the development of SDI and GIS-implementations for sustainable development in the Caribbean happens to be ad hoc and fragmented. Initiatives started at various levels of government. Island nations as well as regional (UN) agencies are working on relatively isolated projects, and most SDI's in the Caribbean, with the exception of Cuba and Jamaica have been categorized (Fernandez Delgado and Crompvoets, 2004) as low performing. Figure 1.2 shows the composite readiness ranking (Fernandez Delgado and Crompvoet, 2004) for some Caribbean countries. The institutional structures, legal frameworks, and data availability that exist in Barbados, as they relate to the establishment of a SDI are discussed in detail in Chapters 4 and 5. A summary of SDI initiatives in the Caribbean that summarize the most notable projects in the Caribbean promoting the development of national and regional SDI's is presented in Appendix 1.

Figure 1.2 SDI Readiness Composite Index (From Fernandez Delgado and Crompvoets, 2004)



Although some island nations in the Caribbean have developed, or are developing coordination mechanisms, there is still a lot of fuzziness about the roles and mandates for building National SDI's (NSDIs). According to Fernandez Delgado and Crompvoets (2004), these efforts should further be enhanced, whether be it through (modified) legislation or more informal procedures for collaboration and division of tasks, as the building blocks pertaining to legal aspects, pricing and funding, and network services have been weakly developed. According to them, one of the first actions to undertake a

Caribbean SDI should be to strengthen the people preparation and SDI culture at all levels, technical, political, and even to the citizen level.

Fernandez Delgado and Crompvoets (2004) note that regarding the formation of partnerships with other sectors, the most relevant issue is the alliance with the academy. Two of the most important universities in Cuba have been joined to the Cuban NSDI work. This is a very recent program, but the expectations are the creation of a new specialization in Geomatics for SDI in the University of Informatics Science involving more than 100 students from the beginning and growing according to the societal demand.

According to Fernandez Delgado and Crompvoets (2004), the status of the SDI-development in the Caribbean shows the importance of the collaboration among the different authorities, horizontally, as well as vertically (national, regional, and local) in the domain of sustainable development. They caution that successful implementation of NSDIs will largely depend on the successful collaboration between intra and inter-government actors as well as with civil groups. Focusing on the most advanced NSDIs in the region, that of Cuba shows that the keys to success might be: the formulation of a long-term NSDI-vision: having someone with strong leadership involved, investing in capacity building and establishing a National GIS association that is involved in the coordination of the NSDI.

In contrast, Canada has been recognized as being exemplary in the successful development and implementation of SDI's (Rajaafard *et al.*, 2002). According to the Canadian geospatial data infrastructure (CGDI) vision, "the CGDI initiative aims to facilitate the sharing of geographic databases, provide mechanisms which transcend the copyright and licensing restrictions, permits data exchange among agencies, and includes funding mechanisms and defines the databases" (Turnbull and Loukes, 1997). This initiative has five inter-related technical components, namely data access, geospatial framework, standards, partnerships, and supportive policy environment (Labonte *et al.*, 1998). Examples of Canadian SDI's are provided in Appendix 1.

Given the availability and access to data and information systems, best provided by an established SDI; decision support systems offer a good means for aiding water resources management in Barbados.

1.7 Decision Support Systems

Tackling decision problems concerning environmental and natural resource management has become increasingly complex due to the amount of conflicting, interwoven and spatially related objectives, and the variety of stakeholders involved. In dealing with environmental management, estimating the effects of a policy measure requires the identification of the causal links between the implementation of the measure, and its ultimate impact on human activities and the environment. (Fassio *et al.*, 2005)

Decision support systems (DSS) are computer technology solutions that can be used to support complex decision making and problem solving; for problems where at least some stage is semi-structured or unstructured. A computer system can be developed to deal with the structured portion of a DSS problem, but the judgment of the decision-maker is brought to bear on the unstructured part; hence constituting a human–machine, problem-solving system (Shim *et al.*, 2002; Sprague, 1980

There are five main specific types of DSS; these include: model-driven DSS, as well as communications-driven, data-driven, document driven and knowledge-driven DSS (Power and Shandra, 2007).

Model-driven DSS emphasize access to and manipulation of a quantitative model and therefore the model or models are the dominant component in the DSS architecture that provides the functionality for the DSS (Power, 2004; Power and Shandra, 2007). The manipulation of model parameters allows the user to examine the sensitivity of outputs or to conduct a more ad hoc "what if?" analysis. A model-driven DSS user interface provides capabilities for inputting values, for manipulating values and of equal importance, the user interface controls how the user views results and influences how the user understands results and hence influences choices (Power and Shandra, 2007).

Algebraic models are perhaps the most frequently used in building model-driven DSS applications (Bell P.C., O'Keefe, 1995).

Power and Shandra, (2007) have shown that DSS, and specifically model driven DSS have extensively used in very diverse applications in different fields. In summary DSSs have become a necessity when some of the following problems arise:

- Uncertain evaluation: lack of information, complexity of system,
- Number of criteria: conflicting objectives and interests,
- Heterogeneous solution possibilities,
- Trans-disciplinary and complex problem situation, which cannot be managed by single person or single group of persons,
- Fast decisions for complex problems.

Most of these problems exist in the case of land use change/management studies for water resource management and can thus be supported by implementation of decision-support system (Kolarits *et al.*, 2006). The diversity of objectives and the spatial ramifications of many forms of land use change place high demands on access to large volumes of land-related information, mechanisms for communicating that information, and facilities for representing differing priorities and values (Feick and Hall, 2000). Problems related to the protection of water quality in Barbados are directly related to many aspects of land use practises and land use changes (UNEP, 2001; Leitch & Harbor, 1999); therefore, the use of a model driven DSS offers an efficient tool for water resources management.

1.7.1 GIS for Environmental Management

Much research has shown that the cumulative impact of individually minor actions that take place across space or through time can have significant regional effects (Feick and Hall, 2000). When spatial heterogeneity of different regions is taken into consideration for the setting of standards and management prescriptions, spatially targeted measures increase the precision with which a policy achieves its goals (OECD, 2001) The ability of geographic information system (GIS) software to manage and prepare the geographic datasets needed for cumulative impact studies is well recognized (Coulson *et al.*, 1991, Parker 1988). GIS are now recognized widely as valuable tools for managing, analyzing, and displaying large volumes of diverse data pertinent to many local and regional planning activities. GIS can provide a coherent data management framework for integrating, manipulating, and visualizing the wide diversity of spatial and non-spatial datasets that are required to address multi-objective planning issues (Feick and Hall, 2000). Recently there has been an increased use of GIS in various aspects of environmental management data collection; specifically, the technology has been used in land-use assessment, coastal zone monitoring, soil erosion monitoring, and freshwater resources monitoring (UN ESA 2003).

However, commercial GIS have had limited success to date when applied to strategic-level planning issues that typically involve a number of individuals or groups of varying authority and viewpoints in the decision-making process (Couclelis 1991). GIS often lack the functionality needed to support the analysis of environmental problems because they cannot simulate dynamic spatial processes across space and through time (Burrough *et al.* 1988; Goodchild 1992,; Densham, 1991;, Bennett, 1997; Bennett & Vitale, 2001) as algebraic models are be able to. GIS tools may only facilitate assembling, display and visualization of model inputs, parameters and outputs that vary spatially (Roaza *et al.*, 1993). Because GIS, do not have the data representation flexibility for both space and time, neither the algorithmic capability to build process based models internally for complex conditions (Corwin and Wagenet, 1996), nor user interaction during a simulated event, simulation models and GIS need to be coupled (Chowdary *et al.*, 2005). To address this, spatial decision support systems (SDSS) are formed through the integration of spatial data handling tools (e.g., GIS software) with problem-specific analytical tools (models), (Densham 1991; Bennett & Vitale, 2001).

1.7.2 GIS and Model coupling to form SDSS for WRM

Coupling can range from loose to tight coupling. In a tight coupling, the data management is integrated into the system; a tight coupling provides a consistent user interface and data structure for both the GIS and model, and the information sharing between the respective components is transparent. In tightly coupled systems, GIS users have access to simulation models through software “hooks” or built in macro languages.

A loose coupling involves an un-automated data transfer from one system to another. The GIS is used to pre-process data that a simulation program can read or to make maps of input data or of model results for display and analysis. The majority of the applications found in the literature (Joao and Walsh, 1992; Chariat and Delleur, 1993; Roaza *et al.*, 1993) adopt the latter approach because it allows use of the existing physical models with little modifications to the software (Chowdary *et al.*, 2005).

The potential utility of SDSS software that integrates models of spatial processes with GIS technology is well recognized (Burrough *et al.* 1988, Goodchild 1992, Densham 1993). Such systems offer a virtual geography within which decision makers can explore the solution set (i.e., the set of competing management strategies or policies). However, a consensus does not exist on the best approach for the integration of spatial data handling tools and simulation software. Nyerges (1993) and Goodchild (1992) describe software integration strategies that range from loosely coupled to fully integrated systems.

A SDSS is not the same as a GIS, although both rely on GIS technology. SDSS offer a solution for a specific problem, whereas traditional GIS provide a highly evolved technical toolbox designed to work for multiple applications (Cooke, 1992; Crossland *et al.*, 2002).

A DSS efficiently coupled with suitable geographical data and models is ideally suited to answering questions arising from policy changes on water resources, by providing the understanding of the processes involved, evaluating the consequences and delivering advice (Fassio *et al.*, 2004). However, despite the growing popularity of spatial decision approaches, a comprehensive understanding of spatial conflicts in environmental decision problems is rare (Fassio *et al.*, 2004).

By combining the capabilities of geographical information systems, database technology, modeling techniques and optimization procedures, a DSS can contribute to the improvement of the quality of decision and policy making in the increasingly complex area of water resources management. Transparency about how decisions are reached is greatly facilitated through the use of a DSS, in which the effects of alternative policies can be explained and their impacts assessed (Fassio *et al.*, 2004). .

1.7.3 Recharge Dynamics and Pollutant transport

The calculation of a water balance as well as groundwater recharge dynamics within a given watershed or catchment unit are fundamental aspects in water resource management. Quantifying the variables necessary to characterize the water balance requires extensive areal coverage of "real time" data. Before, "real time" data with adequate spatial coverage was difficult and costly to obtain. However, with the availability of satellite imagery, monitoring equipment, information technologies for the collection and dissemination of data and the widespread use of Geographic Information Systems, a more comprehensive and reliable approach for calculating these is now possible (Hoag *et al.* 2001). "Due to the temporal and spatial nature of groundwater recharge, a multifaceted analysis approach which considers temporal and spatial variations is necessary to obtain accurate estimates of recharge" (Hoag *et al.* 2001, p16).

The importance of accounting for and understanding groundwater recharge dynamics lies in the relationship between land use practices and the movement of pollutants resulting from these as a consequence of overland flow and recharge processes. Therefore in a DSS for water resources management purposes it is essential to integrate the effects of land-use practices through an evaluation of effects with regard to their influence on the water system and its vulnerability. These effects can be differentiated between direct influences (e.g. contamination in bacteriological terms due to pasture) and indirect influences (increase of vulnerability due to soil changes/ vegetation changes as effect of tilling practices or urbanization). In a DSS for different land-use categories the effects on different levels can therefore be identified and weighed (high or/low) and their effects identified (local/regional, short/ medium/long-term). Furthermore, the effects of a certain and-use category can be demonstrated (Kolarits *et al.*, 2006).

1.8 Hydrologic Models and Karst Systems

Hydrologic models are the principal component in a Model Driven DSS which allow for the simulation and identification of effects inflicted by land use practices. Hydrologic models are important tools because they can be used to understand hydrologic (surface and subsurface) processes, develop and evaluate management practices, and evaluate the risks and benefits of land use over various periods of time and at varied spatial scales. Typically different models are used to focus on a specific aspect of hydrologic processes. In most cases models have been successfully applied across varied climates and hydrologic systems; however, in the case of Karst topography, the interactions between groundwater and surface water can be difficult to determine and model and therefore these interactions, unique to Karst terrains are not incorporated into the frequently used predictive models (Fogle, 1998, Spruill *et al.*, 2000).

Surface runoff models, which constitute the fundamental basis for hydrologic modeling, rely heavily on data such as land slope, slope shape, slope length, channel slope, and drainage area, which are derived from topographic maps. Part of the usefulness of watershed modeling is that many, if not all, of these data can be derived, when available, from topographic maps instead of collecting the data in the field (Fogle 1998).

1.8.1 Groundwater Flow Models

Groundwater basin simulation models solve a two or three-dimensional distributed parameter groundwater flow equation to obtain the groundwater heads over the region of study. Recharge, pumping, boundary conditions and aquifer parameters constitute the main input data for these models. Because all of these vary spatially over a large area, the models use a finite difference or finite element scheme to represent the variations and solve the flow equation using numerical techniques (Chowdary *et al.*, 2005). Most conventional groundwater flow models are based on the applicability of Darcy's law in porous media (Field, 1996). Stoertz and Bradbury (1989) and Krabbenhoft and Baanarz (1992) provide an extensive review of groundwater modeling methods and applications.

Recharge by percolation losses from fields can be estimated by soil water balance models (Howard and Lloyd, 1979; Rushton and Ward, 1979; Sarma *et al.*, 1980; Hajilal *et al.*, 1998; Arora and Gajri, 1996; Xevi *et al.*, 1996; Chowdary *et al.*, 2005). These models are also of two types: those based on simple book keeping procedures (Rao *et al.*, 1990) or those based on the physics of soil water flow (Feddes *et al.*, 1988). The former require data of soil water storage characteristics (field capacity and permanent wilting point) while the latter require data of both storage and transmission characteristics. However, recharge estimations in Karst topography through the use of frequently used surface and subsurface models based on Darcian flow are faced with the challenge posed by preferential flow through macropores, and the inability to readily locate subsurface conduits, which are characteristic of Karst systems (Field, 1996).

Examples of groundwater flow models include: MODFLOW (Harbaugh *et al. 2000*) and Hydrus 2D/3D (Simunek *et al.*).

1.8.2 Pollutant Transport Models

Solute transport model simulations provide information on the spatial and temporal distributions of contaminants in subsurface media (Field, 1996). These models are commonly used to estimate soil, nutrient, and pesticide movement via surface runoff, and their infiltration into the ground before and after best management practice (BMP) implementation. However, the interactions between surface water and groundwater that are unique to Karst terrains, where conduit flow is important, are not incorporated into the frequently used predictive models since their application to Karst aquifers is difficult (Fogle 1998).

Generally, once a pollutant enters the groundwater system, its transport in groundwater can be by advection, dispersion, adsorption, decay or by chemical reaction or a mixture of these. Pollutant transport models require prior development of a calibrated groundwater flow model (Chowdary *et al.*, 2005). The incorporation of the transport mechanisms into groundwater model formulations is described in detail by Bredehoeft and Pinder (1973) and Bear (1979). While some groundwater transport models are used to simulate movement of point-source pollution only (Little *et al.*, 1996; Younger *et al.*, 1993), some of the mass transport problems for non-point sources consider one transport mechanism only (i.e. dispersion) (Guymon, 1970; Guymon *et al.*, 1970). Just and Antle (1990) developed a conceptual integral framework to assess potential impacts of agricultural practices on groundwater quality. However, this framework was not validated with field data. In the majority of groundwater contamination research has concentrated on detailed studies of agricultural fields of small watersheds only, and generally validation of models have been done by idealized laboratory experiments and a few field experiments at relatively homogeneous sites (Fedler *et al.*, 1989; Gaily *et al.*, 1991; Teresa and Christine, 1993; Robert *et al.*, 1993; Vassilis, 1993).

Richter *et al.* (1993) and Addiscott and Wagenet (1995) provide a good overview of the various individual models for simulating nitrogen behaviour in soils. Ling and Aly (1998) developed a lumped parameter model for the assessment of nitrate leaching. Hutson and Wagenet (1991) developed the LEACHM model, which numerically solves the Richard's equation for water flow and the convection–dispersion equation for nitrate transport in a vertical layered soil profile. However, most of these models often require extensive and detailed data for inputs, making them inconvenient and expensive for use over large areas (Chowdary *et al.*, 2005). A clear dilemma thus exists between data availability, scale of application and accuracy of the transport model used which affects the practical application of models for the purposes of water resource management. This dilemma is further complicated by the inadequacy of most models for applications in Karst topography.

1.8.3 Modeling Karst Systems

Conventional groundwater models, dependent on the applicability of Darcy's law, are inappropriate when applied to Karst aquifers because of the non-applicability of Darcian-flow parameters, the typically non-linear flow regime, and the inability to locate the Karst conduits through which most flow and contaminant transport occurs (Field 1996). Field (1996) suggests that surface-water flow and solute-transport models conditioned on a set of parameters determined empirically from quantitative ground-water tracing studies may be effectively used to render fate-and-transport values of contaminants in Karst conduits.

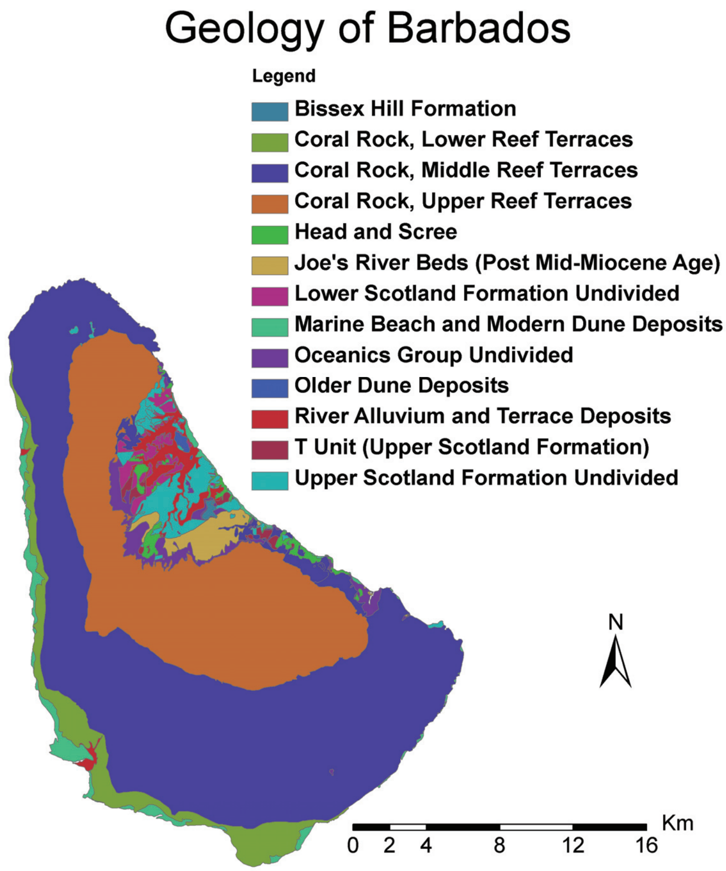
In general contaminated Karst aquifers are rarely treated differently from porous-media aquifers except in rare instances when qualitative dye-tracing studies are available. Qualitative dye traces do not provide correct or adequate information necessary for determining solute-migration rates and downgradient concentrations. Analytical and numerical ground-water models based on the applicability of Darcy's law are still routinely employed as a means for assessing solute-migration rates and for determining downgradient concentrations. Such models generally form the basis for most site risk assessments in Karst terrains despite considerable evidence to refute their reliability (Field, 1996).

Chapter 2: Barbados' Water Resources: Physical Background

This chapter provides an in depth introduction to the physical background of the island of Barbados. The physical relationships and dynamics here described are the main drivers of the "water system" and a solid knowledge and understanding of them is therefore of high importance in the context of water quality protection and management.

In particular this chapter focuses on: the formation of the island and how that has shaped *biophysical makeup of the island* such as its Geology (Figure 2.1) which characterizes this island as a Karstic system. *Dissolution channels and fissures* are discussed as important elements of *Karst topography* which dominates the island and is central to *Unconfined Pleistocene limestone Aquifer* which is the islands main water reserve. *Recharge dynamics* and their vital role affecting water quality are then presented, putting focus on how *precipitation, evaporation and evapotranspiration* come into play in the water cycle and recharge process, which mainly occurs by the infiltration of *surface runoff* into the aquifer. The discussion lastly turns to *water quality of the resource in Barbados*; how it is affected and how it may be managed from a physical dynamics point of view.

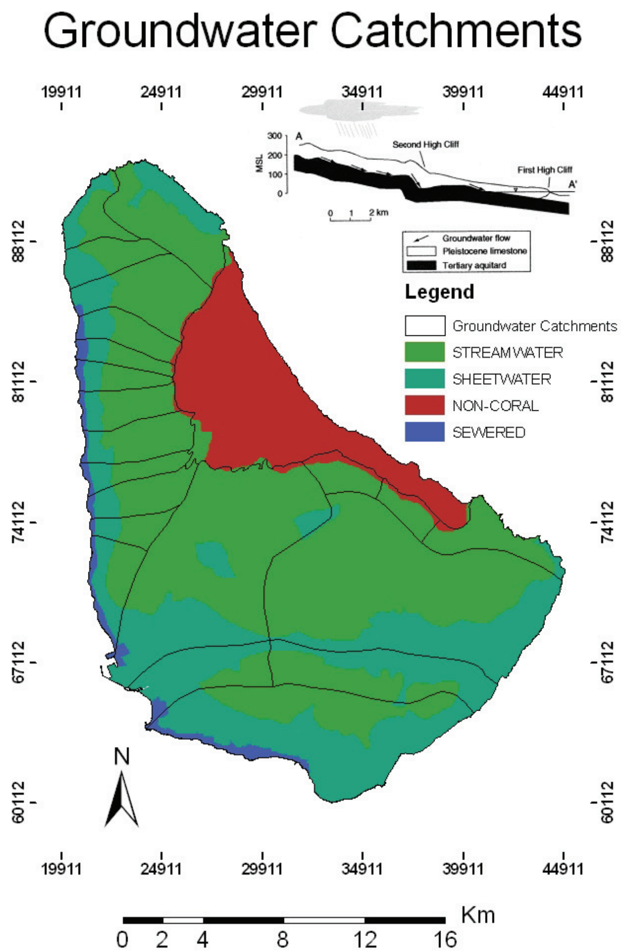
Figure 2.1 Geology of Barbados (Created from NRDB data)



2.1 The Biophysical Makeup of Barbados

The island of Barbados is predominantly composed of Pleistocene-age coral reef limestones (that crop out over 87% of the island and act as the aquifer) underlain by Tertiary-age (Cretaceous) deep-sea sedimentary rocks (basal oceanic deposits which typically consist of low permeability clays, shales and marls) that act as an aquitard. In Barbados there are two main types of coral limestone. The first, formed in deep water offshore, is a massive bedded limestone constructed of small organisms called Amphineria forming Arnphestegina limestone. The second, known as coralline, formed near shore in shallow water and is constructed of larger organisms. This type of coral contains many vugs and cavities. Total porosity varies between 20 and 50 percent in this coralline limestone (Klohn Crippen Consultants, 1997c). Over a period of 650,000 years (Bender *et al.*, 1979), due to intermittent uplift, the reef limestone was deposited outward from the center of the island forming a series of terraces that decrease in age with decreasing elevation. Coupled with changes in mean sea level, the successive coral reefs formed between each period of uplift. These three prominent limestone terraces (Lower Coral Reef terrace, Middle Coral Reef terrace, and Upper Coral Reef terrace) are the primary features of the limestone cap that forms the island and are separated by the First and Second High Cliffs, respectively (Figure 2.2) (Senn, 1946; Jones *et al.*, 2000; Jones and Banner, 2003; Mayers *et al.*, 2005; Stanley, 1998). The terrace above the Second [~30m] High Cliff is highly karstified, and occurs at an elevation of approximately 100 m (Jones and Banner, 2003).

Figure 2.2 Groundwater Catchments of Barbados Adopted from Jones *et al.*, 2000 (Created from NRDB and BWA data)



Sewered areas refer to those areas that a drained directly out to sea by drainage infrastructure, therefore not accounted as "recharge" areas.

The hydrogeolgy of the island is dominated by the local topography (Stanley, 1998). The combination of the highest rainfall areas on the island existing in the upper reaches of the water catchments, the erodable nature of the coral limestone and significant topographic relief have resulted in a well-developed drainage system. The topography of the West Coast of the island is characterized by the presence of numerous steep-sided gullies cut into the coral rock by earlier stream flows. In the upper portions of water catchments, gullies are typically connected to extensive solution channels and fissures in the coral rock resulting in significant recharge to the coral aquifer via the gully systems during major rainfall events. In the lower reaches, the gully floors are typically lined with clay (Tullstrom, 1964; Stanley, 1998)

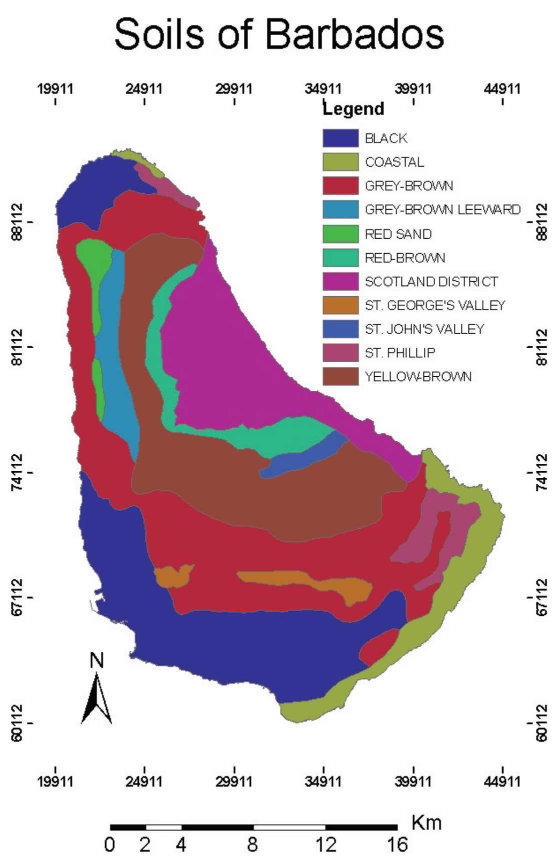
2.2 Dissolution Channels and Fissures; Karst Topography

Freshwater is unsaturated with respect to limestone and thus has a potential to dissolve a portion of it, whereas sea water is saturated with respect to limestone and has little capacity to dissolve it (Klohn Crippen Consultants, 1997c; Stanley, 1998); these dynamics in conjunction with the local topography play a key role in defining the hydrogeology of Barbados. The surface hydrology of Barbados is influenced by secondary porosity produced within the underlying coral. Secondary porosity refers to the enlargement of pores already present in the coral at the time of deposition by means of dissolution (Vernon and Carroll, 1965). Cracks and fissures, enlarged by dissolution, often create funnel-shaped depressions known as sinkholes, which locally cause very high water penetration rates into groundwater (Vernon and Carroll, 1965). As a result of dissolution of the limestone, significant cave systems have also developed on the island, best illustrated by Harrisons Cave and Bowmanston Cave. Dissolution can form other types of limestone structures other than major cave systems. Some parts of the limestone exhibit a very porous structure as a result of dissolution, forming extensive water conduit systems and channels. These solution (Karstic) features are characteristic of Karst topographies, and an important aspect of the groundwater flow system in Barbados (Klohn Crippen Consultants, 1997c).

On the other hand, some limestones exhibit extensive cementation which has rendered the limestone nearly impermeable (Klohn Crippen Consultants, 1997c). Zones of lower permeability may also be present within the coral. For example, in general, the Amphestegina limestone is expected to be less permeable and possibly even less susceptible to secondary solution cavity development than the coralline (Klohn Crippen Consultants, 1997c).

The soil associations overlying the coral limestone, though variable due to their composition and depth, are generally moderately-well to well drained, exhibit a moderate to moderately rapid level of permeability, and are thereby classified as hydrologic soil group "B" (Vernon and Carroll, 1965). The distribution of soils in Barbados is illustrated by figure 2.3.

Figure 2.3 Soils of Barbados (Created from NRDB data)



2.3 The Unconfined Pleistocene limestone Aquifer

Groundwater occurrence, of importance for water use, occurs within the coral. The oceanic sedimentary base-rocks, for practical purposes, provide an impermeable lower boundary to the coral (an aquitard); a contour plan of the contact between the top of these rocks and the base of the coral (Klohn Crippen Consultants, 1997c). A map showing the base of coral contours is presented in Klohn Crippen Consultants, 1997c as Figure 2.1 which would be reproduced in low quality if included in this thesis (it was not possible to acquire this map as it only exists in large format at the BWA). The coral itself is referred to as the aquifer. Groundwater-flow within the coral may be transmitted through primary and secondary porosity. Primary porosity is the result of openings left within the coral during deposition and is expected to be greater in the reef coralline limestone than the Amphestegina Limestone (Klohn Crippen Consultants, 1997c). Secondary porosity (discussed earlier) however, provides the dominant pathways for groundwater movement. Secondary features are more likely at, and above, the water table (Klohn Crippen Consultants, 1997c). In addition Groundwater flow patterns in the aquifer are controlled by the distribution of rainfall recharge in the central parts of the island (discussed below). The most productive aquifers are typically found in the upper limestone unit, or within the cave systems (Stanley, 1998).

2.3.1 Streamwater and Sheetwater Groundwater Zones

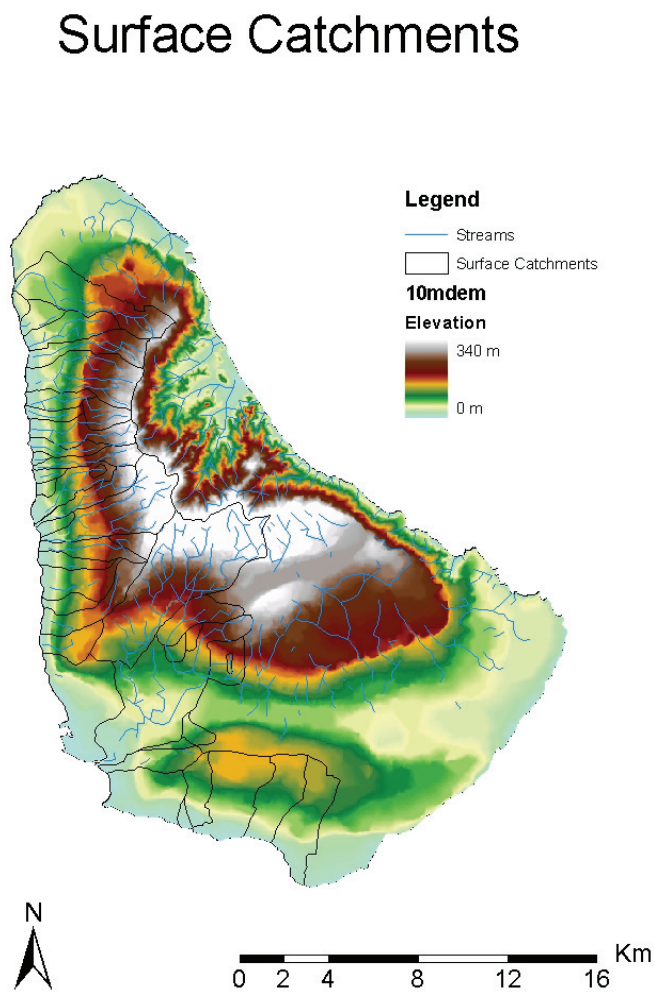
Recharge to the aquifer occurs by diffuse and discrete infiltration to the water table that occurs close to the base of the Pleistocene limestone (Base of Coral). Groundwater generally flows from the elevated central portion of the island outward toward the coast perpendicular to the contours of the top of the aquitard. The aquifer is divided into two hydrogeologic zones (Fig 2.2): 1. *The streamwater zone*, which is the upland portion of the aquifer characterized by diffuse infiltration and conduit discrete flow of precipitation originating in the highlands which flow seaward at the base of the limestone. 2. *The sheetwater zone*, which refers to the freshwater lens that occurs within the coastal strip area, where groundwater flowing seaward forms a freshwater lens on top of the saltwater wedge due to differential density effects. Here groundwater flows through both primary and secondary features towards the sea or abstraction wells. The transition point between the streamwater and sheetwater zones is defined by the intersection of the water table of the sheetwater zone and the impermeable oceanic sediments. Within the uplands area (streamwater zone), the coral is mostly unsaturated, with flow occurring in discrete solution channels and fissures. In the sheetwater areas, the groundwater is composed of both a freshwater zone and a salt water zone; the less dense freshwater "floats" over the salt water with an interface between the two (Stanley, 1998; Klohn Crippen Consultants, 1997e; Jones *et al.*, 2000).

The water table in the sheetwater zone is close to sea level due to the high permeability of the limestone, with only a very slight gradient to the sea (Stanley, 1998). Steinen *et al.*, (1978) reported that saline concentrations in the aquifer varied seasonally in response to recharge, however, the elevation of the water-table remained more or less static, indicating that the aquifer is very permeable (Mayers *et al.*, 2005).

2.3.2 Groundwater "catchments"

Groundwater catchment boundaries (Figure 2.2) typically run roughly east/ west, in general conformity with the surface topography. Catchment boundaries have been defined on the basis of the base of coral contours, determined from historical borehole data. The catchment boundaries are defined primarily on the basis of minor ridge lines running roughly east-west at the base of coral, which are expected to control subsurface flow within the streamwater areas, at least with respect to the component flowing along the base of coral contact, as lateral flows are expected above. However, within the sheetwater zones, the catchment boundaries are less defined, as the freshwater lens exists in the form of a reservoir overlying the salt water wedge, with no obvious lateral partitioning (Stanley, 1998). Mayers *et al.* (2005) indicate an apparent confining/semi-confining layer in the sheetwater zone which may influence lateral groundwater flow at depth. Surface-flow watersheds (Figure 2.4) are not commonly used for water resource management in Barbados; instead the groundwater catchments are usually the units of consideration (Dr. Ifil and Mwansa personal communication, 2005)

Figure 2.4 Surface Catchments, Streams and Topography

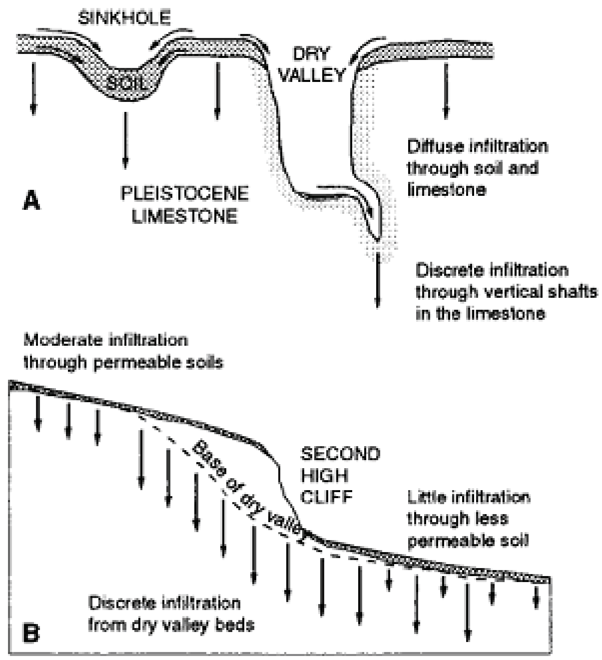


2.4 Recharge dynamics

Groundwater recharge to the island consists of three components: natural recharge from precipitation, artificial recharge from irrigation and wastewater disposal, and potable water distribution system water losses (Klohn Crippen Consultants, 1997c). Natural recharge to the aquifer primarily occurs during rainfall events that are sufficiently significant to generate surface runoff (Jones and Banner, 2003). During these rainfall events, ephemeral streams (Figure 2.4) that occur may flow into karstic features and recharge the aquifer (Mayers *et al.*, 2005). Work conducted by Tullstrom (1964) on soil infiltration rates and runoff and their relationship to rainfall intensity indicated that virtually no runoff occurred at rainfall/irrigation loading rates of less than 2cm/hr. It is therefore reasonable to use 2 cm/hr as an indicator of when recharge will occur through Karstic drainage features (Stanley, 1998; Klohn Crippen Consultants, 1997c; Jones *et al.*, 2000; Jones and Banner 2003). It has been further determined that significant runoff and groundwater recharge only occurs as a result of this intense precipitation with a duration of at least an hour (Klohn Crippen Consultants, 1997d).

Infiltration is "completely dependent on the existence of root channels, deep fissures or cracks and openings" in the coral limestone, and "there are vast areas, most of which are at low altitudes where the soil permits little water to pass into the coral rock below" (Tullstrom 1964, p.43). Pleistocene limestone is frequently exposed at the surface in dry valleys, especially where these valleys cut through the Second High Cliff forming deep, narrow channels, or gullies. Small caves or karstic shafts (known as sinkholes) that frequently occur along the sides of these gullies act as vertical conduits for water to infiltrate directly into the limestone and rapidly recharge the aquifer (Figure 2.5) (Jones *et al.*, 2000).

Figure 2.5 Groundwater recharge pathways; from Jones *et al.* (2000) p8



Schematic diagrams showing different pathways by which infiltrating water recharges the limestone aquifer of Barbados: (a) oriented perpendicular and (b) parallel to a hypothetical dry valleys

The coral cap is typically overlain by a thin veneer of clayey soil, typically ranging between 0.5m and 1m in total thickness, which impedes the percolation of rainfall into the underlying coral rock, due to its low permeability. Recharge to the coral via soil diffuse infiltration is also diminished as a result of the soil moisture losses within the soil profile due to evaporation and evapotranspiration. Therefore, the major source of groundwater recharge is associated with discrete infiltration of runoff into suck wells, soakaways (used for sewage disposal) sinkholes and solution channels. Most runoff events are confined almost exclusively to the wet season where rapid diffuse infiltration is also higher as moist soils have the greatest capacity to transmit water (Stanley, 1998; Jones *et al.*, 2000). Furthermore, variations in soil permeability with elevation play different roles in recharge. The soils that occur above the Second High Cliff have infiltration rates of approximately 250mm/h (Tullstrom, 1964). Below the Second High Cliff, at elevations less than 100m, infiltration rates through the soils range from 12.5mm/h to 250mm/h, but typically, they are approximately 50 mm/h

(Tullstrom, 1964). In comparison, the Pleistocene limestone has measured infiltration rates of 700–70,000mm/h (Tullstrom, 1964; Smart and Ketterling, 1997). Using these values, recharge to the aquifer is estimated at 15–20% of average annual rainfall above the Second High Cliff, increasing to 25–30% at lower elevations in response to discrete infiltration of large volumes of water through the highly permeable limestone (Jones *et al.*, 2000, Jones and Banner, 2003).

It is important to summarize that recharge to the aquifer in Barbados:

- is rapid, taking place through cracks and fissures, channels, suck wells and sinkholes by discrete infiltration mainly occurring in dry valleys and gullies, with some diffuse, variant infiltration through the soil layer.
- Takes place only during the 1-3 wettest months of the year (the wet season), when precipitation occurs at 200mm/hr for a duration of one hour.
- Is higher by discrete infiltration through Karstic features occurring above the Second High Cliff, and higher by diffuse infiltration occurring through soils below the Second High Cliff.

2.4.1 Residence Times

Infiltration tests and field observations in Barbados indicate that water residence-time in the vadose zone ranges from several minutes to a few days for water infiltrating through sinkholes or drainage wells (Mwansa and Barker, 1996; Smart and Ketterling, 1997). Residence times associated with diffuse infiltration are believed to be much longer, ranging from days to several months (Senn, 1946).

2.4.2 Recharge Estimates

Recharge estimates have previously been made by (1) direct measurement methods using water balance based on potential evapotranspiration (PET) or groundwater discharge; (2) indirect measurements based on dissolved constituents in both groundwater and rainwater; and (3) groundwater modeling (Jones *et al.*, 2000; Jones and Banner, 2003).

The most presently adopted, recharge estimates are presented in Table 2.1 (estimated by a combination of methods 2 and 3 above):

Table 2.1 Recharge estimates for Barbados (Klohn Crippen Consultants, 1997c)

	Natural Recharge (million m^3/yr)	**Recharge from Wastewater (million m^3/yr)**	**From Distribution Network Losses (million m^3/yr)**
Average Year	59.0	18.3	31.8*

*Based on 60% losses in the distribution system. (Klohn Crippen Consultants, 1997c)

The various components of aquifer recharge are not evenly distributed throughout the coral rock watersheds, with the natural recharge component weighted more heavily to the uplands streamwater area, and the water loss and wastewater recharge components weighted more heavily to the more densely developed coastal strip (sheetwater) areas (Stanley, 1998).

Water-balance recharge estimates based on coastal discharge data from Proctor and Redfern International Ltd. (1983) and Lewis (1987) and water-balance calculations by Stanley Associates Engineering Ltd. (1978) and Delcan (1995) for the same groundwater catchments vary dramatically in some cases (Table 2.2). On the west coast of Barbados, water-balance recharge estimates lie within the range 6–25% of average annual rainfall, with an average of 14%. Recharge estimates based on chloride concentrations and dissolved oxygen isotopes in Barbados vary from 1% to 20% of annual rainfall and increase with elevation (Jones *et al.*, 2000, Jones and Banner, 2003).

Reduction of recharge or increases in well yield will reduce the volume of water in storage, which will cause a small decrease in the water table and a much more significant decrease in the freshwater lens thickness (Klohn Crippen Consultants, 1997c). Most importantly, recharge dynamics play a key role affecting water quality (discussed below) of the Plestiocene aquifer in Barbados.

Table 2.2 From Jones et al., 2000 p1294 Results of different water balance calculations for Barbaods

Catchment	Potential Recharge Estimate FAO Data*	*Lewis* [1987] Data†	*Proctor and Redfern International Ltd.* [1983] Data‡	*Stanley Associates Engineering Ltd.* [1978] (Dry Year)§	*Stanley Associates Engineering Ltd.* [1978] (Average Year)§	*DELCAN* [1995]‖
Carlton	6	14.1	15.4	10.0	16.1	20.5
Haymans	6	5.7	6.3	8.6	17.4	19.2
The Whim	6	12.3	25.0	9.7	18.3	20.4
Ashton Hall	6	7.6	15.0	12.1	16.5	20.1
Alleynedale	6	6.6	13.1	12.4	14.1	16.9
Bourbon	6	12.6	16.2	9.3	13.0	15.0
Entire west coast	6	9.3	14.5	10.8	15.2	18.1
St. Philip North	6	···	···	5.8	15.1	···

Values are expressed as percent of annual rainfall in the respective catchments. Catchments are shown on Figure 2.
*Estimates are based on mean monthly potential evapotranspiration and rainfall data for Barbados from the *Food and Agriculture Organization* [1985].
†Water-balance calculations are based on measured coastal discharge rates from *Lewis* [1987].
‡Water-balance calculations are based on measured coastal discharge rates from *Proctor and Redfern International Ltd*. [1983].
§Water-balance calculations are given by *Stanley Associates Engineering Ltd*. [1978]. In dry and average years it is assumed that Barbados receives average annual rainfall of 1000 mm/yr and 1500 mm/yr, respectively.
‖Water-balance calculations are given by *DELCAN* [1995].

Precipitation

Precipitation on the island is either consumed by evapotranspiration, infiltrated to the groundwater system, or runoff as streamflow (surface water) to the sea. A significant portion of the water which may otherwise report to the sea infiltrates to the groundwater regime in Barbados via suck wells and sink holes under special circumstances as discussed above (Klohn Crippen Consultants, 1997c).

The long-term average annual precipitation value from the start of recordkeeping in 1847 up to 1965 is 1514 mm/yr, which has generally rounded off to an annual average precipitation value of 1524 mm/yr. and has been widely quoted in the existing Barbados water resources literature (Klohn Crippen Consultants, 1997c; Stanley, 1998). However, based on weighting the data towards current climatic conditions, Klohn Krippen Consultants (Klohn Crippen Consultants, 1997c) have selected a design annual average precipitation value of 1,422 mm/yr. This represents a decrease of roughly 102mm, or approximately 6% of the previously estimated annual average (Klohn Crippen Consultants, 1997c). The value for drought design is 1,066 mm; this represents approximately 25% reduction in annual precipitation levels from the average precipitation year (Stanley, 1998).

Relative humidity in Barbados is high throughout the year, with maximum humidity values of 82 to 84% occurring during the wet season and minimum humidity values of 68 to 70% occurring in the dry season (Stanley, 1998).

Precipitation levels vary significantly both spatially and seasonally over the island. The island has two distinct seasons, a wet season, running from June to December where approximately 75% of precipitation occurs and a dry season from January to May during which the remaining 25% of rainfall occurs (Stanley, 1998; Jones and Banner 2003). Rainfall intensities also increase during the wet season, with intensities of 2cm/hr or greater only observed during the wet season. Based on available hourly precipitation data, four of these major rainfall events occur during a drought year and five during an average year (Stanley, 1998). Rainfall intensities increase with elevation on the island (Cumming and Cockburn, 1996). Rainfall patterns are highly variable year to year as well.

Evaporation & Evapotranspiration

In order to estimate natural groundwater recharge to the coral aquifer, estimation of evaporation and evapotranspiration losses is essential to determine the average long-term precipitation distribution for the island (Klohn Crippen Consultants, 1997c).

Calculations made during the course of the water resources and water loss studies (Klohn Crippen Consultants, 1997e) concluded that evaporation accounts for more than 80% of the precipitation lost from the ground over the aquifer in Barbados. This includes direct evaporation of free water from the ground surface, evapotranspiration, and secondary evaporation of water (water temporarily stored in soil pore spaces following precipitation (Klohn Crippen Consultants, 1997d). Annual actual evapotranspiration ranges between approximately 1,120 mm along the eastern and southern coastal lowlands to a maximum of approximately 1,400 mm along the central western coastal strip (Rouse, 1966).

2.5 Surface Runoff

The estimation of runoff plays an essential role in the evaluation of the movement of pollutants and their potential infiltration into the aquifer (Cumming and Cockburn, 1996). Historical measurements of surface runoff on the island have been attempted by a number of previous investigators, including Stanley (1978), Delcan (1995) and Cumming and Cockburn (1996). However, historical records of runoff are very limited, with little reliable data available. Prior to the 1978 Water Resources Study (Stanley, 1978), the only available data on runoff pertained to major flood events (Klohn Crippen Consultants, 1997d; Stanley, 1998).

As mentioned previously, surface water runoff on the island is essentially limited to the wet season months, and is observed during major rainfall events (Stanley, 1998). Similarly runoff from tilled agricultural fields reportedly only occurs when water is applied at rates greater than 2 cm/hr (Stanley, 1998b).

The Cumming and Cockburn study (1996) concluded that the ratio of annual runoff to annual precipitation for the island varied between 1 to 3%. On the other hand, Delcan (1995) concluded that, overall, runoff in the western and south-western catchment areas represented approximately 3% of total annual precipitation. Klohn and Krippen (Klohn Crippen Consultants, 1997c) have recommended Delcan's (1995) data to be the best available.

Despite the inconsistencies of historical runoff calculations, variance exists in runoff values associated with different catchments. The Delcan runoff estimate for the Holetown catchment was 7% of annual precipitation; which is relatively high (Klohn Crippen Consultants, 1997c). The high runoff potential for this catchment is due to the ·fact that the upper reaches of the catchment are underlain by relatively impermeable oceanic deposits and that it lies within one of the highest precipitation zones on the island. As such, the Holetown catchment is considered atypical of the other catchments but represents an upper boundary for runoff rates on the island, apart from the urban Bridgetown catchment (Klohn Crippen Consultants, 1997c).

The Stanley study (1978) concluded that runoff from the island to the sea was minimal, with an assumed average runoff estimate for the island of 6.35mm, or 0.4% of the estimated average annual precipitation value of 1,524 mm (Stanley, 1998).

2.6 Water Quality of the Resources in Barbados

Water quality of the groundwater and coastal waters in and around Barbados is influenced significantly by the urban, commercial, industrial, recreational and agricultural activities which are developed on the island, and is further influenced by the characteristics of the coral limestone formation through which it flows and in which it is contained (as it has been already described). Recharge (described earlier) and contaminant-loading to the aquifer occur via infiltration of: rainfall, irrigation water and waste water discharges applied to the land surface or discharged via "suck wells" to the aquifer. As previously discussed, aquifer recharge is relatively rapid due to the secondary permeability of the coral rock and the poorly developed soil veneer (Klohn Crippen Consultants, 1997b). Potential and existing impacts on groundwater quality arise from two general categories often referred to as diffuse and point source pollution. Point sources are those which can readily be identified at point of origin. Diffuse pollution sources of concern are agricultural practices through the widespread application of agricultural chemicals including pesticides and fertilizers; and sewage disposal (Willms & Shier *et al.*, 1998d). The coral aquifer is currently the recipient of all the wastewater (domestic, commercial and industrial generated in the country with the exception of Bridgetown and the South Coast (covered by a sewage system and ocean outfall), and the Scotland District (surface drainage) (Klohn Crippen Consultants, 1997a). In Barbados, wastewater treatment facilities only treat approximately 10% of wastewater generated (Bridgetown Water Treatment Facility, 2005). Wastewater percolates downward through the top soil and unsaturated coral to the groundwater table where it recharges the aquifer. In Barbados, sanitary waste disposal represents a source of diffuse pollution, as in most of the island (with the exception of Bridgetown and the South Coast, which have a sewage system in place); sewage is disposed of directly into the limestone rock by means of "soak away pits" or suckwells (Klohn Crippen Consultants, 1997a). Because of the high permeability of the coral formation, mobile pollutants such as nitrates and bacterial species derived from unsewered sanitary disposal are readily transported to the water table and through the coral aquifer to the nearshore waters (Willms & Shier *et al.*, 1998d, 1998b; Klohn-Crippen Consultants, 1997a; Lewis, 1987).

In the agricultural sector, the application of a wide range of pesticides and herbicides is common practice throughout Barbados (Klohn-Crippen Consultants, 1997b, Dr. Ifil personal communication, 2005). Application rates are not precisely known, and cannot easily be regulated and no controls exist to manage individual users. Most of these compounds are toxic and/or carcinogenic to humans at very low concentrations in water. The fate of most of the compounds applied has not been researched in Barbados. (Dr. Ifil personal communication 2005; Dr. Seally personal communication 2005; Klohn-Crippen Consultants, 1997b) However, based on island-wide water quality monitoring programme results, it is known that agricultural chemicals are impacting the groundwater quality (Mwansa and Brewster, 2001; Klohn Crippen Consultants, 1997e). Furthermore, the risks associated with the leaching of agricultural chemicals have increased on the island as a function of soil erosion problems; as consequence of erosion of the thin layer of soil cover, there is a reduction in the pollution attenuation capacity of watersheds, with potential negative impact on groundwater quality (Mwansa and Brewster, 2001).

Nitrogenous fertilizers applied to cropped fields reach the groundwater as nitrates dissolved in the water percolating out of the crop root zone from excess rainfall or from irrigation. Human and animal wastes also contain significant quantities of Nitrogen as organic nitrogen which rapidly degrades to ammonia through the action of heterotrophic bacteria, and subsequently to nitrate through the activity of autotrophic bacteria in the soils and substrata. Nitrate may also be generated from natural soil nitrogen reserves by aeration of soils during ploughing. The concentration of nitrate in the percolated water from agricultural fields depends on the amount of fertilizer and water from irrigation or runoff. Its concentration in the groundwater depends on additional recharge from other sources (e.g. seepage, groundwater flow and solute transport within the aquifer). Nitrate is highly mobile in groundwater and once it reaches the saturated zone there is little adsorption or further bacterial uptake (Chowdary *et al.*, 2005; Klohn-Crippen Consultants, 1997b). Nitrates are considered to be a key factor responsible for the deterioration of the coral reef structure found along the west and south coasts of Barbados (Stanley, 1998)

The impact of bacteriological contamination derived from sewage disposal practices is of increasing concern, especially in the realm of its effects on nearshore water quality and coral reef health. Results of sampling conducted for the West Coast Sewage project (Stanley, 1998) show that 80% of the West Coast beaches sampled for that study should have been posted “closed for swimming” for the duration of the sampling period because of non compliance with national bacteriological bathing beach water quality standards. If this type of sampling were extended throughout the island for a complete year there is a possibility that all of the beaches could fail at least once (Willms & Shier *et al.*, 1998d). Publicity resulting from a beach closure resulting from bacteriological contamination would, no doubt, have a serious effect on tourism and the economy of Barbados since tourism is deemed by the Barbados government to be the number one economic generator (Willms & Shier *et al.*, 1998d).

Other major concerns for groundwater quality, mainly derived by possible pollutant infiltration in Barbados include: (Willms & Shier *et al.*, 1998d)

- Petroleum hydrocarbon extraction. Hazardous materials and waste contamination-potential, during transport, storage and use, pose substantial risks to groundwater.
- Aircraft toilet waste disposal in suckwells near the airport. This waste contains complex ammonia and in some instances formaldehyde.
- Poorly or inadequately constructed containment areas at gas stations and other underground storage tanks.
- Observed disposal of fuel and chemical containers in gullies, drainage suckwells and at waste disposal sites not designed for hazardous materials
- Illicit dumps and garbage piles, and
- Leachate infiltration from Landfill sites into the groundwater aquifer.

Concerns over the above identified potential pollutants include the lack of a detailed inventory of activities related to them, as well as information on their storage, handling and disposal. Especially in activities involving the of use of chemicals, a detailed understanding on the types of materials stored, by whom these are stored, and their location of use and storage are needed. Hazardous chemicals’ handling, use and disposal, including 'expired' chemicals are presently not accurately known. (Willms & Shier *et al.*, 1998d)

2.6.1 Chemical pollution control and remediation

Chemical contaminants such as nitrates, pesticides and petroleum hydrocarbons are amenable to specialized forms of treatment but these are generally expensive and complex to implement. Control of chemical contaminant-risks by water treatment is usually not a favourable option (Klohn-Crippen Consultants, 1997a).

Source control may take the form of reducing the probability of contaminants entering the ground by appropriate contaminant handling, by regulations, and/or by limiting the presence of contaminants within a given distance of a water source (well or spring), allowing for natural remediation to attenuate the concentration of contaminants reaching the well (Klohn-Crippen Consultants, 1997a). Water quality protection is usually provided by a nominal "time of travel" (Bear and Jacobs, 1965) from contaminant source to drinking water abstraction point. The greatest single technical difficulty in implementing this approach, specially in Barbados due to its physical makeup, is the translation of "time of travel" criteria into physical zone boundaries for different constituents, which govern permitted pollutant loadings for a given time of travel for a given constituent or pollutant (Klohn-Crippen Consultants, 1997a, Field 1996).

In Barbados regulations for chemical contaminants are less clear than those for biological contaminants, which are mainly regulated by a zoning policy based on bacteriological time of travel (discussed in Chapter 3). In the areas of chemical protection from: agricultural practices, chemical sewage contaminants (nitrates), petrochemical industry practices, industrial facilities, urban development and waste disposal; apart from specific references to petrol and fuel storage regulations, much is left to the discretion of the Minister of Environment, and there exists no clear mechanism to implement actions or to evaluate, regulate or attenuate discharged chemical pollutants or their amounts (Klohn-Crippen Consultants, 1997a).

2.7 Conclusion

In the context concerned with water quality protection and management decision making, it is essential to have a solid understanding of the functioning of the physical system being dealt with. Furthermore in the context of a Decision Support System to aid in these purposes the comprehension of physical dynamics is also paramount as the models that mainly drive the DSS are based on the simulation of the physical dynamics here presented. Although this chapter is largely descriptive it provides an essential pillar for unveiling the potential of a spatial DSS for water quality protection and management (Chapter 6). At the same time, an understanding of physical mechanisms and their dynamics serves to better highlight the essential need to supply the DSS with good and accurate data (Discussed in Chapters 4 and 5).

Chapter 3: Institutional Background

This chapter provides quick summary of *water consumption in Barbados* while placing more focus on an overview of the *institutional dimension of water resource management and use in Barbados*, where the key institutions are presented and their roles described. The *policy and legal mechanisms in place for water resource management* are then presented in the context of how they are implemented, by whom, and what they generally consist of and how they relate to water quality protection and management. With these foundations, the discussion turns to *criticisms and recommendations previously made in regards to water resource management*. *Recommendations* have mainly entailed policy and practical/structural implementations, which are presented in light of enhancing water quality protection and management. The chapter ends by putting this imminent institutional dimension into the context of how it may interact with and be aided by a decision support system in order to explore the physical dimension (previously discussed) to achieve enhanced water quality protection and management. In a preliminary assessment of the institutional dimension particular attention is drawn to the necessary institutional arrangements and frameworks which may efficiently facilitate such interactions, explorations and followed actions by the aid of a DSS.

3.1 Water Consumption

As a result of the topography and mode of occurrence of the groundwater, approximately 90% of the public water supply is from wells located in the freshwater lens “sheetwater zone”; 64% of the private wells are located in this same area. Present public water supply amounts to 142,747.23m^3/day (31.4 MGD) from groundwater wells, 2,727.65m^3/day (0.6 MGD) from two spring sources and 13,638.27 to 18,184.36 m^3/day (3 to 4 MGD) from a brackish water Reverse Osmosis Desalination Plant (Mwansa & Brewster, 2001). However, groundwater officially pumped for use in agriculture, as well as private and clandestine well abstractions are not accounted for in these figures. In addition, many farmers use water from the public supply system to irrigate their crops (Klohn Crippen Consultants, 1997e).

Current agricultural irrigation water allocation amounts to 16,200,000 m^3 per year, and water deficits are generally experienced during the dry season resulting in low yields and occasionally crop failures. The exact calculation of the figure presented previously is not known; however, some of this water comes from BWA supply system (Ministry of Physical Development and Environment, 2001, 1998), and the rest from private wells for which there little knowledge and/or control of pumping rates. Out of the approximately 21,000 hectares in agricultural holdings, 17,000 hectares are non-irrigated and therefore rain fed. Irrigation water demand has been forecast to increase 15 to 20% over the next 10 to 15 years if export markets can be gained, and less than 7 to 10% if only local markets are supplied (Mwansa & Brewster, 2001).

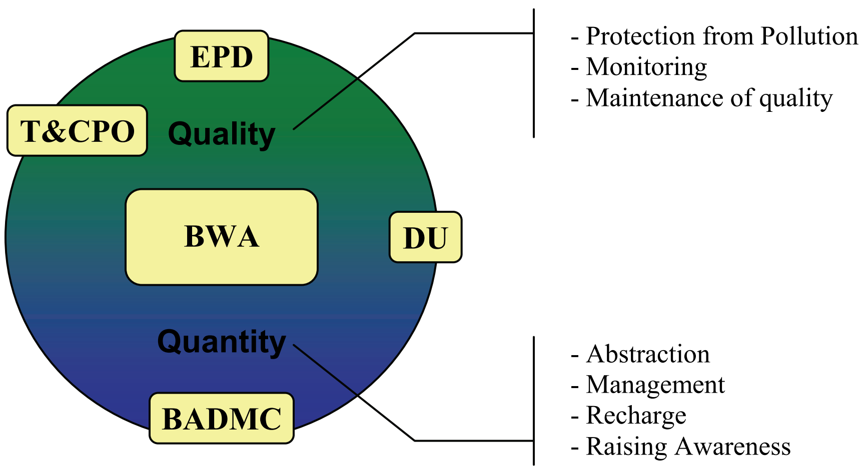
Other water demands include the irrigation needs for three golf courses, two of which are irrigated from private wells and the third with treated wastewater. The total amount of groundwater used for golf course irrigation presently amounts to 2,368 m^3/day. The amount of treated wastewater used could not be ascertained. Two other golf courses, which were previously in use, are being rebuilt. One is an eighteen-hole course and the other is being expanded from 18 to 45 holes (Mwansa & Brewster, 2001). A number of other golf course developments have been approved and are likely to come into play in the near future with total estimated water needs of 11,930m^3/day for all approved proposals (Mwansa & Brewster, 2001).

A number of hotels are utilizing treated wastewater for irrigating their lawns and plants as a way of reducing their freshwater demands. Reuse has been shown to be acceptable to the public for uses such as groundwater recharge and irrigation, based on a survey conducted under the Water Resources Management and Water Loss Studies, (1997) (Mwansa & Brewster, 2001).

3.2 Institutional Dimension of Water Resource Management In Barbados

Several institutions are directly and indirectly involved in the management of water resources in Barbados. Figure 3.1 provides a summary of institutions involved; they and their roles in water resource management are briefly described below.

Figure 3.1 Institutions Involved in Water Resource Management in Barbados



3.2.1 The Barbados Water Authority (BWA)

The Barbados Water Authority (BWA), is a statutory body falling under the Ministry of Public Works, Transport and Housing, and has been given the responsibility for water resources management in Barbados, for most public water resources (two spring sources; Three Houses Spring and Porey Spring are controlled by separate acts) (Mwansa and Brewster, 2001). The BWA also has complete responsibility for the operation and maintenance of the island's public water and wastewater systems (Stanley, 1998).

The BWA Act empowers the Authority to provide water and sewerage services for the entire island as well as the jurisdiction to formulate regulations, educate and advise the public on water related issues and to manage, allocate and monitor the water resources of Barbados with a view to ensuring their best development, utilization, conservation and protection in the public interest. The BWA is also required to obtain and analyse information and maintain records of the total water resources of Barbados as well as conduct research programmes and prepare pertinent statistics (Mwansa and Brewster, 2001; UNESA).

In summary, the BWA has the major responsibilities for water resource management in areas that include policy formulation, research, treatment, distribution (production), wastewater treatment and handling, source protection and resource assessment (Mwansa and Brewster, 2001).

The BWA self-finances the majority of its capital works programmes. In addition, some major projects are financed by loans secured on BWA's behalf by the Barbadian government from international funding agencies (Mwansa and Brewster, 2001).

The waterworks system services approximately 94,600 residential, institutional, commercial and industrial customers throughout the island and consists of 20 pumping stations, 27 reservoirs and 2,420 km of transmission and distribution mains (Stanley, 1998).

The Authority is administered by a government-appointed 10 member Board of Directors which reports to the Minister of Transportation and Public Works. The BWA operates with a staff complement of 760 people and an annual operating budget of U.S. $23.3 million (Stanley, 1998).

3.2.2 Barbados Agricultural Development and Marketing Corporation (BADMC)

The Ministry of Agriculture and Rural Development (MARD) has a Land and Water Use Unit which is responsible for developing and delivering water for irrigation. Through the Barbados Agricultural Development and Marketing Corporation (BADMC), the MARD operates a number of wells for this purpose

(Mwansa and Brewster, 1997). The BADMC does not maintain a formal record on how much water is used in irrigation from its wells. Furthermore many farmers have their own sources of water such as wells or springs in some cases and therefore don't rely on the BADMC, and no records are kept on their water consumption or where they withdraw their water from.

3.2.3 Environmental Protection Division (EPD)

The Environmental Protection Division (EPD) of the Ministry of Health (MOH) is responsible for the monitoring and control of conditions likely to affect the quality of land, air, water and general health and environmental well-being of the inhabitants of Barbados (Mwansa and Brewster, 2001). They are also required to review all development applications to ensure compliance with the groundwater protection zoning policy (discussed in section 3.3.1) and currently carry out a monthly monitoring programme of BWA's wells and some private wells for chemical and bacteriological contaminants (Mwansa and Brewster, 1997).

3.2.4 Town and Country Planning Office (T&CPO)

The Town and Country Planning Office oversees the enforcement of the zoning policy (described in Table 3.1) carried out through the Physical development Plan and implemented in the development-application review process (Mwansa and Brewster, 2001).

3.2.5 Drainage Unit (DU)

The Drainage Unit has a broad mandate with regard to monitoring and maintaining components of the natural and constructed drainage system of the island, including wells, drains and watercourses. In addition, the DU is directed to liaise with the T&CPO, regarding the application-review process, to restrict development in watercourses (gullies) and designated flood areas of the island. The DU is further directed to liaise with the Coastal Conservation Division on drainage as it affects beaches. These functions directly relate to environmental issues relevant to the island gulley system, groundwater, and surface runoff (Mwansa and Brewster, 1997).

3.3 Policy and Legal Mechanisms In Place For Water Resource Management

A substantial body of laws and policies exists to address groundwater development and management in Barbados. However, presently the major policy framework is contained in the Draft Policy Framework for Water Resources Development in Barbados (DPFWRD) (BWA, 1997), which was approved by the Barbadian government in 1997. This policy framework was prepared by a team of technocrats appointed by the Planning and Priorities Committee (PPC), a sub-committee of Cabinet (Mwansa and Brewster, 2001). However, the main legal framework for the protection of the water resource base is provided by the Groundwater Protection Zoning Policy or Groundwater Protection Plan (GPP) (Section 3.3.1 and Table 3.1).

In summary, the main laws and policies affecting water resource management in Barbados are:

- The Groundwater Protection Plan (GPP, 1973)
- The Physical Development Plan, (PDP, 1998) and
- The Draft Policy Framework For Water Resource Development & Management (DPFWRDM) (BWA, 1997)

3.3.1 The Groundwater Protection [Zoning] Plan

The existing groundwater protection policy was enunciated by the Barbadian cabinet as government policy in 1963 and was later revised in 1973. The policy seeks to protect the groundwater resources from bacteriological contamination, and is mainly based on bacteriological travel times to source well-heads (BWA, 1997). Current travel times were derived from computer groundwater models based on Darcian flow during the revision in 1973. Table 3.1 and Figure 3.2

provide a summary of the different zones which comprise this policy. The groundwater protection policy is embodied and implemented through the Physical development Plan.

Figure 3.2 Groundwater Protection Zones (BWA)

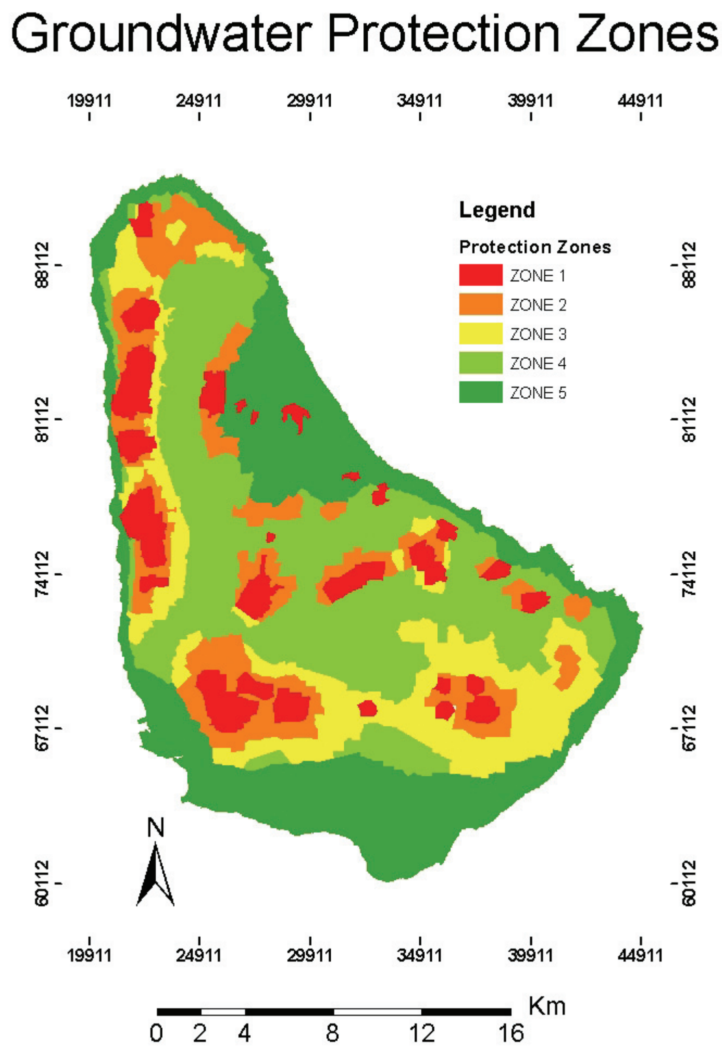


Table 3.1: Summary of GPP after BWA (1997) and (Klohn Crippen Consultants, 1997a)

Zone	Definition of Outer Boundary	Maximum depth of soak-away pits	Domestic Control Restrictions	Industrial Control Restrictions	Delineation Rationale
1	300 day travel time	None allowed	No new* housing or water connections. No changes to existing wastewater disposal except when Water Authority secures improvements.	No new industrial development.	Exceeds the survival period for enteric bacteria and viruses
2	600 day travel time	6.5m	Septic tank of approved design, discharge to soak-a-way pits. Separate soak-a-way pits for toilet effluent and other domestic wastewater. No storm runoff to sewage soak-a-way pit. No new petrol fuel or oil tanks.	All liquid industrial wastes to be dealt with as specified by the Water Authority.	Permits attenuation of "hard to degrade" Organics
3	5-6 year travel time	13m	As above for domestic wastewater. Petrol fuel or oil tanks to approved leak proof design.	Maximum soak-away pit depths as for domestic wastes.	Permits attenuation of "extremely hard to degrade" organics such as petroleum hydrocarbons
4	Extends to all high land	No limit	No restrictions on domestic wastewater disposal. Petrol fuel or oil tanks to approved leak proof design.		Incorporates the remainder of the recharge catchment
5	Coastline	No limit	No restrictions on domestic wastewater disposal. Sitting of new fuel storage of Water Authority.		Incorporates non-recharge areas.

* "new" refers to additions post-1973

It is important to note that Zone I areas are generally in agricultural use and are therefore subject to potential contamination by agricultural chemicals (Klohn Crippen Consultants, 1997a).

3.4 Criticisms & Recommendations Previously Made In Regards To Water Resource Management

3.4.1 Criticisms of water resources management aspects:

Criticisms of water resources management have been made by the Barbadian government, and consultants of both the overall water resources management framework, as well as the institutions that are involved in it.

Due to the multi-institutional nature of water resources management and the varied policies concerned with its execution, it has been suggested (Mwansa and Brewster, 2001) that there is a demonstrated need to enhance and harmonise the existing body of legal and policy provisions to facilitate and ensure an integrated approach to watershed and coastal area management. Towards this end, instruments, which clearly and unambiguously allocate responsibilities for enforcement, monitoring, compliance and consultation for environmental matters in a multidisciplinary fashion, need to be developed and adopted (Mwansa and Brewster, 2001).

The only existing document or provision that may help induce an integrated approach to watershed management, is the National Sustainable Development Policy Framework produced by the National Commission for Sustainable Development (NCSD). This document is still at draft stage, but takes a holistic approach to addressing issues in a multidisciplinary fashion, with broad consultation and participation of stakeholders. However, it must be noted that the NCSD is only and advisory body and its recommendation may not be accepted or enforced (Mwansa and Brewster, 2001).

On the zoning policy it has been noted (Klohn Crippen Consultants, 1997a) that the effectiveness of the existing zone boundaries has been constrained by the presence of development and other activities, in zone 1 areas, which may be incompatible with groundwater protection objectives (e.g. residential, industrial and waste disposal activities) (Klohn Crippen Consultants, 1997a). Furthermore, the DFDMWR (BWA, 1997) identifies that the GPP requires further modification to allow for chemical protection of the groundwater resources as chemical pollution was not taken into account in the delineation of existing boundaries. In addition, while the GPP is enforced through the planning legislation, the DFDMWR (BWA, 1997) suggests that this zoning system needs to be given its own specific legislative authority (BWA, 1997). Furthermore, considering the physical makeup of the island and the role of Karstic topography on water dynamics, laws based on matrix flow become questionable as to how effective they may be.

A lack of specific expertise and competence have been noted to exist (Stanley, 1998) within the BWA in certain areas such as hydrogeology, water auditing, water quality and chemistry, geographic information systems (GIS) and management information systems (MIS), metering of supplies (pump stations), advanced wastewater treatment technical and plant operations specialists, long range planning relative to water and wastewater management, and water and sewer tariff planning in conjunction with projected capital expenditures (Stanley, 1998).

3.5 Recommendations

In light of the prevailing situation in water resource management, a number of policy-related, practical and technical recommendations have been put forward over the years by different studies conducted for the government in areas pertaining to environmental and water resource management.

3.5.1 Policy and Structural Recommendations for water management:

Water Board

The creation of a Water Resources Unit (WRU) and a Water Resources Board (WRB) under the umbrella of The Ministry of the Environment, Energy and Natural Resources has been proposed (Willms & Shier *et al.,* 1998d) and has been in consideration by the Barbadian government since. This proposal is mainly predicated on the premise that the present arrangement, whereby the BWA has responsibility for both regulating and licensing of groundwater abstractions and supplying water, raises potential areas of conflict (Mwansa and Brewster, 2001; Willms & Shier *et al.,* 1998d).

The Board as proposed would be responsible for the development of policy, standards and regulations for the management of water resources. The WRU would provide the technical and administrative support that the Board requires to enable it to set policy and carry out its legal mandate in accordance with water resources management plans and policies. The Board would prepare and implement a Water Resources Management Plan (WRMP). This plan would provide directions to those bodies who are responsible for the abstraction of groundwater, including the BWA, MARD, and individual abstractors, and would ensure, through monitoring, that their operations are in compliance with "sound water resources and environmental management practices" (Willms & Shier *et al.,* 1998d p15). The Board would have the legal authority to: set fees for abstraction of water, allocate water to competing entities, reallocate or restrict water abstraction or distribution in the event of water shortages, monitor water quality, and to establish water quality standards with collaboration from the EPD (Willms & Shier *et al.,* 1998d). It has further been suggested that the WRMP would be related to the PDP application-control for land use; similarly to how the GPP currently is. Under this proposal, the WRB would have a special obligation to work directly with the EPD, to identify risks of contamination to the groundwater resource and eliminate or reduce them using a Pollution Control Division of the WRB Act. The Director of the Board would have the duty to make or modify groundwater protection zones, based on scientific information as it becomes available. These would then replace the existing groundwater protection zones as delineated and regulated in the existing GPP embedded in the PDP (Willms & Shier *et al.,* 1998d). In response to concerns over travel time for chemical pollutants, the Barbadian government will consider the implementation of overlapping zoning recommendations for different contaminant sources (Willms & Shier *et al.,* 1998d).

There has been an apparent impasse and stagnation of the creation of a Water Resources Board (Mwansa and Brewster 2001). In light of this impasse and stagnation, Mwansa and Brewster (2001) have suggested that the recommendations contained in the Draft National Sustainable Development Policy paper (prepared by the NCSD) should be reviewed. They argue, this paper may provide the basic framework for the establishment of an overarching and explicit legal and policy framework, and will serve as a first step to the development, harmonisation and enhancement of existing legislation and policy frameworks; which are needed to facilitate an integrated approach to integrated watershed management (Mwansa and Brewster, 2001).

Aquifer recharge by runoff retention and infiltration of major storm events

Over the years suggestions and recommendations of artificial aquifer recharge have been made by different studies to augment the water supply (Cumming And Cockburn, 1996; Klohn Crippen Consultants, 1997e; Stanley, 1998; Willms & Shier *et al.,* 1998d). The DPFWRDM (BWA, 1997) has adopted these recommendations into future policy. The rationale behind these recommendations is that any increase in the volume of surface runoff recharged to the aquifer, rather than lost to the sea, increases the volume of water available to meet the water supply needs of Barbados and reduces the potential need to supplement the fresh water lens through desalinization (BWA, 1997). Barbados ranks within the 10 most water scarce countries in the world (UNEP, 2001).

However, the use of stormwater for groundwater recharge poses some potential for groundwater pollution (Cumming And Cockburn, 1996) as many pollutants (animal waste, fertilizers, pesticides, petroleum hydrocarbons, chemicals, etc.) might be entrained in recharge-grade runoff and may quickly infiltrate into the aquifer (Willms & Shier *et al.,* 1998d).

Suggestions for artificial recharge have often been accompanied with practical and technical means of achieving such artificial or induced recharge. These mainly entail (Cumming And Cockburn, 1996):

- using existing quarries as infiltration ponds to divert runoff to prevent floods and recharge the aquifer.
- increased recharge through restoration and maintenance of the existing suckwells, sinkholes and soakaways, and

- lot-level increases in recharge by capturing runoff from roofs and other impermeable surfaces.

For the purpose of mitigating pollution from artificial aquifer recharge the following are some of the technical/practical recommendations that have been put forward:

- Re-direction of a portion of storm water runoff to grassed areas (fields, pastures, parks and golf courses) to provide a means of removing or reducing sediment picked-up from agricultural lands (Cumming And Cockburn, 1996).
- The incorporation of grassed buffer zones around the edges of fields to reduce sediment in the surface runoff (Cumming And Cockburn, 1996).
- Implementing a cleaning and maintenance programme for suckwells (BWA, 1997)
- Research into suckwell and stormwater detention pond designs to protect groundwater quality (BWA, 1997).
- Vegetation of critical slopes, drainage channels, swales and areas adjacent to suckwells, and/or reserving these as "no cultivation" areas in order to impede and/or remove silt which enters fissures (Cumming And Cockburn, 1996).
- Implementing surface water quality monitoring programs and collecting and analyzing water quality samples on an ongoing basis (Cumming And Cockburn, 1996).
- Initiating a formal program for disposal of chemical containers; strictly prohibiting the disposal of chemical containers in suckwells and in open areas to avoid contamination of surface and groundwater. The disposal and management of pesticide and fuel containers has been identified as a serious problem (Cumming And Cockburn, 1996) and disposal of such containers directly to suckwells has been observed (Cumming And Cockburn, 1996).
- Revising proposed land uses within catchment areas of the quarries proposed for recharge to ensure no additional sources of contaminants are introduced into the area (i.e. locating fuel storage, vehicle maintenance and refuelling outside the potential flood area) (Cumming And Cockburn, 1996).

Other recommendations and possible adopted policies involve the reuse of wastewater, and possibly the recharge of the aquifer by wastewater (Willms & Shier *et al.,* 1998d; Stanley, 1998; Klohn Crippen Consultants, 1997b; Seally Personal Communication, 2005). The most likely candidates for wastewater reuse would be agricultural and golf course irrigation (Klohn Crippen Consultants, 1997b; Willms & Shier *et al.,* 1998d). Further, Klohn Crippen Consultants, 1997b suggested wastewater artificial recharge of a catchment reserved exclusively for industrial/agricultural abstraction as a good option for Barbados; particularly in catchments experiencing problems with discoloured water or high salinity levels (Klohn Crippen Consultants, 1997b). The EMP (Willms & Shier *et al.,* 1998d) recommends that the WRB should carefully consider opportunities for re-use of treated sewage and wastewater in irrigation and groundwater re-charge.

Recommendations for groundwater pollution control and prevention for natural recharge conditions

In addition to artificial-recharge-methods and measures to mitigate their associated potential pollution, studies in the areas of water and environmental management conducted for the government have put forward recommendations for groundwater pollution-control and prevention for natural recharge conditions. The following are some of the most relevant:

- Revising and updating zoning and land use controls (Klohn Crippen Consultants, 1997b).
- Alternative programs for assisting property owners with proper management of residential wastes (Klohn Crippen Consultants, 1997b).
- Creating, managing and updating a contaminant inventory database (Klohn Crippen Consultants, 1997b).
- Periodic site inspections and regular land use documentation (Klohn Crippen Consultants, 1997b).

- Encouraging participation of the general public by minor local initiatives, such as clearing suckwells and improving drainage to infiltration areas (Klohn Crippen Consultants, 1997b).
- Agricultural practices to reduce surface runoff and to maintain agricultural soakaways and suckwells (Cumming And Cockburn, 1996),
- Best management practices for storage, handling and application of agricultural chemicals (Cumming And Cockburn, 1996).
- Best management practices for the storage, handling and disposal of fuels and lubricants (Cumming And Cockburn, 1996).
- Maintenance of suckwells, particularly of the surface inlets to free them from refuse (Cumming And Cockburn, 1996).
- A sectoral description of activities and reconnaissance level mapping of the potential contaminant sources which might impact groundwater (Klohn Crippen Consultants, 1997a).
- Revival and continuation of the once-initiated suckwell inventory programme to be followed by a qualitative risk assessment to identify suckwells that require blocking or filtering (Klohn Crippen Consultants, 1997d).

In water supply zones and in groundwater aquifers (Zone 1 Areas):

- Improving the management of agricultural chemicals (storage, disposal and handling) (Klohn Crippen Consultants, 1997e; Willms & Shier *et al.,* 1998d).
- Improving regulation and control of illegal solid waste dumps (Klohn Crippen Consultants, 1997e; Willms & Shier *et al.,* 1998d)
- Stricter control on suitable locations for heavy industry by excluding them from groundwater zones one and two (Klohn Crippen Consultants, 1997e, Willms & Shier *et al.,* 1998d).
- To clear of waste, on a high priority basis, all suckwells within Zone 1 areas which contain waste (Klohn Crippen Consultants, 1997d).
- Forbidding fertilizers, pesticide and herbicide applications or strictly controlling their quantities and timing within Zone l (Klohn Crippen Consultants, 1997b).

- Providing protection from excessive nitrate loading on the groundwater by means of: nutrient management, manure application handling and storage controls and use of cover crops and rotations (Klohn Crippen Consultants, 1997b).

It has been highlighted (Klohn Crippen Consultants, 1997b) that agricultural pollution sources are not susceptible to short term remedial action and should be addressed by long term source-control measures and resource management initiatives envisaged by a broad-scale groundwater protection strategy complimented by public education (Klohn Crippen Consultants, 1997b). One of the recommended source-control measures is for the existing Pesticide Control Board to apply considerations for pesticides registered for use in Barbados, thus far largely ignored (Klohn Crippen Consultants, 1997b). Resource management initiatives recommended include (Klohn Crippen Consultants, 1997b):

- long term groundwater monitoring programme
- creating a contaminant inventory programme linked to a GIS management system
- contingency planning to be triggered by monitoring results

In relation to agricultural chemical control Klohn and Crippen Consultants (Klohn Crippen Consultants, 1997b) have noted that most of these chemicals are imported from overseas and therefore the government could impose import controls on the users of these materials. It has been further suggested (Klohn Crippen Consultants, 1997b) that controls could consist of a quota system for farmers based upon the area of each specific crop under cultivation by that enterprise or individual. The users could be required to maintain a manifest system itemizing the application and disposition of all the purchased chemicals and their containers (Klohn Crippen Consultants, 1997b).

Klohn Crippen Consultants, 1997b recommended that the WRB become the primary monitoring agency with powers of enforcement and regulation. Most of the monitoring program would be the responsibility of the proposed WRB, while the BWA would conduct all the elements of monitoring which are required for its own operational purposes (Klohn Crippen Consultants, 1997b).

3.6 Conclusions:

The development and successful implementation of a DSS for water quality protection may embody and analyze the effects of adopting the large majority of the recommendations that have been presented above. The evaluation and implementation of these recommendations aided by use of a DSS (Chapter 6) would be mainly provided by:

- Providing the means for the evaluation (by simulation and/or real state modeling) of the different management (practical and policy) strategies that have been recommended / proposed,
- Providing the basis for the storage and analysis of the proposed monitoring and inventories data, and
- The systemic identification of key areas for prioritizing enforcement, control, revising, management, monitoring and maintenance efforts.

However, considering the multi-party involvement currently employed in water resources management, and the multiple legal and policy frameworks which are ambiguous in their provisions for implementation; it is clear that the establishment of a decision support system for groundwater protection seems mostly achievable under (or imminently relies upon) the accomplishment of either the Water Resource Board, or of an overarching legal and policy framework based on the draft NSDP.

Chapter 4: Data Availability

This chapter focuses on the description of data availability pertinent to water resource management and the implementation of a DSS for water quality protection and management by discussing the *existing institutional arrangements for the collection and dissemination of data for environmental purposes* in Barbados. *The Environmental Management and Land Use Planning project and the Natural Resources Database* are identified as the main sources of spatial data, and the unique effort previously conducted for the establishment of a NSDI for environmental management purposes. Existing *data collection programmes related to water resource management* are described and assessed in terms of their relevance to provide information for water quality protection and management through the use of a DSS. Ultimately this chapter provides a listing of *existing geospatial datasets and data holding relevant for W-DSS implementation*.

4.1 Existing Institutional arrangements for the collection analysis and dissemination of data for environmental management purposes.

There is, at present, no functioning formal inter-ministerial or interdepartmental forum, framework or policy for the exchange of environmental management-, or GIS-related information in Barbados. Further, there are no established standards for GIS use and/or GIS implementation within the government of Barbados (Willms & Shier *et al.*, 1998b).

Where GIS use exists within government institutions, most of the existing GIS systems are used primarily for data capture and display. For the most part, these systems have not yet reached a level of maturity where sufficient documented data sets are available to support routine technical and analytical work within the GIS (Willms & Shier *et al.*, 1998b). Many of the existing systems were developed by [foreign] consultants for specific projects, and then handed over to the client-department. Because these systems have been project-specific, they have not been defined in response to an overall analysis of the operational requirements of the departments concerned (Willms & Shier *et al.*, 1998b). Most of the departments with a GIS have a shortage of staff trained to develop, manage and use the system as there is a national shortage of GIS specialists, and trained staff often move on to pursue opportunities in other agencies or ministries, forcing departments to recommence the training process (Willms & Shier *et al.*, 1998b).

Continuity of data has been identified to be a problem, largely blamed on personnel turnover (Willms & Shier *et al.*, 1998b). Creation of metadata is perceived to be costly and difficult, and unless specified in the Terms of Reference, consultants have not been diligent to prepare it. A similar situation occurs within government offices; “the position of "why bother, I know the stuff" is prevalent, but staff turnover ends the continuity of knowledge” (Willms & Shier *et al.*, 1998b p10).

The standard of documentation, where available, is variable and quality control is inconsistent. Data dictionaries and metadata are often limited or missing and no national standards exist for their creation or maintenance. Most of the existing GIS applications are on free-standing hardware platforms and there are no government local area or wide area networks (LANs / WANs) in place in Barbados. Data sharing generally occurs through individual personal contacts, on an informal basis, without arrangements for data maintenance and with no opportunity for cost recovery by the data supplier (Willms & Shier *et al.*, 1998b).

In response to the above described situation, a major attempt was conducted to lay the foundations of what would constitute a NGDI (Chapter 1) for environmental management in Barbados. In 1998, this attempt constituted of the compilation, and establishment of the National Natural Resources Database, and Natural Resources GIS (NRDB and NRGIS) (Willms & Shier *et al.*, 1998c) created under the Environmental Management and Landuse Planning For Sustainable Development Project (EMLUP).

4.2 The Environmental Management and Land Use Planning (EMLUP) Project and the Natural Resources Database (NRDB)

The main purpose of the NRDB was to collect all available descriptive and quantitative data on the natural resources of Barbados, to categorize and organize these data into a national information database for easy reference and retrieval. This entailed addressing the biophysical information resources of Barbados and examining those resources that are required for effective planning and environmental management. The information base developed for this project comprises a bibliography of some 700 titles and a Natural Resources Geographic Information System (NRGIS) with about 160 data sets (Willms & Shier *et al.*, 1998c). The NRDB report (Willms & Shier *et al.*, 1998c) identifies the information that should be used in the evaluation of development proposals, and then systematically explains the rationale behind the use of this needed information. It explains why the subject matter is important in the context of environmental management. It describes the specific type of information needed, and, if it is available, shows where the information is stored within the information resource base. Availability is examined in terms of the NRGIS mapping and the bibliography. In short, the NRDB specifically provides a means to conduct a systematic evaluation of the most important natural biophysical variables that affect environmental sustainability and the state of natural resources; in the context of how these may be affected by proposed land use changes (Willms & Shier *et al.*, 1998c).

In addition, the information that was documented within the NRDB has been used to inform and develop: the Physical Development Plan (1998), the Environmental and Natural Resources Draft Management Plan (Willms & Shier *et al.*, 1998d) local area growth management plans for major urban areas, the national land use

plan, and management guidelines for the National Park as well as other protected landscapes (Willms & Shier *et al.*, 1998c).
Parallel to the creation of the NRDB, a specific framework for the creation, implementation and maintenance of a National GIS was presented to the government of Barbados through the EMLUP project in a report entitled “Future Data Specifications and Custody” (Willms & Shier *et al.*, 1998a). That report specifically addresses the natural resources data required in support of the Environmental and Natural Resources Draft Management Plan (Willms & Shier *et al.,* 1998d) and the Physical Development Plan (PDP); including reference to the status of the existing data, who should collect and manage data needed to fill gaps, and the desired frequency of revision. In that report, the data needs are prioritized with regard to the implementation of the EMP and the PDP, as well as in consideration of the new requirements for Environmental Impact Assessments (EIAs). That report includes specific guidelines that could be followed to achieve: monitored and maintained coordinated data collection and production, quality assurance, data archiving and security, dissemination protocols, creation of standards, and maintenance of metadata records (Willms & Shier *et al.*, 1998b). In particular that report calls for “an application to illustrate GIS as a policy development tool, by showing the distribution of hazardous chemical storage sites with respect to population centres, environmentally sensitive sites and water supplies”, as a means to demonstrate the importance and functionality of a national GIS (Willms & Shier *et al.*, 1998b p32). The work comprised in this thesis stems from the desire to provide such application, within the context of water quality protection, with the aim to revive the establishment of a NSDI in Barbados.

At the time of EMLUP reporting it was envisioned that “the natural resources GIS [becomes] a tool for research, monitoring, policy making, policy implementation, and environmental education” (Willms & Shier *et al.*, 1998b p23).

The NRDB report (Willms & Shier *et al.*, 1998c) in its introduction of the NRGIS states that:

> *"It behoves the Government of Barbados to protect this valuable asset by assembling all data sets into one location, recovering and publishing as much information about them as possible and then establishing a mechanism or infrastructure component which could ensure their proper maintenance and dissemination. The study team views this as one of the major objectives of the NRGIS work, and are confident that the system, the data it contains, the metadata which describes the data, and the proposed system integration into the Environmental Unit, will achieve that goal"* (Willms & Shier *et al.*, 1998c p85).

Up to date, since the establishment of the NRDB, little work has been carried out by taking advantage of its existence, and despite failed attempts by a proposed GIS standing committee in the past (Chapter 5), practically no formal work has been conducted to revive it, enhance it or evolve it to make practical use of spatial data and GIS for environmental management purposes. Chapter 5 will focus on describing the present situation as it relates to the state of a NSDI which was once set in motion by the EMLUP project.

4.3 Data Collection Programmes related to Water Resource Management

Two agencies; the BWA and EPD are responsible for the monitoring of water quality, and thus maintain two separate water monitoring programmes.

4.3.1 The EPD's Water Monitoring Program

The EPD program consists of monthly sampling of 16 public wells, seven agricultural wells and six springs. The parameters analyzed include pH, conductivity, potassium, chloride, sulphate, nitrate, total phosphorus, faecal coliform and residual chlorine (Klohn Crippen Consultants, 1997b).

The parameters covered by the existing EPD program as described cannot provide sufficient water quality characterization to adequately monitor the potential impact of the extensive set of existing potential pollution sources (Chapter 2) affecting abstracted and non-abstracted water resources in Barbados (Klohn Crippen Consultants, 1997b). This is mainly due to the fact that monitoring efforts are focused on testing groundwater at the supply points, rather than monitoring "recharge points". The type of tests needed to comprehensively evaluate the presence of potential pollutants such as agrochemicals and hydrocarbons is of high cost and not readily available in the island for many constituents (Dr. Ifil personal communication, 2005). While it is logical and expected that the public water supply quality be monitored for public health; in parallel, focus could also be placed on recharge sources. In conjunction with recommended enhanced monitoring programs (Chapter 5), the implementation of a DSS for water quality protection and management (Chapter 6) may offer "proxy" means to focus on "recharge grade" and quality protection.

4.3.2 The BWA's Water Monitoring Programme

The BWA conducts weekly monitoring of the public water supply distribution system as well as public supply wells with the focus to monitor chloride levels for the purposes of managing pumping rates. BWA have assessed other chemical parameters on an irregular basis; mainly pesticide and hydrocarbon residues in public supply wells (Klohn Crippen Consultants, 1997b).

Quality control and quality assurance of monitoring results is provided by overlapping monitoring of 10% of the BWA monitoring locations with results from the EPD monitoring program. However, besides this overlap, no systematic data analysis program has been established to monitor the accuracy or precision of the data generated by both monitoring programs (Klohn Crippen Consultants, 1997b).

The BWA currently does not have a centralised electronic database for storing or analyzing its monitoring data (Klohn Crippen Consultants, 1997b). The EPD had designed in a tender document a database management system (DBMS) to store and analyze data for its different monitoring programmes (water quality included)

(Dr. Headley, personal communication, 2005). However, it has not been confirmed by the EPD weather whether this DBMS tender was ever developed and acquired by the EPD. The BWA's distribution system and wells monitoring data is stored as a combination of hard copy old records, and spreadsheet files, while public water-supply-source monitoring data (EPD) and other ad hoc data (such as that obtained during previous studies) is stored at the BWA Drawing office and EPD office (Klohn Crippen Consultants, 1997b; Ifil personal communication, 2005).

4.4 Existing geospatial datasets and data holdings relevant for W-DSS implementation

So far, the 1998 NRDB report (Willms & Shier *et al.*, 1998c) constitutes the most comprehensive geospatial dataset listing and description available for Barbados. However, its scope is quite general in terms of applying the data contained within it for environmental management analysis purposes. Furthermore, further studies (see below) have been conducted in the island pertaining to issues concerning environmental management since EMLUP, and the datasets and knowledge produced from these has not been incorporated into the NRDB. Furthermore, many of the datasets contained within the NRDB can be considered to now be drastically outdated for environmental management purposes. The following is supplementary to the NRDB report, and provides a listing of available data and datasets relevant to the creation and implementation of a DSS for water resource quality protection and management. Relevant entries contained in the NRDB for this domain have also been presented in this thesis in Tables 4.1 to 4.8.

Table 4.1 Datasets Related to Land Use

Custodian / Creator	Title Theme	Description	Format
NRDB	Landuse map for 1997	Generalized landuse map updated from aerial photography and field surveys	GIS layer
Tosic (2007)	Landuse map for Holetown "River" Watershed	Field verification and update from 1997 landuse map	GIS layer
Lands & Surveys Department	Landuse/cover map for 2006/7	Detailed Landuse maps derived from Orthorectified Aerial photography	GIS layer
Jedlic and Lafremiere (2008)	Landuse map for Holetown watershed	Digitized from GoogleEarth imagery verified through students' field surveys and other sources	GIS layer

Table 4.2 Datasets related to Hydrology

Custodian / Creator	Title Theme	Description	Format
Tosic (2007)	Discharge into Holetown Lagoon and streamflow throughout Holetown Hole Watershed	Measured discharge for 4 "major" rainfall events during 2006, for 4 subwatersheds; outlets peak discharge was measured and for the main outlet a hydrograph was constructed.	Spreadsheet, hydrographs, GIS layer of sampling sites
Cumming and Cockburn	Streamflow	Streamflows for various catchments produced for the "Stormwater Drainage Report" (C&CB)	Stage curve, tables, and GIS layer for location of study sights
Cumming and Cockburn / Lands & Surveys	Gullies / Streams	Mapping of Gullies presented as water stream lines	GIS Layer
Lands & Surveys Department[+]	Digital Terrain Model	High definition Digital Terrain Model (DTM) for all urban and impervious surfaces created for the DMP.	GIS layer

BWA	Wells	Public supply and some private well locations and characteristics	GIS layer and spreadsheet
Baird and Associates	Stage and Discharge (measurements for 2006)	Continuous stage measured by pressure transducer at “Holetown Hole” Watershed outlet	Spreadsheet
DU	Stage levels for streams in the Holetown Watershed	Different stage readings for varying periods of time in varied locations. Locations include “Jtown new drain”, and “Farmer’s dam” as well as “Holetown Lagoon”	Spreadsheet
Lands & Surveys Department+	Digital Elevation Model	Produced from 1m elevation contours as part of the DMP, this constitutes the most accurate and up to date topography of the island.	GIS Layer
Lands & Surveys Department	Landcover features	Detailed mapping of impervious surfaces (paved areas and buildings)	GIS layer

+ The actual existence, or adherence to the mentioned specifics of these products could not be ascertained. The information presented here was derived from the technical tender documents for the DMP (Government of Barbados, 2005).
DMP stands for Digital Mapping Project

Table 4.3 Datasets related to Hydrogeology

Custodian / Creator	Title Theme	Description	Format
BWA	Groundwater catchments	Delineation of groundwater catchments and identification of sheetwater and streamwater zones	GIS Layer
NRDB	Sinkholes	Sinkhole points digitized from 1983 paper maps	GIS layer
DU	Drainage suckwells and soakawyas	Inventory of suckwells and some hydraulic characteristics associated	GIS layer
NRDB	Soils	General soil categories and basic characteristics	GIS layer
Tosic (2007)	Sinkholes in Holetown “River” watershed	Sinkhole verification and delineation for some sinkholes in the Holetown “River” Watershed	GIS layer

BWA	Base of Coral Contours	Contours delineating the base of coral oceanic rock topography used in the delineation of groundwater catchments	GIS layer
BWA	Geophysical tests	Geophysical tests conducted in the west coast to investigate aquifer dynamics (Mayers *et al.*, 2005)	Model results

Table 4.4 Meteorological Data

Custodian / Creator	Areal and temporal coverage	Description	Format
BWA	Varied, non-continuous	Data from weatherstations managed by the BWA	GIS layer, and spreadsheet
Cumming and Cockburn	Rainfall Distribution maps for design storms	Distribution of design storms of different intensities and different reoccurring times have been mapped	Image files
Baird & Associates	Holetown Hole Watershed (2006-2007)	Four 1mm Tipping buckets installed throughout the Holetown Hole Watershed	Spreadsheet
DU	Holetown watershed, (2006 – onwards)	0.2 mm tipping bucket, and rain gage measuring precipitation in 2h intervals.	Spreadsheet
Sandy Lane Golf Course	Sandy lane, unknown coverage period	1h recording interval	Spreadsheet
CZMU	Several weather stations operated across the island.	Data recorded hourly include min/max temperature, Dew point, wind speed and direction, atmospheric pressure, Heat index, THW index, accumulated precipitation and precipitation rate.	Spreadsheet
CIMH	Island wide coverage by various weather stations with the oldest and widest historical record available on the island (1981 – onwards)	Data recorded daily include: min /max temperature; accumulated precipitation, Evaporation and Sunshine hours.	Spreadsheet

Table 4.5 Policy / Administrative Datasets

Custodian / Creator	Title Theme	Description	Format
BWA	GPP Zones	Delineation of groundwater protection zones	GIS layer
NRDB	Enumeration Districts	Delineation of Census enumeration districts	GIS layer

Table 4.6 Water Quality Datasets

Custodian / Creator	Title Theme	Description	Format
BWA	PSW sampling test	Test results from the monitoring program of public supply wells	Spreadsheet
Tosic, 2007	Surface water quality sampling	samples 3 major rainfall events in the Holetown “River” Watershed in 2006	Spreadsheet and GIS layer for sampling sites
Baird & Associates	Surface water sampling	Surface sampling conducted for an unascertained period during 2006.	Format unknown
BWA	Surface water sampling	Tests results obtained for the WRMLS in 1995 (Klohn Crippen Consultants, 1997b)	Spreadsheet

Table 4.7 Datasets related to Potential pollution sources

Custodian / Creator	Title Theme	Description	Format
NRDB	Waste management facilities	Sanitary landfill locations	GIS layer
NRDB	Industry	Location of heavy industry	GIS layer
WRWLS (Klohn Crippen Consultants, 1997e) / BWA	Chemical use and location in industry	Inventory of heavy industry locations and use of chemicals	GIS layer (unascertained if still available within the BWA).
Cumming and Cockburn (1996)	Agriculture	Results from the agricultural surveys conducted for the “Stormwater Drainage Management Report” including crops cultivated and agrochemical use and application	Tables

		rates	
MARD	Agricultural Census 1998	Location and type of agricultural practices as well as information of agricultural chemical use	Spreadsheet
EPD	Hazardous materials and illegal dumping sites.	Inventory (lacking positional information)	Tabular (format unknown)

Table 4.8 Topography Datasets

Custodian / Creator	**Title Theme**	**Description**	**Format**
NRDB	10m Elevation contours	Elevation contours digitized from 1983 paper maps	GIS layer
Baird & Associates	3.05m (10ft) Elevation contours for Holetown watershed	Elevation contour digitized from topographical surveying	GIS layer
Stanley, 1998	1m elevation contours	1997/8 Survey contours for 1km inland of the West coast	GIS layer

Chapter 5 discusses the suitability and applicability of these data in the context of implementing a Decision Support System demonstration application for water quality protection. Emphasis will be given to issues concerned with the accessibility to data, and to the efforts that have been made in Barbados to constitute a NSDI to safeguard data quality and standards, and to facilitate the means for data access. Chapter 6 presents an attempted application of the WARMF DSS for a sub-basin of the Holetown “River” watershed by employing whatever existing and available datasets are suitable towards these ends to achieve best results in presenting a demonstration application.

Chapter 5: Considerations for the implementation of a DSS for WRMF in Barbados

This chapter sets the final foundations for strengthening the importance of the understanding and fulfilment of the various dimensions involved in the establishment and implementation of a DSS for water quality protection and management (Chapter 6). These dimensions are: the functioning of the physical system (Chapter 2), the adequate institutional frameworks for facilitation of implementation (Chapter 3), and data quality, availability and accessibility (Chapter 4 and this chapter). This chapter presents *an overview of the "water system" for the case of Barbados* to summarize the physical dimension (Chapter 2) and how it specifically relates in translation to the implementation of a DSS for water quality protection and management. Subsequently, the *WARMF main data requirements and an assessment of available data to meet them* are presented. Following from the assessment of meeting data requirements, *the reality of lack of data accessibility in Barbados* is presented and discussed, in relation to how it affects the potential of implementing a DSS for water quality protection and management. In light of this reality, *previous NSDI attempts* are discussed under the premise that a NSDI (Chapter 1) offers the formalization means to ensure data quality, availability and accessibility. The fate and status of such attempts is presented. In an attempt to provide a way forward, *propositions for further data gathering and recommendations to appropriately meet requirements and maximize W-DSS potential* are provided.

The Draft Environmental Management Plan (Willms & Shier *et al.,* 1998d) Recommended that "the Water Resources Board in association with the Environmental Section of Government Analytical Services and the [EPD] … upgrade the long-term groundwater monitoring programme, in order to:

- track trends in water quality parameters
- determine the impact of future development
- establish the effectiveness of pollution control strategies

- provide data for water quality modelling
- measure for compliance with water quality regulations and standards" (Willms & Shier *et al.*, 1998d p109-110)

This recommendation lacked the consideration of surface water quantity and quality monitoring and the role the DU would play in regards to surface water monitoring. In partial response to the above recommendation, and in combination with, giving more emphasis to the consideration of surface water monitoring, this thesis has taken the aim to implement a pilot study using a DSS for water quality protection (Chapter 6).

5.1 Overview of the Watershed Analysis Risk Management Framework (WARMF)

The Watershed Analysis Risk Management Framework (WARMF) has been chosen as a DSS platform to provide a practical example of what the use of such tools may provide the government of Barbados (be it through the BWA presently or WRB in the future) in the area of water resource quality protection.

WARMF was developed by the United States Environmental Protection Agency (USEPA) and the Electric Power Research Institute (EPRI) (Chen and Weintraub, 2000) as a tightly coupled, model-based decision support system to facilitate the analysis of Total Maximum Daily Loads (TMDLs) (USEPA, 2008) and for watershed planning. The system provides a road map to calculate TMDLs for most conventional pollutants (coliform, TSS, BOD, nutrients). It also provides a road map to guide stakeholders to reach consensus on an implementation plan (Chen *et al.,* 2001). The scientific basis of the model and the consensus process have undergone several peer reviews (Keller, 2000) by independent experts under USEPA guidelines.

WARMF is organized into five (5) linked modules under one, GIS-based graphical user interface (GUI). It is "a very user friendly tool suitable for expert modellers as well as general stakeholders" (Chen *et al.,* 2001 p1).

“The Engineering Module is a GIS-based watershed model that calculates daily runoff, shallow groundwater flow, hydrology and water quality of a river basin. A river basin is divided into a network of land catchments (including canopy and soil layers), stream segments, and lake layers for hydrologic and water quality simulations. Land surface is characterized by land use / land cover and precipitation is deposited on the land catchments to calculate snow and soil hydrology, and resulting surface runoff and groundwater accretion to river segments. Water is then routed from one river segment to the next, from river segments to reservoirs, and then from reservoirs to river segments, until watershed terminus is reached” (Chen *et al.,* 2001 p1). Even though the hydrological setting in Barbados is not governed by “conventional” watersheds and permanent rivers (Chapter 2) and lakes; the approach taken by WARMF may provide useful insights into surface water quality dynamics.

In WARMF “pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and nonpoint loads are routed through the system with the mass [surface and groundwater flows] so the source of nonpoint loading can be tracked back to land use and location” (Chen *et al.,* 2001 p1).

“The Data Module contains meteorology, air quality, point source, reservoir release, and flow diversion data used to drive the model. It also contains observed flow and water quality data used for calibration. The data is accessed through the map-based interface and can be viewed and edited in both graphical and tabular format. The Knowledge Module stores supplemental watershed data, documents, case studies, or reports of past modeling activities for easy access by model users” (Chen *et al.,* 2001 p1).

The algorithms of WARMF were derived from many well established codes such as ILWAS (Chen *et al.*, 1983; Gherini *et al.*, 1985), SWMM (USEPA, 1992), ANSWERS (Beasley, and Huggins, 1991a; 1991b), WASP (Ambrose *et al.*, 1991).

"The Consensus Module of WARMF provides information in a series of steps for stakeholders to learn about the issues, formulate and evaluate alternatives, and negotiate a consensus. Outputs are displayed in coloured maps and graphs. A GIS map is used to show the bar charts of pollution loads from various sub regions of the river basin. Another GIS map is used to show the consequence of the pollution loads, in which water bodies suitable for a designated use are shaded green and those not suitable are shaded red. Through the TMDL Module, calculations are made for a series of control points from the upstream to the downstream of a river basin. A road map is provided for the step-by-step procedure. An iterative set of simulations are performed to calculate various combination s of point and nonpoint loads that the waterbody can accept and meet the water quality criteria of the designated uses. The water quality criteria can be specified [by the user] for multiple parameters and based on percent compliance" (Chen *et al.,* 2001 p1).

In particular interest for the Barbados context WARMF can help answer water resource and water quality questions such as (Chen *et al.,* 2001):

- What are the cumulative water quality impacts under various watershed management scenarios?
- Will best management practices (BMPs) such as buffer strips or livestock fencing be effective for nonpoint load reduction?

The advantages of WARMF include (Chen *et al.,* 2001):

- Integrates models, databases, and graphical software into a map-based stand alone tool that does not require proprietary GIS software
- Links catchments and river segments to form a seamless river basin model which computes soil and surface hydrology, pollutant build up and washoff based on physical principles instead of SCS curve numbers and runoff coefficients
- Contains a user friendly GUI and unique decision support tools that allow a variety of stakeholders (including modellers and lay persons) to run the model and to take ownership of their watershed by learning about the science behind their water quality issues
- Models flow, temperature, nutrients, bacteria, dissolved oxygen, sediment transport, periphyton, phytoplankton, and loading from onsite wastewater systems
- Displays sources of point and nonpoint loading using easy-to-understand GIS maps

- Displays water quality status in terms of suitability for fish habitat, swimming, water supply, and other uses with red and green color codes
- Simulates the impact of controls on atmospheric deposition, point source loads, and BMPs for nonpoint source loads such as buffer strips, street sweeping, livestock exclusion, and fertilizer reduction

WARMF has been applied to over 15 watersheds in the United States and internationally. The studies have addressed the TMDLs of nutrients, sediment, fecal coliform, and the impact of onsite wastewater systems on a watershed scale (Chen *et al.,* 2001). In the context of its possible application in Barbados, it offers interesting potential beyond that presented in this thesis (Chapter 6), as suggested by the system capabilities.

"There is no limit on the size or scale of a potential WARMF application as long as adequate topography data are available" (the high importance of this point in the context of Karst topography is further discussed in Chapter 6 and 7) (Chen *et al.,* 2001 p2).

5.2 Overview of the "water system" for the case of Barbados

In order to accommodate for the planning of an application of a DSS to address the surface water quality in the Barbadian context, a systems approach has been adopted to facilitate data requirements and conceptual analysis of water flows and their fate. Figure 5.1 builds on and summarizes the content presented in Chapters 1 and 2, and presents the system's analysis of surface hydrology in Barbados.

Figure 5.1 Surface Hydrology System's overview for Barbados

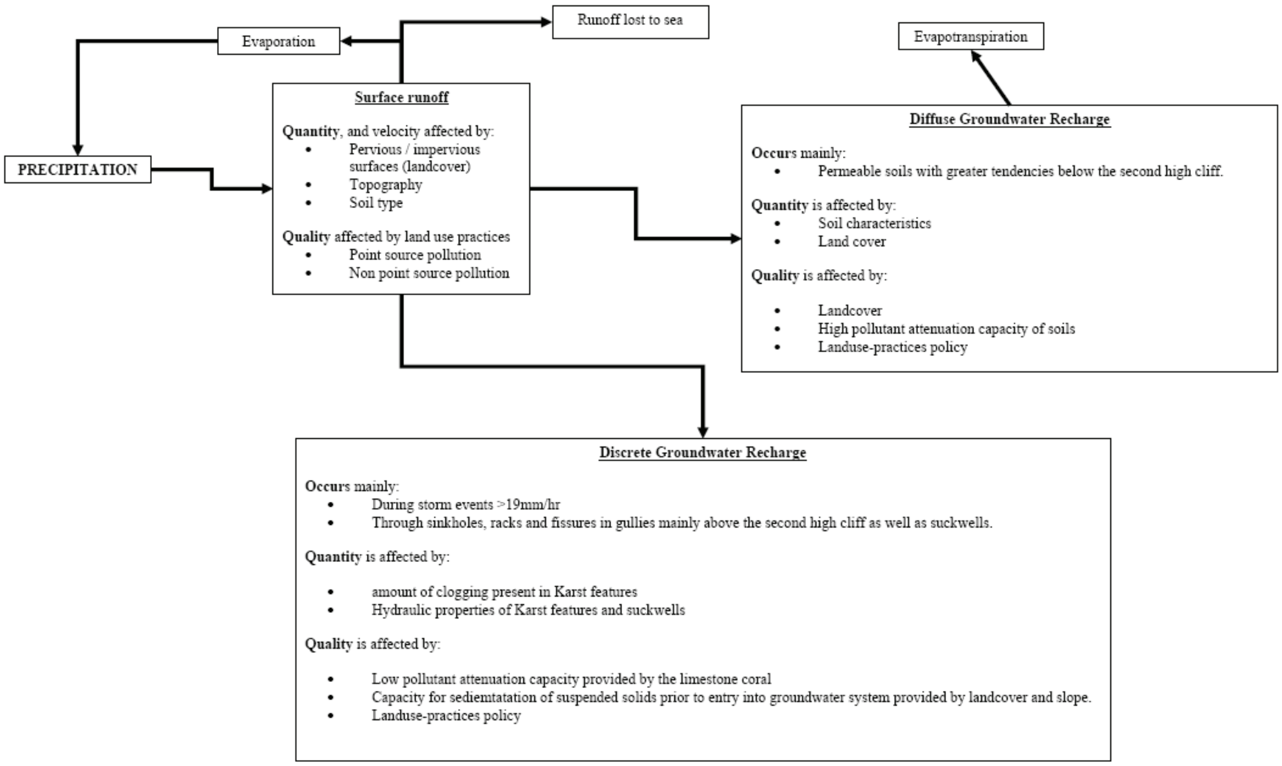


Figure 5.1, presents a simplified schematic view of the surface-hydrologic system in Barbados and how it relates to groundwater recharge and quality. Groundwater movement and quality dynamics have been omitted as they are beyond the purposes of the present work, especially due to their complicated nature in Karstic systems (Discussed in Chapter 1).

5.3 WARMF Main Data requirements and an assessment of available data to meet them.

From an understanding of Figure 5.1, the main data input requirements required (Chen *et al.,* 2001) for the Model-base part of the DSS can be readily identified. For WARMF these are:

5.3.1 Precipitation:

Precipitation is the main input element feeding the entire system, and in the case of Barbados represents the primary water source (Ministry of Physical

Development and Environment, 2001, 1998). Therefore, precipitation-quantity over time is an essential input requirement for modeling purposes. Precipitation data can be presented as daily totals accumulated in rain-gages over a period of usually 24 hours (daily records), or it can be provided as rainfall intensities which give an idea of precipitation amounts over a smaller time span (i.e. mm/hr). WARMF requires precipitation data to be input as daily records including dew point temperature, and air pressure.

Assessment of available data for Barbados

In light of the different sources for climate data identified in Chapter 4, and the input requirements of WARMF; many of those datasets are usable for an application of WARMF in Barbados. The limiting factor for this component will be the desired spatial extent to be modeled and the desire for a given degree of accuracy for the desired simulation period. Model accuracy would be affected by both, the spatial extent of weather station coverage, and by the consistency of rainfall data itself. In order to accommodate for rainfall spatial variation (Chapter 2), a good coverage of weather stations is desired, especially for larger watersheds. Furthermore, the historical record and recording interval need to be equal for all stations used in the modeling inputs.

5.3.2 Evaporation

Evaporation rates are mainly governed by cloud-cover, wind speed, and solar radiation. WARMF requires the following input data to calculate evaporation losses: minimum and maximum temperature, cloud cover, wind speed.

Assessment of available data for Barbados

The combination of CIMH and CZMU weather station datasets provide sufficient information parameters to be used for modeling purposes. However, the spatial coverage provided by these weather stations that record the necessary parameters is limited, affecting accuracy by spatial variation as mentioned before. However, in the absence of cloud cover and wind speed it is possible to extrapolate values from other (more distant) stations recording these, without compromising results significantly (Chen *et al.,* 2001).

5.3.3 Surface Runoff

Quantity

Landcover and topography information are necessary to be able to model surface runoff-movement dynamics. For these purposes WARMF requires the following input data: DEM, a landuse layer as well as the surface streams network. Discharge measurements are used for model calibration. Catchment slopes and true aspects are derived from the DEM by the hydrologic model imbedded in WARMF. A substantial set of observed stream flows is needed for calibration of the hydrological model (Chen *et al.,* 2001).

Quality

Point (i.e. industrial discharges, landfill sites and illegal dumps) and nonpoint (agrochemical use and application rates) source-pollution information is essential to determining water quality and its deterioration as surface runoff assimilates pollutants by flowing over the land. WARMF requires the following data input to asses water quality: For point sources, loadings discharged over time. For nonpoint sources, it relies on the landuse layer, and can be supplemented by agrochemical application rates. A substantial set of observed surface water quality samples are used to calibrate the models.

Assessment of available data for Barbados

For surface runoff quantity and movement dynamics, the existing high resolution DEM and DTM produced for the DMP offer great possibilities; specially the DTM as this provides the most accurate and updated representation of not just the natural topography, but of the built-up terrain, which incorporates the existing drainage infrastructure. Using these datasets can provide the most comprehensive hydrologic modeling for the island. The use of any other readily available topographic data is limited by coarse contour intervals (10m for widest coverage), and possibilities of being outdated, as it was discovered that in some parts of the island the topography has been intentionally altered for construction purposes. Fogle (1998) demonstrated that there are quite significant effects on hydrologic modeling of Karts terrains dependent on the DEM resolution (a factor of elevation contour interval). This holds particularly true for smaller watersheds in Karst topographies (*Fogle, 1998*).

For water quality the data requirements pose one of the furthest limitations as accurate and updated spatial data on point sources (i.e. pollutants and hazardous material storage and handling) are lacking. However, the inventories of hazardous materials and illegal dumping sites held by the EPD can provide a starting point in this area especially if they have been georeferenced as previously intended (Dr. Headley personal communication, 2005). Non-point sources are also outdated and inaccurate, as agrochemical application rates are not exactly known or accurately associated to a spatial location.

Lack of (spatially and temporarily) comprehensive surface water quality sampling and surface water discharge measurements for calibration purposes will present limitation for increasing and assessing the accuracy of the model by means of calibration and validation processes.

5.3.4 Discrete Groundwater Recharge

In order to account for discrete recharge, knowledge of surface runoff quantities and quality together with their precise spatial and temporal distributions are essentially needed. In this regard, the location and characteristics (hydraulics, status, etc..) of Karst features (sinkholes, cracks and fissures) as well as suckwells, are essential. The models in WARMF (as most surface hydrology models) don't have the capacity to account for discrete infiltration. However, for the case of Barbados, a conceptual workaround to the problem posed by this limitation is proposed and examined in Chapter 6 for the purposes of decision support.

Assessment of available data for Barbados

Provided a computational/technical workaround to the surface hydrologic models' lack of discrete infiltration consideration, the state of datasets in Barbados as they pertain to this component pose a further limiting factor. An accurate and updated mapping of sinkholes and major karstic features in Barbados is lacking. Furthermore, for those features mapped, with the exception for suckwells mapped by the DU, any information on their characteristics is completely absent.

5.3.5 Diffuse Groundwater Recharge

The main elements governing diffuse infiltration relate to soil characteristics, and landcover as well as a direct association to surface runoff quantities and movement dynamics. For the purposes of diffuse infiltration WARMF requires the following input data: Soils layer defining soil type (horizons) hydraulic characteristics and layer thickness and soil erosivity.

Assessment of available data for Barbados

The existing updated (DMP) landuse/cover maps provide information beyond the model requirements for this aspect; however, the use of outdated landuse/cover maps will provide erroneous results as landuse in Barbados has seen a significant change over a small time horizon (Leitch and Harbor, 1999). The existing soils data are quite limited in the potential they can provide for modeling purposes. The existing soils map available in digital format only contains soil type class, and lacks information about soil horizons' hydraulic characteristics, depths and soil profile. However, the existing data can be used to provide a generalized modeling of diffuse infiltration and hydrology with an unknown degree of uncertainty. However, much could be gained by improving the specificity and accuracy of this element, as Cumming and Cockburn (1996) point out that in areas where soil layers are thin, pollution attenuation may not be sufficient to safeguard recharge water quality.

5.3.6 Evapotranspiration

Accurate estimates of evapotranspiration (ET) are hard to make as they require extensive and costly field measurements. WARMF calculates monthly PET in the following manner (Chen *et al.,* 2001):

The potential evapotranspiration for each month is calculated as a function of latitude according to Hargreave (1974). The monthly potential is converted to daily potential by:

$$E_p(t) = \frac{E_p(mon) T_a E_c C_H}{n}$$

Equation 5.1

where $E_p(t)$ = potential evapotranspiration in mm/day; $E_p(mon)$ = evapotranspiration of the month according to the empirical equation of Hargreaves (1974) in mm/^{o}F/month; T_a = mean ambient temperature of the day in ^{o}F; E_c = a calibration parameter; and CH = humidity correction factor.

$$C_H = 0.166(100 - H)^{0.5}$$

Equation 5.2

where H = relative humidity in percent. The value of CH is set equal to unity for H less than 64 percent (Chen *et al., 2001*).

Assessment of available data for Barbados

In light of the method of calculation employed, the only local data required for this component is relative humidity, which is computed by WARMF from the meteorology input data.

5.4 The reality of lack of data accessibility in Barbados

In making an assessment of existing datasets the issue and the reality of data accessibility deserves particular attention, as this can prove to be the biggest limiting factor despite having good quality (accurate and updated) data, and comprehensive models.

5.4.1 Agricultural census

As mentioned in section 5.3.3, nonpoint source pollution data is an important element for modeling pollutant-fate transport in order to allow for an understanding and evaluation of land-use practices on water quality. Chapter 4 identified the Agricultural Census (conducted by the MARD) as the main existing data-source for non-point source pollution from agricultural practices in Barbados, which largely contribute to Nitrate and Phosphorus pollution (Tosic, 2007) as well as additional chemical pollution (Klohn Crippen Consultants, 1997e). According to MARD personnel (anonymous, personal communication, 2007) this census (last conducted in 2006) contains information on: cultivated area, cultivated crop-type, agrochemical use, and possibly chemical application rates and irrigation methods and regimes. Despite numerous attempts throughout 8 months, and an initial assurance that data excerpts for a defined study-area would be provided for this thesis, the MARD was not forthcoming with the data, and simply refused to reply to any communication related to the matter. It should be noted that a formal request for this data, endorsed by senior staff at BWA was submitted to the MARD Permanent Secretary (2008). Without this data, an accurate account of recent actual agricultural practices and extent has not been provided, and besides the data contained in this census there is no other reliable source providing insight into the use of agrochemicals (specially of application rates) in Barbados. The lack of this data represents a substantial gap in the capabilities to provide decision support for water quality protection given the important role that agricultural land practices have on their effects on surface water quality in Barbados (Klohn Crippen Consultants, 1997e; Cumming and Cockburn, 1996; Leitch and Harbor, 1999; National Report; Tosic, 2007).

5.4.2 Latest landuse map

Similarly, as mentioned in section 5.3 one of the most essential elements for hydrologic modeling is accurate and updated landuse information which allows for: a) deriving the appropriate parameters associated to each land use category, which determine surface-flow characteristics (Chen *et al.,* 2001), and b) to spatially identify landuse activities and account for pollutants associated with these (Chen *et al.,* 2001). As illustrated in Table 4.1 (Chapter 4), national landuse maps exist for 1997, and 2006/7. The 1997 landuse map is actually a simplified update of a generalized landuse map created from 1996 air photos (Willms & Shier *et al.*, 1998c), and is now highly outdated for most of the island, given the rapid land use change (Leitch and Harbor, 1999) Barbados experiences. The 2006/7 landuse map (L&SD) produced for the "Digital Mapping Project" (DMP) starting in 2006 was derived from digital aerial orthophotography flown during 2006/7 and digitized at high resolution yielding a very accurate coverage (positional error of >20cm) of the entire island (Government of Barbados, 2005). The level of landuse categorization (weather generalized or specific) adopted for this landuse maps has not been ascertained. However, it can be said that this landuse map constitutes the most accurate and up to date map that exists for the whole of Barbados.

Numerous attempts were made to obtain a sub sample of this dataset, free of charge, from the Lands and Surveys Department (L&SD) for a determined study-area (Chapter 6) to be used for this thesis; all have not been successful. The formal request (2007) made to L&SD was endorsed by senior staff from BWA, McGill University Academics and the Barbadian Chief Town Planner. Despite coming very close to the acquisition of this data, ultimately, according to L&SD, the landuse data could not be provided at the time (December, 2007) as the appropriate copyright policies associated with this data had not been finalized then (Murrell-Forde personal communication, 2007). Furthermore, the data could not be acquired by the BWA directly as there was also at the time a deadlock on a previously negotiated cabinet decree related to the use of data produced for the

DMP by Government agencies (Dr. Ifil personal communication, 2007). Since the official announcement of the completion of the Digital Mapping Project, much concern has been raised about the inaccessibility of the data produced to both the general public and government agencies (Barbados Free Press, 2007; Dr. Ifil personal Communication, 2008). Furthermore, it was suggested by a member of the DMP tender review committee (Anonymous personal communication, 2005) that the data ultimately produced for the DMP was not derived from georectified (geometrically corrected) digital aerial photography (orthophotographs) with a positional accuracy of >20cm, as presented earlier and requested by the project's tender documents, (Government of Barbados, 2005). Anonymous (personal communication, 2005) instead suggests that the DMP constituted a "conventional" aerial photography exercise lacking the high spatial precession and accuracy provided by orthophotographs, and the requested (Government of Barbados, 2005) specifications for DMP products It was not possible to ascertain this information as Lands and Surveys Department declined to comment on the nature and specifics of available products produced for the DMP when further enquiries were made about the commercial purchase of this data in 2008.

5.4.3 Latest DTM DEM

As mentioned in table 4.1 (Chapter 4) an updated Digital Terrain Model, (DTM) and Digital Elevation Model (DEM) would have been produced as part of the DMP in 2006/7 (Government of Barbados, 2005). For the purposes of hydrologic modeling conducted under WARMF, accurate and updated topographic relief provided by a DEM (or even better DTM, as it allows accounting for drainage affected by manmade structures) constitute the most fundamental data input requirement (Chen *et al.,* 2001). The DEM resolution is of high importance especially in the case of Karst topographies, as different DEM resolutions can produce significantly large differences in modeling efforts as has been demonstrated by Fogle (1998). Considering these two products form part of the DMP data products, the acquisition efforts of these two datasets for the purposes of this thesis, where subject to the same fate as that described earlier for the new landuse maps. Furthermore, in the case that the argument presented earlier regarding the nature of final DMP products (Anonymous personal communication, 2005) holds true, the DEM and DTM previously mentioned would not have been possible to produce and therefore do not exist for Barbados.

5.4.4 Hazardous materials and illegal dumping sites information

Access to the EPD's information on hazardous materials storage, and illegal dumping sites was not permitted as a "government block" has been imposed on all data emanating from the EPD (Dr. Headley personal communication, 2005). This information, although lacking spatial reference to its occurrence could have provided useful information specially if it could be incorporated and analyzed in conjunction with the detailed and updated landuse map.

5.5 Previous NSDI attempts

Under the recommendations put forward by the Environmental Plan (Willms & Shier *et al.*, 1998d) and the work produced for EMLUP (Willms & Shier *et al.*, 1998c; Willms & Shier *et al.*, 1998b; Willms & Shier *et al.*, 1998a), an initiative was started to set in motion the formalization, adoption and utilization of GIS within the Barbadian government. This initiative entailed what can be considered to constitute the first formal effort to establish a NSDI in Barbados. This initiative mainly constituted the establishment of a "GIS National Committee", composed largely of government users, and some from the private sector, whose main purpose was to create and monitor national standards for data production, maintenance, quality assurance, data archives and security, metadata and dissemination of spatial data, as well as to advice on the development of appropriate frameworks and protocols for effective use of GIS in the island (Willms & Shier *et al.*, 1998b). At the onset of the committee the Chief Land Surveyor received the mandate to develop the use of GIS on the island; however after the committee's installation activities quickly stagnated, and to the frustration of many government users, nothing substantive from this NSDI initiative has been achieved up to date (Data Processing Department, 2005); Dr.

Brewster personal communication, 2005; Dr. Ward personal communication 2005; Dr. Yearwood personal communication 2005). To eventually materialize this NSDI initiative, it was formally agreed by cabinet, that the recommendations finally agreed upon by the National Committee be adopted into the national and departmental information technology (IT) policies (Data Processing Department, 2005).

5.6 Further data gathering and recommendations to appropriately meet requirements and maximize W-DSS potential

A more successful and insightful application of a Decision Support System for water quality protection than the work presented in Chapter 6 imminently necessitates of further data gathering efforts in order to fill the data gaps that presently exist in Barbados (previously discussed). Furthermore, accompanying data collection, it is also imminent that the appropriate institutional frameworks are established to ensure accessibility to this data if it is to be conducted for the purposes of implementing a DSS for water quality protection and management.

5.6.1 Surface runoff quantity and quality monitoring

In order to provide estimates of surface runoff with more certainty than values previously derived and presently used for various aspects of water resource management (i.e. Klohn Crippen Consultants, 1997c; Cumming and Cockburn, 1996; Stanley, 1998) in Barbados, the Stanley, 1998(1998) suggests that a significantly extensive stream gauging monitoring network is required, operating over a number of annual cycles, (Stanley, 1998).

It has been suggested (Cumming and Cockburn, 1996) that surface runoff quantity be monitored by the Drainage unit. Furthermore, Cumming and Cockburn (1996) suggest that the Drainage Unit should also assume the overall responsibility for the collection, analysis and publication of flow measurements resulting from other and previous investigation in Barbados. In these regards, it has been suggested (Yearwood personal communication, 2007) that the Drainage Unit in collaboration with Bellairs Research Institute and McGill University, initially focus on one “pilot” catchment to establish this surface water monitoring network to undertake further studies to understand surface runoff dynamics, sinkhole and suckwell hydraulics. The DU already has a fair amount of monitoring equipment for these purposes, but is overstretched for conducting this very important type of research fundamentally affecting water resource management in Barbados (Yearwood personal communication, 2007). The concept of establishing a “pilot” catchment study-site has also been previously proposed by Klohn and Crippen Consultants (Klohn Crippen Consultants, 1997b).

It has also been suggested (Cumming and Cockburn, 1996) that the installation and operation of a long-term surface water quality monitoring network be undertaken by the DU in conjunction with the proposed surface runoff [quantity] monitoring network to obtain a consistent data base of surface water quality inflows and outflows from sinkholes and suckwells in order to better understand water recharge and the potential for groundwater pollution (Cumming and Cockburn, 1996).

Cumming and Cockburn (1996) suggest that this quality monitoring programme could initially focus on a limited number of water quality parameters, such as: phosphorus, suspended solids, heavy metals and pesticides, as indicators of surface water pollution, which could then be expanded in the future as required. The objective of such a programme as suggested by Cumming and Cockburn (1996) is to identify management measures which should be implemented to prevent surface water pollution (Cumming and Cockburn, 1996). The use of a DSS can, in a shorter time period than that required for the approach implicit in Cumming and Cockburn’s suggestion, provide a large part of the assessment of the origins and amounts of pollutant loadings, and the evaluation of the management measures for reducing pollutant loadings. In this case, the data from the surface runoff monitoring network here described would merely provide the means to calibrate the surface hydrology models (by surface runoff quantity), and the means to calibrate the models assessing impacts on water quality (by water quality monitoring results). Ultimately water quality monitoring would serve the means to evaluate management-measure-effectiveness, and compliance to these as originally proposed by Cumming and Cockburn (1996).

5.6.2 Identification and categorization of critical suckwells and sinkholes

Given the role that Karst features play in water recharge (Chapter 2), it is crucial that these be systematically identified and categorized based on their hydraulic properties for the purposes of their monitoring and maintenance for water quality protection. Such categorization could be achieved by the DSS under a robust surface hydrology modeling effort provided these features were mapped and available digitally. As it has been previously postulated by Cumming and Cockburn (1996), the EMP (1998), and the BWA, it is imminent that the suckwell cataloguing/monitoring program be resumed and that it take further includes "sensitive" sinkholes found along waterways (possibly identified by surface hydrology modeling and GIS).

5.6.3 Extension to groundwater monitoring program

An extension to the groundwater monitoring programs to test for, on a regular basis, among other things, Nitrates and Phosphates was put forward by Klohn and Crippen Consultants (Klohn Crippen Consultants, 1997b) to be able to identify trends of significant concern that enable corrective action to be taken prior to degradation of the resource. Such an extension could serve the means of evaluating the effectiveness of management measures adopted to reduce groundwater pollution and could provide further insights into recharge, and pollutant-fate dynamics in Barbados. Groundwater monitoring results could be analyzed in relation to surface water quality monitoring results and through the aid of the DSS related or traced to a specific source. Klohn and Crippen Consultants (Klohn Crippen Consultants, 1997b Table 4.1) have provided a detailed proposal for a comprehensive water quality monitoring programme. Furthermore, the digital compilation of groundwater quality test results would largely facilitate data cross-checking and validation (Klohn Crippen Consultants, 1997b), analysis and further input into a more complex DSS than the one presented in this thesis (Chapter 6).

5.6.4 Reinforced weather station network and data collection

Given the existing weather station network in Barbados, which provides a long historical record, albeit with inconsistent spatial coverage; a strengthening of weather-station data collection with a focus on ample spatial coverage, and extended parameter recording, would be complementary to water management efforts. As Klohn and Crippen Consultants (Klohn Crippen Consultants, 1997b), the draft EMP (1998), and Cumming and Cockburn (1996), have previously highlighted; improvements in the collection of rainfall data, would require recording rainfall intensities, relative humidity, minimum and maximum temperature, and wind speed. Weather station distribution would be designed to be representative of, and provide data over, a range of elevations and aspects (slopes). Furthermore, it has been recommended (Klohn Crippen Consultants, 1997b) that for "pilot study areas", solar radiation be recorded at weather stations, as well as evaporation if possible. The EMP (1998) has further proposed that statistical analysis of storm rainfall be updated every five years to consolidate intensity duration frequency (IDF) curves, rainfall distribution maps and design storm characteristics. In addition, as has been previously recommended by Klohn Crippen Consultants (Klohn Crippen Consultants, 1997b) and the EMP (1998), it is important that weather station data be assembled and constantly fed into a database for easy access, analysis and reporting. A more comprehensive weather-station network with data accessible by digital means would significantly improve modeling efforts conducted within a DSS for water resource management.

5.6.5 Comprehensive contaminants inventory and database

The formalisation of established efforts in the area of possible and existing pollution point-sources identification, such as the EPD's illegal dumping sites monitoring programme, and the Pesticide Control Board's activities; can culminate in the establishment of a comprehensive contaminants inventory and database. Further information derived from landuse activities should also be considered and provided by the T&CPO. Such an inventory database would be best achieved within a GIS. The creation establishment of such georeferenced inventory has previously been recommended by the EMP (1998) and Klohn Crippen Consultants (Klohn Crippen Consultants, 1997a), who have provided detailed requirements for such database. Data availability on point-source pollution would certainly contribute towards water quality protection through the analysis and evaluation of their effects on the water resource provided by a DSS.

5.6.6 Strengthening of information on soil and soil profiles

Considering the state of the existing soils digital map discussed in section 5.3.5, and following from the recommendations put forward by EMLUP (Willms & Shier *et al.*, 1998c) in this domain, a strengthening of information on soil and soil profiles would prove beneficial to water resource management and protection by the aid of a DSS. This would mainly constitute of the full digitizing of the Vernon and Carroll (1964) soils map and associated information as previously recommended by EMLUP (Willms & Shier *et al.*, 1998c). For "pilot study" sites it has been suggested (Klohn Crippen Consultants, 1997b) that soil moisture profiles be acquired. If the Vernon and Carroll studies and maps do not contain significant information on soil horizon profiles, these should be undertaken for "pilot study" sites as well. (It was not possible to acquire the Vernon and Carroll studies and maps for evaluation in this thesis).

5.6.7 Establishment of an imminent NSDI

Reviving or re-establishing an initiative to create a NSDI would provide the most effective means for the compilation, storage, analysis and dissemination of the information produced from the data gathering efforts recommended above. However, as noted by (Willms & Shier *et al.*, 1998b; p7) "the absence of a government wide-area and local cabling infrastructure is a major constraint to implementation of improved government information systems and the development of fast, effective and modern communications". Willms & Shier *et al.*, (1998b) provide numerous useful recommendations for pursuing the establishment of a NSDI in Barbados, by simultaneously tackling technical and infrastructural requirements as well as the institutional aspects required. The Willms & Shier *et al.*, 1998a report specifically addresses the natural resources data required in support of the draft Environmental Management Plan (Willms & Shier *et al.*, 1998d) and Physical Development Plan (1998), specifying who should collect and manage it, and the desired frequency of revision. (Willms & Shier *et al.*, 1998a) Further advantages can be gained by learning from other Caribbean countries' experiences in creating and adopting SDIs by participating in fora such as the URISA 4th GIS Conference held in Grand Cayman in 2008 (URISA, 2008).

5.7 Conclusion

While a preliminary demonstrative application of a DSS for water quality protection and management has been achieved in an academic setting (Chapter 6) by using some of the datasets available in Barbados hereto presented and described; it should be noted that, under the prevailing circumstances, as they relate to institutional aspects and data availability and accessibility; such application in a larger scale to be employed for real water quality protection and management decision making is not deemed possible in Barbados at the time. The following Chapter provides a demonstration of some of the possibilities offered by the application of a DSS for water quality protection and management, further highlighting the necessity and importance of availability and accessibility of adequate data to yield meaningful and useful results (further discussed in Chapter 7).

Chapter 6: A demonstrative application of WARMF as a DSS for water quality protection and management

6.1 Introduction

This Chapter presents the demonstrative application of a DSS for water quality protection and Management. In contrast to the rest of this thesis, the discussion in this chapter is more technical in nature, but builds upon, and reinforces the material covered in previous chapters. While the detailed exploration and technical discussions about modeling a Karstic system such as that of Barbados is worthy of the entire focus and research of an entire thesis; in this thesis they have been limited to the final two chapters. This has been done under the premise that: in the context of a pragmatic approach for implementing a DSS for water quality protection and management in a national setting; the importance of attaining the necessary institutional frameworks, and provision of necessary "data bases" [not databases] for achieving modeling efforts efficiently, take precedence over the in-depth conceptual and practical technicalities associated with hydrological modeling and decision support. However, these practical and conceptual technicalities cannot be left out of sight, as they in turn shape the nature of the "data bases" and, to a certain degree, the institutional characteristics required for a meaningful and successful DSS application as this thesis aims to demonstrate.

Against the backdrop of the relevance of previously presented material, in particular this chapter presents an overview of the *data used* for DSS implementation, the *data preparation process*, the *choice of a study subwaterhed*, the subsequent *data integration into WARMF*, together with the *system parameters used in WARMF base simulation*, as well as a description of *simulation-run characteristics and alternative scenario*. Finally the *Results* from both base and alternative scenarios are presented, paying particular attention reiterate the importance and necessity of adequate data and exploring the effects of its use.

6.2 Data Used for Study-Watershed Delineation

The following data layers were used in order to delineate the study watersheds. These data were chosen as they were readily available, and the most suitable (in terms of data integrity, and collective spatial coverage) to conduct a modeling effort appropriate for the intended purposes of demonstrating the potential of WARMF as a DSS for water quality protection and management.

Table 6.1 Data used for the implementation of WARMF DSS

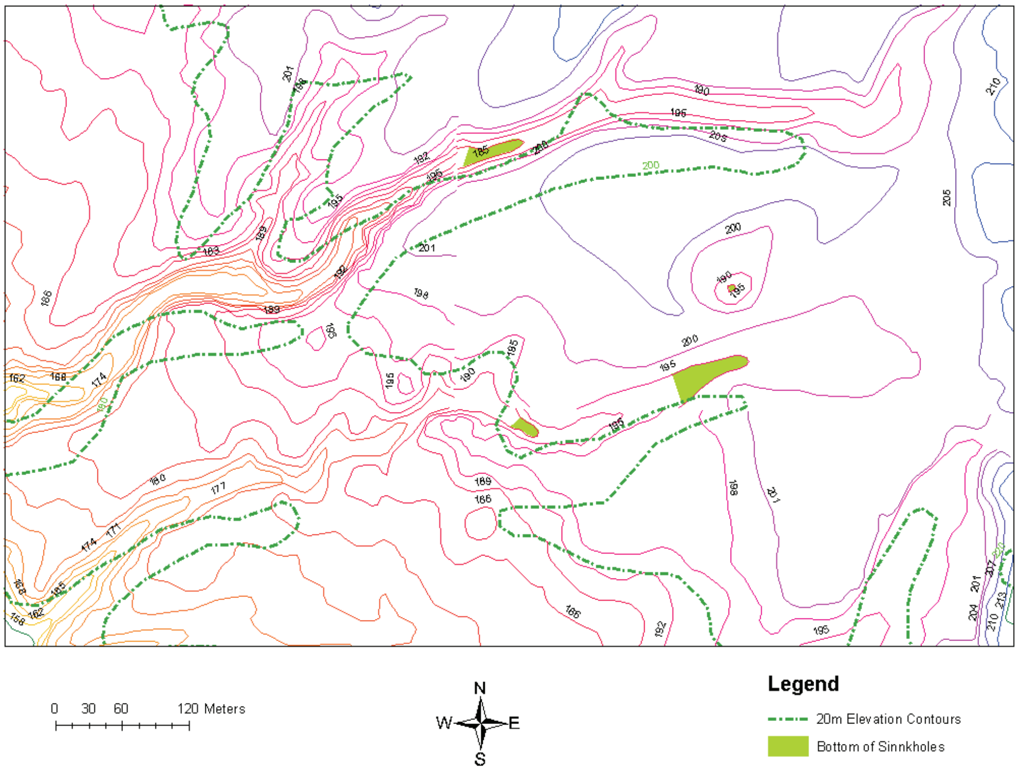
Data layer	**Source**
10ft contours from	*Baird and Associates Consultants*
Rationale:	In order to account for the occurrence of Karst features, and detailed drainage dynamics in Karst topographies, it is necessary to use the finest scale of available topographic survey data (*Fogle, 1998*). This is the finest scale dataset, which accounts for the occurrence of sinkholes and Karst features, and was readily available for this thesis.
2006 Landuse map	*Tosic (2007)*
Rationale:	It is important to account for the reality of landuse related to the timeframe of the modeling carried out in order to properly understand and account for pollutants and their transport associated to landuse practices. This landuse map is the most updated and was the most readily available for this thesis.
Weatherstations	*CIMH, CZMU, Baird* and *Associates Consultants*
Rationale:	As discussed in Chapter 5, weather station data is one of the most fundamental requirements of WARMF. The Datasets used (Table 6.8) provided the most adequate spatial and temporal coverage associated with available water quality and quantity observations (Tosic, 2007), and were the most readily available for this thesis.
Soil profile	*Muhs (2001)*
Rationale:	It is important to account for soil hydraulic characteristics to provide more accurate modeling of hydrologic dynamics (Chen *et al.,* 2001). Muhs (2001) provided the only available detailed soil profile information readily available from soil samples for an area 135m away from the delineated watershed (see below) at its closest, and 3.5km away at its furthest point.
Water quality measurements	*Tosic (2007)*
Rationale:	These data were/could have been used to calibrate the WARMF models. This data is of the few of its kind available (Chapter 5) and was the most readily available for this thesis.
Surface water quantity observations	*Tosic (2007), Baird and Associates Consultants*

Rationale:	These data were/could have been used to calibrate the WARMF hydrologic model. This data is also of the few of its kind available (Chapter 5) and was the most readily available for this thesis.

6.3 Data Preparation Process

In order to delineate watersheds a Digital Elevation Model (DEM) derived from topographic survey contours may be used (*Fogle, 1998*; Jenson and Domingue, 1988, Tarboton *et al.*, 1991). Using ESRI's ArcInfo 9.1 with Spatial Analyst and 3D Analyst extensions, a 1m DEM was created from ~3m (10ft) contours (Baird and Associates Consultants). A cellsize of 1m was chosen, after analysis of the elevation contours revealed that the closest distance between two consecutive contours found was ~60cm; a 1m grid cellsize would provide detailed coverage of such "abrupt" changes in topography over small distances (especially found along Karst features and gullies). Figure 6.1 shows an example of abrupt changes in topography shown by the ~3m (10ft) contours, and the occurrence of sinkholes. For comparison purposes the 20m contours available in the NRDB are shown. The details provided by the ~3m (10ft) Baird and Associates contours are completely missed out by the 20m contours; furthermore, the latter are spatially off-shifted South-Westerly.

Figure 6.1 Elevation contour display and comparison

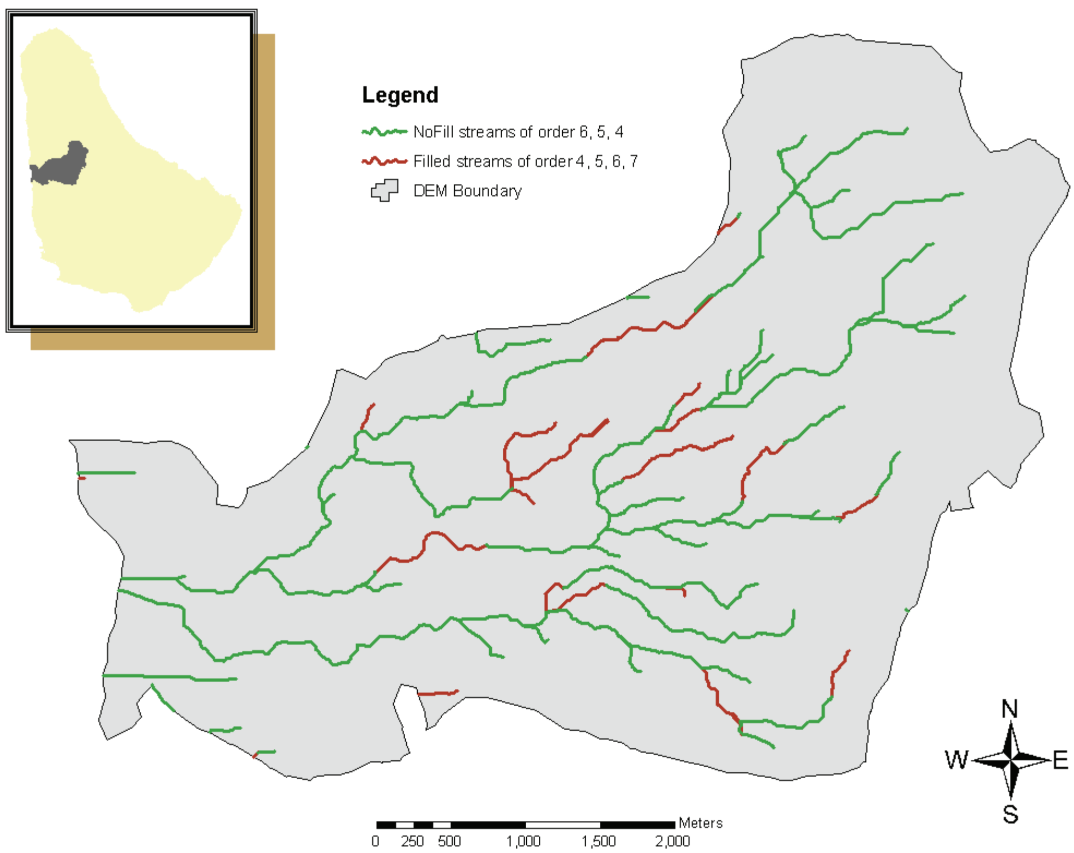


6.3.1 Filled Vs Not-Filled DEMs and Stream Networks

According to the procedures set forth by Tarboton *et al.* (1991) and Jenson and Domingue (1988) for watershed delineation from DEMs within a GIS, the DEM used must be "hydrologically corrected" to eliminate internal drainage prior to stream extraction and watershed delineation. However, in the case of Barbados the internal drainage that occurs within catchment areas is a reality attributed to Karst features (Chapter 2), and not merely the result from DEM inaccuracies (Mark, 1988). In light of this, the produced DEM was studied to reveal areas of internal drainage. Areas >1m^2 in most cases appeared to be "surveyed" sinkholes, and were thus excluded from the "hydrologic correction / Fill", processing of the DEM for watershed and stream network delineation (Mark, 1988; Jenson and Domingue, 1988; Tarboton *et al.*, 1999) and they are assumed to represent existing sinkholes.

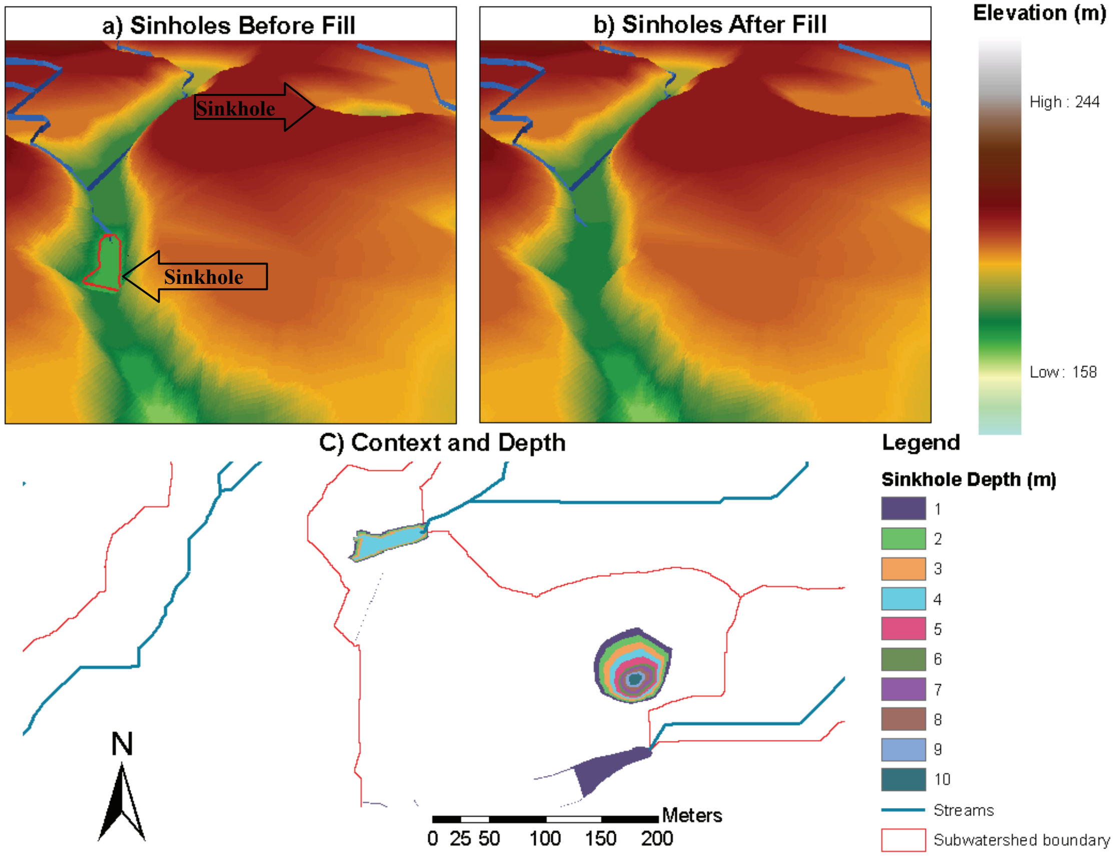
By using the DEM retaining sinkholes, the stream network (surface water accumulating in gullies) was derived from the DEM in accordance with Tarboton *et al.* (1991). From "Accumulated flow" a "rivers/streams" vector file was created from areas where 1,000 cells' accumulated flow (Tarboton *et al.*, 1991) occurred. These streams were subsequently ordered (Strahler, 1957). Figure 6.2 illustrates a comparison of streams produced from the filled and un-filled DEMs. Figure 6.6 illustrates the difference (in 3D view) between the un-filled DEM (**a**), and the filled DEM (**b**) in an area where sinkholes occur both in a gully and outside of it.

Figure 6.2 Comparison of streams produced from Filled and Non-Filled DEMs



The streams produced from the Filed DEM are long and contiguous across the entire watershed, and are only revealed where Non Filled streams become intermittent. The difference in the number of orders obtained for Filled and Non-Filled streams is associated with more cells accumulated flow for those streams extracted from the filled DEM. In both cases the threshold used to extract streams (Tarboton *et al.*, 1991) was 1,000 cells of flow. It's important to reiterate that Non Filled streams end in areas of internal drainage that have been identified as (or assumed to be) sinkholes.

Figure 6.3 Comparison of Filled and Non-Filled DEMs, and the occurrence of Sinkholes



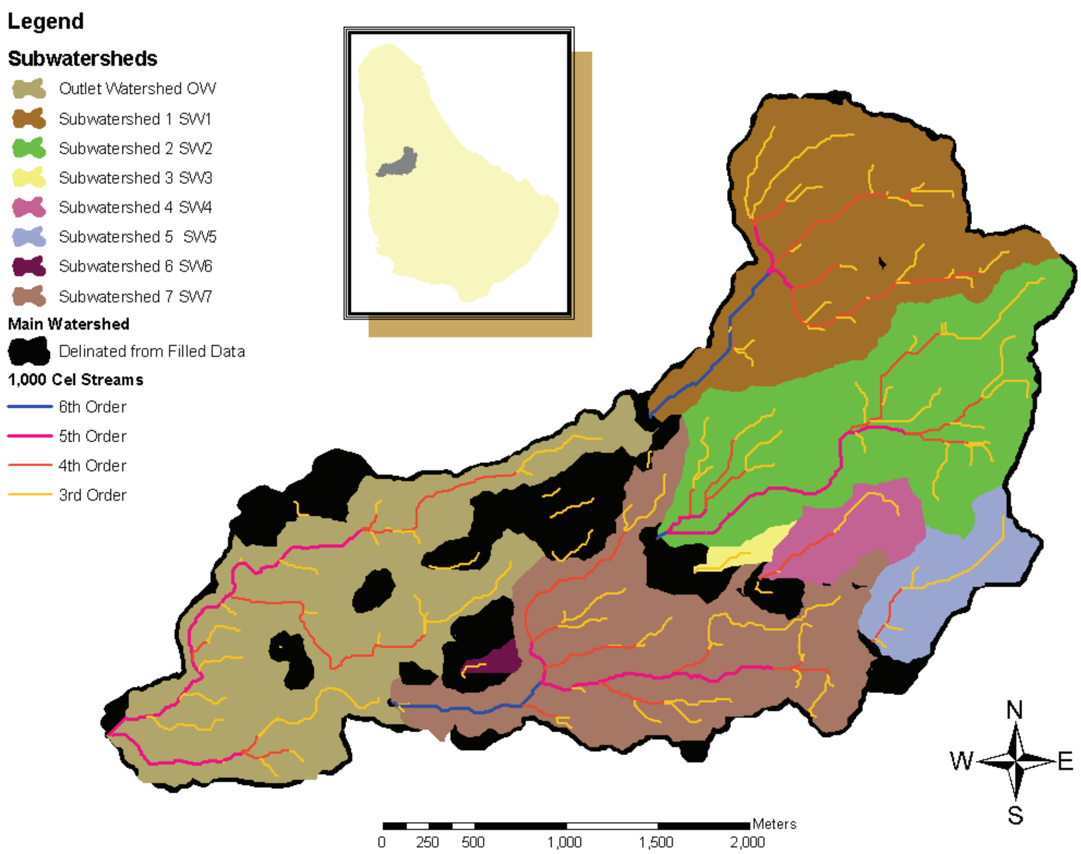
(**a**) Non Filled DEM with sinkhole occurring within the gully and outside of it. (**b**) Filled DEM shows the "disappearance" of sinkholes by the "hydrological correction / Fill" process. (**c**) The sinkholes appear at the edge of delineated subwatersheds as they have been used as outlets/pour points. Depths of sinkholes are shown. Streaks of 1m^2 cells can be observed which are exemplary of DEM creation inaccuracies, for which the "hydrologic correction" process is normally necessitated (Mark, 1988).

6.3.2 Watershed / Sub-watershed Delineation

Following the procedures put forth by Jenson and Dmingue (1988) and Tarboton *et al.* (1991) the Holetown watershed draining into the "Holetown lagoon" (Tosic, 2007) was delineated using the "Filled streams" network (Figure 6.2).

In light of the occurrence of internal drainage into sinkholes that occurs in Barbados (Chapter 2), and evidence supporting internal drainage and aquifer recharge in the Holetown watershed (Tosic, 2007); sinkholes occurring in gullies (along streams) were used as “outlets / pour points’ for delineation (Jenson and Domingue, 1988; Tarboton *et al.*, 1991) of subwatersheds (Figure 6.3 a, and c). Through this process 8 subwatersheds were thus obtained (Figure 6.4)

Figure 6.4 Deliniated Watershed and Subwatersheds



The “Main watershed” (shown in the background of subwatersheds) has been delineated from the Filled DEM and by using the streams extracted from the same DEM, and the Holetown lagoon channel Inlet used as a pour point. The subwatersheds were delineated from the Non-Filled DEM using the sinkholes (areas of internal drainage >1m^2), and stream network derived from the Non-filled DEM as outlets for all SW subwatersheds. For OW, the Holetown lagoon channel inlet has been used as an outlet. Blank areas in the subwatersheds (where the main watershed is revealed in the background) indicate areas where water drains into a sinkhole, that were not deemed large enough, lacking an “insignificant” stream network (>4th order) to constitute a subwatershed. SW3 and SW4 are examples of the size and nature of subwatersheds delineated for these “insignificant stream” areas.

6.4 Choice of a Study Subwatersheds

In order to explore and provide a demonstration of the potential WARMF offers as a DSS for water quality protection and management efforts have been focused on one of the delineated subwatersheds as a study site. The choice to focus at such a large spatial scale is due to the high computational requirements associated with the use of 1m DEM processing, and the associated lengthy data preparation.

The study-subwatershed has been chosen under the criteria provided in Table 6.2.

Table 6.2 Study-site selection criteria and rationale

Criterion	Rationale
Meeting availability of water quantity and quality observations.	It is necessary to calibrate the hydrological model driving WARMF's water quality models in order to assimilate the model as close as possible to reality. Observed data water quality data, and surface discharges are essential for calibration purposes (Chen *et al.,* 2001).
Meeting availability of nearby comprehensive set of weather-station data (satisfying WARMF requirements)	Weather station data is the main driver of WARMF models (Chen *et al.,* 2001) and a reliable and complete (as much as possible) long term historical record of weather station data is required in order to provide long term predictions and evaluations (Chen *et al.,* 2001).
Varied landuse including significant agriculture.	Different landuses have different effects on water quality, and hydrologic dynamics (Chen *et al.,* 2001). It serves to study various land uses in isolation and in combination and how they affect water quality. A combination of varied landuses would allow to investigate varied management practices or policies.
Relation to water protection zones, groundwater catchments, public supply wells and other abstraction wells.	As aquifer recharge mainly occurs through sinkholes and Karst features (Chapter 2) it is important to account for the locations where water quality degradation occurs and where the degraded water is possibly discharging to and how it may be contributing to groundwater recharge.
Availability of nearby detailed soil profiles.	Soil hydraulic parameters (derived from soil profile information such as soil texture) are an important element for model adaptation and calibration (Chen *et al.,* 2001).

Fig 6.5 provides the means used to evaluate the criteria presented in Table 6.2 for the selection of a study subwatershed.

Figure 6.5 Context for Study-site selection criteria

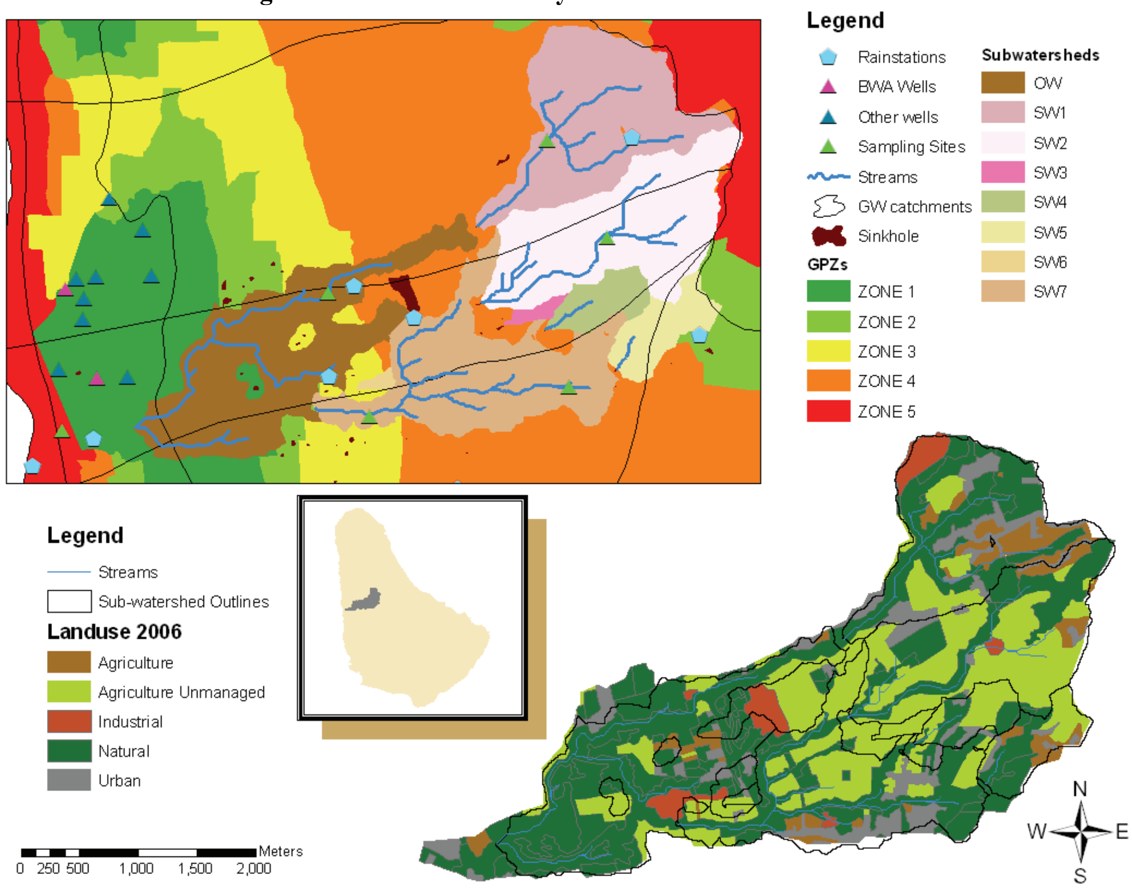


Figure 6.5 Top presents the delineated subwatersheds superimposed on GPZs (Chapter 3). Groundwater catchments (Chapter 2) have been superimposed on top of subwatersheds, and abstraction wells (PWS and other) are shown together along with weather station and observed data sites available for use. The large "sinkhole" found in the middle of the main watershed is a Quarry (Tosic, 2007). Bottom presents the generalized 2006 landuse categorization (Tosic, 2007) for the entire "Main" watershed together with the outlines of subwatersheds.

6.4.1 Selected Study Site

Subwatershed 1 (SW1) has been chosen as the study site for demonstration proposes of using WARMF as a DSS for water quality protection and management. This subwatershed is situated on a predominantly Zone 4 area (98.53%) and partly on Zone 5(1.47%) which is indicative of few restrictions affecting water quality (Chapter 3), has the most varied landuse (Figure 6.5) of the main watershed, lies completely within a groundwater catchment where a public supply well (PSW) is located downstream (the recharge flowing into the sinkhole at its outlet could be well connected with the well's influence area).

Furthermore, SW1 contains a weather station within it, and is situated in Mount Hilaby; the area of highest precipitation in the entire island. Lastly, water quality measurements are available (Tosic, 2007) for a sampling site within SW1, and the closest soil profile sample point (Muhs, 2001) is 3.5 Km away. Figure 6.6 provides a more detailed view of SW1 and its choice-criteria context.

Table 6.3 Landuse areas and percentages for Study site

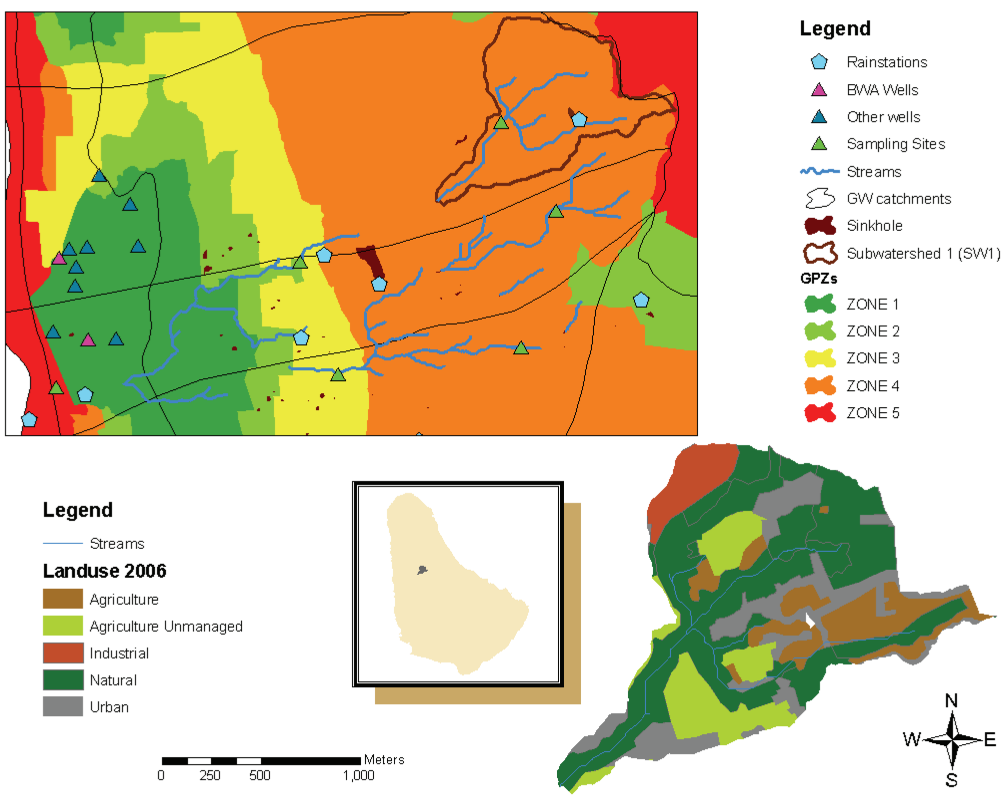
Agriculture	Natural	Urban	Industrial	Agriculture Unmanaged
0.236 Km^2	0.871 Km^2	0.318 Km^2	0.103 Km^2	0.254 Km^2
13.23 %	48.88 %	17.86 %	5.79 %	14.25 %

Table 6.4 Soil profile for B6 sample 3.5 Km SW of SW1 (From Muhs, 2001)

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	BD (g/cm^3)
A	0 - 5	16	6	78	1.35
AB	05 - 15	16	3	81	1.46
Bwl	15 - 19	12	1	87	1.46
Bw2	19 - 39	12	1	87	1.33
Bw3	39 - 44	2	2	96	1.22

BD = Bulk Density

Figure 6.6 Subwatershed 1 (SW1) selection context



6.5 Data integration into WARMF

The public domain version of WARMF has been used to provide a demonstration of the potential of using WARMF as a DSS for water quality protection and management. This public domain version has certain limitations (Chen *et al.,* 2001); the main one being the delineation of watersheds and watershed characteristics from within WARMF. In order to achieve this essential task for subwatershed 1 (SW1), the USEPA's (1998) Better Assessment Science Integrating Point & Nonpoint Sources (BASINS) model (v4.0) was used externally as indicated by a technical document provided with WARMF (Chen *et al.,* 2001).

After a successful [re]-delineation of SW1 (using the original Non-filled DEM and Non-Filled streams network as inputs) SW1 watershed, sub-basins (delineated for each stream segment) and watershed characteristics produced by BASINS were imported into WARMF following the procedures outlined in Chen *et al.,* (2001). (The subwatershed delineated by BASINS corresponding WS1 is for all practical purposes identical to the original SW1 discussed earlier; similarly the stream network is also identical as 1,000 cells was chosen as extraction threshold). The attribute tables for the SW1 watershed delineation and streams files produced by BASINS have been provided in Appendix 2.

6.6 System Parameters used in WARMF base simulation

A printout of WARMFs control file, which provides a detailed listing of all parameters used to run the presented WARMF simulation is presented in Appendix 2. Key parameters used are presented hereafter.

6.6.1 Land Use

Landuse information was imported from the 2006 landuse map for the Holetown watershed (Tosic, 2007). WARMF uses different landuse categorization (Chen *et al.,* 2001), associated to predetermined parameters, than that provided in the original map. A re-categorization using WARMF landuses was performed prior to importing this data into WARMF. Table 6.5 presents a summary of the new categorization for SW1.

Table 6.5 WS1 WARMF landuse categories and areas

WARMF Landuse Category	Area Km^2	Percent
Barren	0.12	2.59%
Commercial / Industrial	0.44	9.81%
Mixed Forest	2.87	64.46%
Pasture / cropland	0.56	12.55%
Rangeland	0.47	10.59%
Grand Total	**4.45**	**100.00%**

6.6.2 Soil

Soil parameter information may require extensive field investigations to acquire the appropriate parameter values for best modeling results (Chen *et al.,* 2001). Various soil layer parameters were derived from Muhs' (2001) soil sample data. Table 6.6 shows soil parameters used in WARMF simulations for WS1; shaded parameters were derived from Muhs' (2001) data. Parameters not highlighted were left with default WARMF values.

Table 6.6 Soil parameters used in WARMF for SW1

Soil Layer	**1**	**2**	**3**	**4**	**5**
Thickness (cm)	5	14	10	10	10
Initial Moisture	0.3	0.2	0.22	0.35	0.35
Field Capacity*	0.45	0.3	0.22	0.2	0.2
Sat. Moisture*	0.6	0.45	0.35	0.35	0.35
Horizontal Conductivity. (cm/d)+	23	12	12	6	6
Vertical Conductivity. (cm/d)*	23	12	12	6	6
Root Distribution.	0.75	0.1	0.1	0.05	0.05
Bulk Density g/cm^3	1.35	1.46	1.46	1.33	1.22
Soil Tortuosity	10	10	10	10	10
Soil Erosivity factor	0.2				

***** The values for these parameters were derived from the USDA's soil characteristics calculator (Saxton and Rawls, 2006) by using soil texture as inputs. However, for high clay compositions such as those found in Barbados it is not possible to compute the desired parameters by soil equations (Saxton and Rawds, 2006). In light of this the highest Clay content soil texture (60%) has been used in association with Sand and Silt percentages given by Muhs (2001).

+ Horizontal conductivity has been assumed to be the same as vertical conductivity for the simulations here presented. The values here assigned have been derived as a combination of results from the soil characteristics calculator (Saxton and Rawds, 2006) for highest % Clay content soil, and the values presented by Tullstrom (1964) for areas above the Second High Cliff (Chapter 2).

6.6.3 Fertilization

In the absence of information related to fertilizer application rates for agricultural areas, WARMF default values have been used for agricultural areas. Furthermore, other pollutant loading values are assigned in WARMF for different landuses. These values can be specified by the user but rely on the knowledge of actual average pollutant loadings associated to landuse; as discussed in Chapter 4, lacking in Barbados. Table 6.7 presents the most relevant WARMF fertilization values used for all months for landuses observed in SW1.

Table 6.7 WARMF Fertilization values for SW1

Landuse	Fecal Coliforms $x10^6$/ha	Potassium kg/ha	Nitrate	Phosphate kg/ha	Ammonia kg/ha
Cropland / Pasture	50,000	4.4	-	1.4	2.1
Mixed forest	20	-	-	-	-
Barren	100,000	-	-	-	-
Residential	50,000	-	0.01	0.01	0.005
Commercial / Industrial	50,000	-	0.03	0.01	0.01

6.6.4 Meteorological data

Since not all parameters needed by WARMF are recorded by any one single weather station in Barbados, a combination of weather stations with close proximity to WS1 was used to derive the final dataset used in WARMF simulations. Table 6.8 presents a summary of data obtained from weather stations.

Table 6.8 Summary of Weather stations and data used in WARMF

Station Name	Latitude	Longitude	Parameters Used	Station managed by:
Hilaby (in SW1)	-59.5904	13.2104	CZMU/Baird	Rainfall
Sunswept	-59.6383	13.1847	CZMU	Min Temp, Max Temp, Dewpoint, Atmospheric Pressure and Wind speed
Husbands	-59.6236	13.1490	CIMH	Hours of sunshine

These data were compiled and put in the format required for input into WARMF. The meteorology file used in WARMF simulations has been provided in Annex 2.

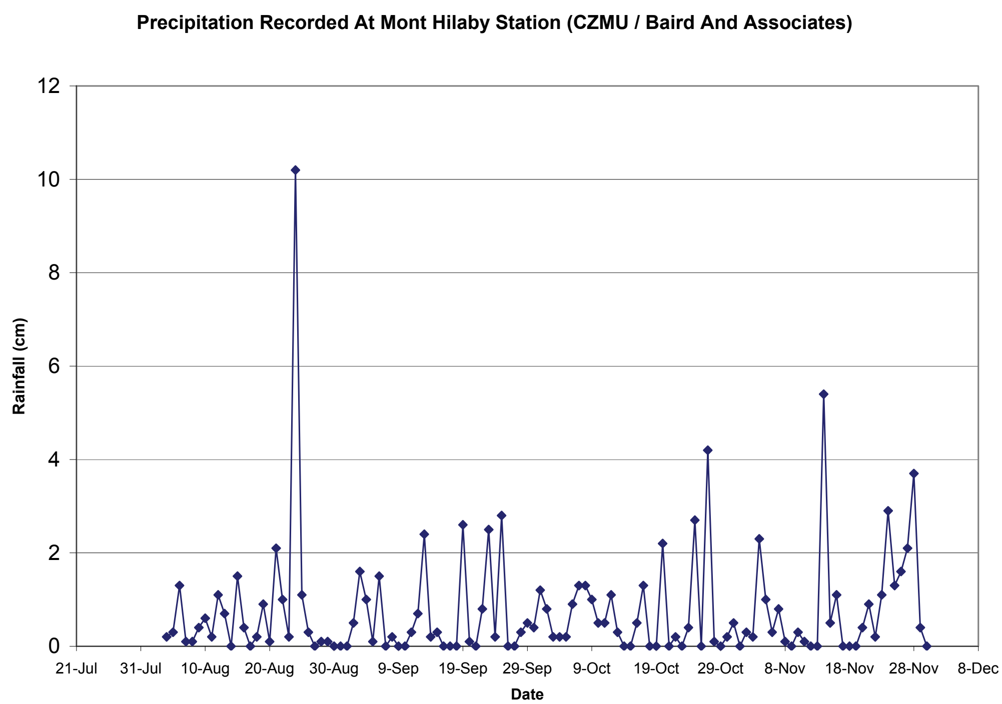
6.7 Simulation Run-characteristics and Alternative scenario

6.7.1 Period of Simulation

The period of simulations presented hereafter has been limited by the availability of weather station data which didn't collectively present many gaps for all weather stations used (Table 6.8). Similarly it was desired to cover a period of time for which observed data (Tosic, 2007) was available for assessing the model (calibration, in Chapter 7, is not possible with the available data).

The simulation period presented, which meets the above criteria is August 1 to November 30, 2006. Within SW1 for this wet season period, several large rain events were registered, with various which produced >20mm "recharge quantity" events (Chapter 2). This time period was therefore used for the elaboration of the "base scenario" and "alternative management scenario".

Figure 6.7 Precipitation Recorded at SW1 for Period of Simulation



The base scenario represents a modeling (simulation) of the system as it "would" be in reality (Chen *et al.,* 2001), adopting as much as possible the model to local characteristics that govern hydrological, biophysical and pollutant-transport dynamics (Chen *et al.,* 2001). The alternative management scenario simulates the effects of altered parameters which resemble the implementation of management measures devised by the user (Chen *et al.,* 2001). For this thesis one alternative management scenario was developed (following).

6.7.2 Scenario Considerations

In order to provide an example of a context for decision support for water quality management, other than that provided by the "base" simulation (discussed later) one scenario has been developed to analyze impacts on water quality as factor of implementing grassed buffer strips on along the edges of streams.

Grassed buffer strips are a structural management measure (Chapter 3) previously suggested for Barbados (Cumming and Cockburn, 1996), their implementation has been simulated in this scenario which has been developed for selected sub basins within WS1 (Figure 6.14) identified after the "base scenario" simulation was preformed (discussed later).

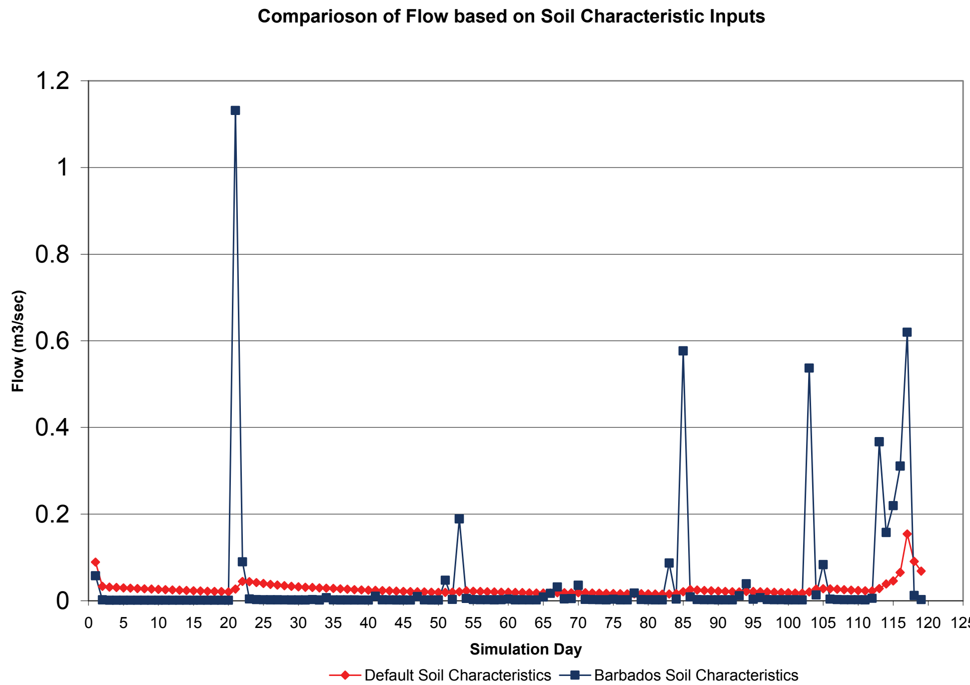
6.8 Results

6.8.1 Base Scenario Simulation

The results obtained, after model setup and preparation (Chen *et al.,* 2001), for the base scenario are presented hereafter. These results mainly constitute of the state of, and changes in, over time and space, of: surface hydrology, water quality, and pollutant transport.

Figure 6.8 presents the simulation of flow in SW1 resultant from the WARMF hydrological model. For demonstration purposes, the simulated flow of a model run where the model hasn't been adapted to local soil characteristics for Barbados (Muhs, 2001) has been presented. With default values, most precipitation is lost by rapid infiltration to the thick soil layers represented by WARMF values, whereas in the case of Barbados, during large rainfall events much runoff is generated soon after the Clay soils become saturated (Chapter 2).

Figure 6.8 Simulated flow for SW1



A large difference in simulated flows can be observed for simulations using Barbados specific soil characteristics (Muhs, 2001) and default WARMF values. The differences are most significant for the system's response to large rainfall events.

Despite having been able to "hydrologically adapt" the model to a certain extent to the local reality of the system, mainly by the use of soil characteristics provided by Muhs (2001), it is very important to emphasize that the model here presented has not been calibrated (Chen *et al.,* 2001) mainly due to the lack of a substantial set of observed flow and water quality data availability, as well as lack of other data for Barbados (Chapter 4 and 5). Therefore the results here presented are merely for demonstration purposes of WARMF as a DSS for water quality protection and management, and cannot be guaranteed accurate or used for any real analysis or decision support. For this reason little attention has been focused on the analysis of these results; their discussion rather focuses on highlighting importance of data availability which would be best provided by a formalized NSDI (Discussed in Chapter 7).

Following are some of the water quality outputs generated by WARMF during the "base scenario" model run. The presented results correspond to the outlet of SW1, which would indicate water quantity and quality parameters that could be expected to partly infiltrate into the sinkhole at the outlet. It should be highlighted that WARMF is able to provide these results for any stream segment, or sub-basin for which the model is setup for. Output constituents simulated by WARMF are presented in table 6.9

Table 6.9 WARMF simulated constituents available

Constituent	Units	Constituent	Units	Constituent	Units
Flow	m^3/s	Aluminum	mg/l	Pesticide 1*	mg/l
Elevation	m	Calcium	mg/l	Pesticide 2*	mg/l
Volume	m^3	Magnesium	mg/l	Pesticide 3*	mg/l
Depth	m	Potassium	mg/l	Fecal Coliform	#/100 ml
Velocity	m/s	Sodium	mg/l	BOD	mg/l
Spill	m^3/s	Sulphate	mg/l S	Dissolved Oxygen	mg/l
Flow Adjust	m^3/s	Nitrate	mg/l N	Carbon Dioxide	mole/l
Temperature	ºC	Chloride	mg/l	BlueGreen	ug/l Chl-a
SOx	ug/ m^3	Phosphate	mg/l P	Diatoms	ug/l Chl-a
NOx	ug/ m^3	Alkalinity	mg/l CaCO3	Green Algae	ug/l Chl-a
pH	S.U.	Org. Carbon	mg/l	Silica	mg/l Si
Ammonia	mg/l N	Inorg. Carbon	mg/l		

* The public domain version of WARMF does not allow modelling the transport and fate of user defined pesticides. However this is available in the paid-for version.

Figures 6.9, 6.10 and 6.11 are presented as examples of the type of output WARMF produces. There is no discussion associated to the results presented in these figures as these results are not accurate due to the lack of model calibration by lack of observed data.

Figure 6.9 Simulated Fecal Coliforms at the outlet of SW1

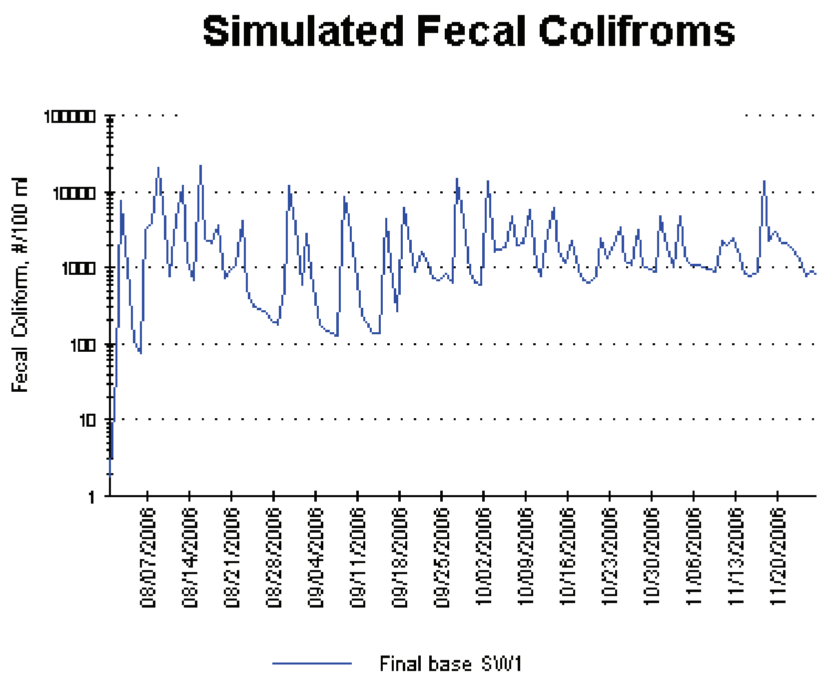


Figure 6.10 Simulated Total Phosphorus at the outlet of SW1

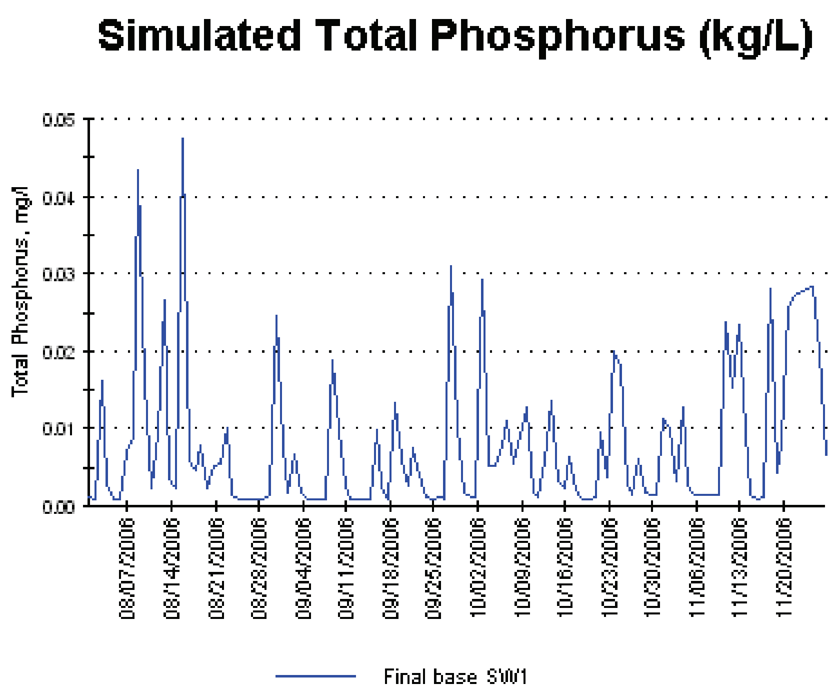
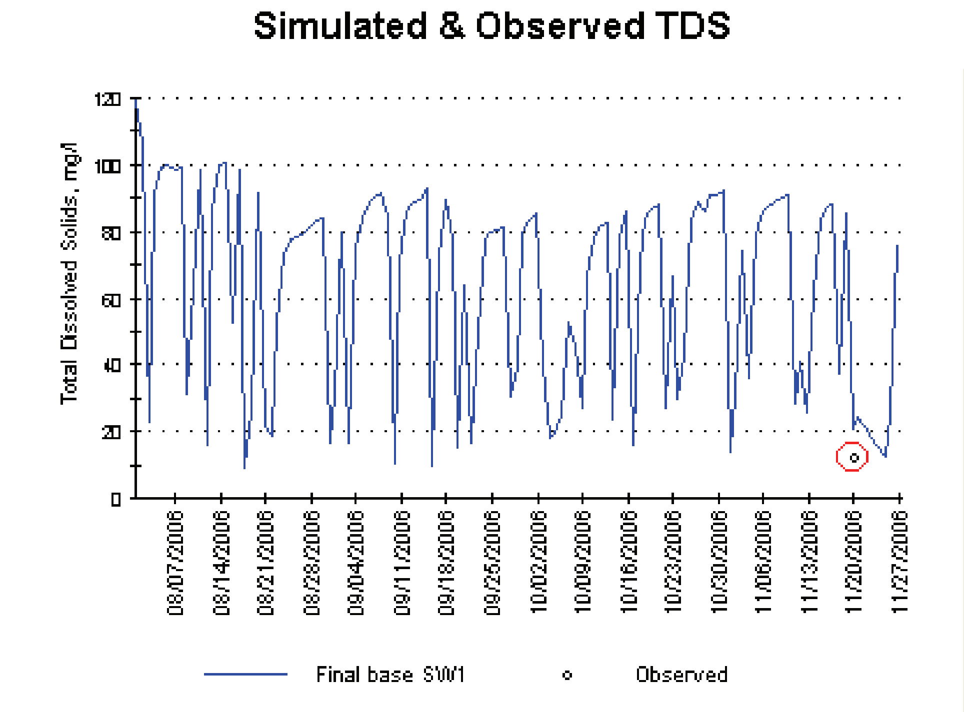


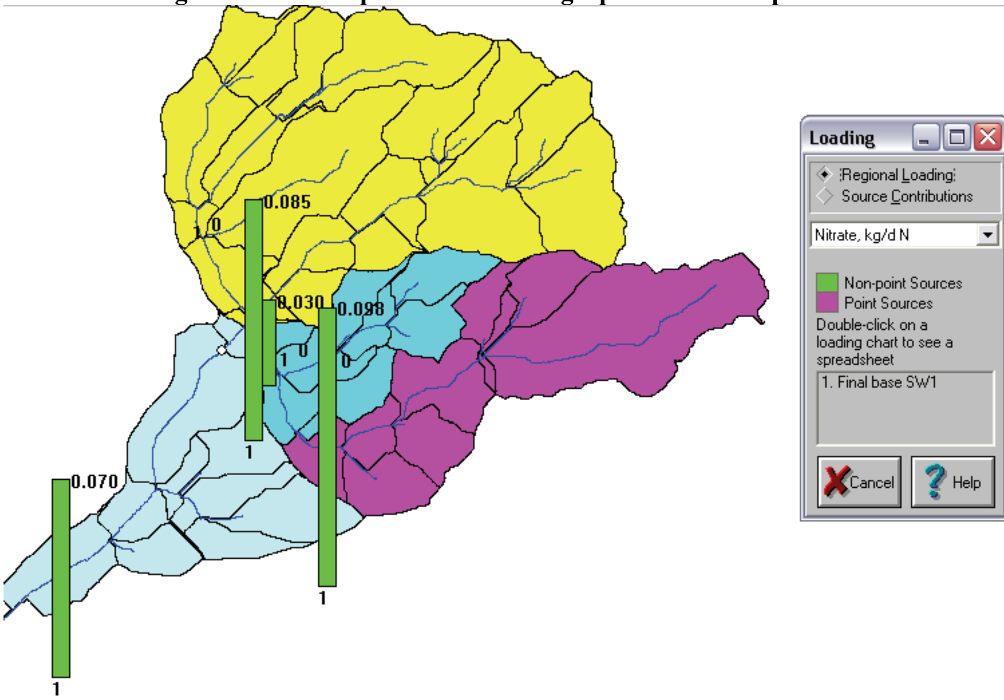
Figure 6.11 Simulated and Observed Total Dissolved Solids for a stream segment in SW1



Only 3 points of observed water quality are available for November 23, 2006 from Tosic (2007) which is useful for model comparison. The one with the least absolute error (Tosic, 2007) (7.841) is presented here (the absolute error for the other two points is: 9.32 and 10.39). It is important to emphasize that 3 points of observed data for one month cannot be used for calibration purposes of an entire model.

WARMF provides a GIS "graphical" output of results to aid decision making. Figure 6.12 presents an example of such graphical representation of results for average (over the simulation period) regional Nitrate loadings attributed to streams from different user-defined sub-watersheds for WS1.

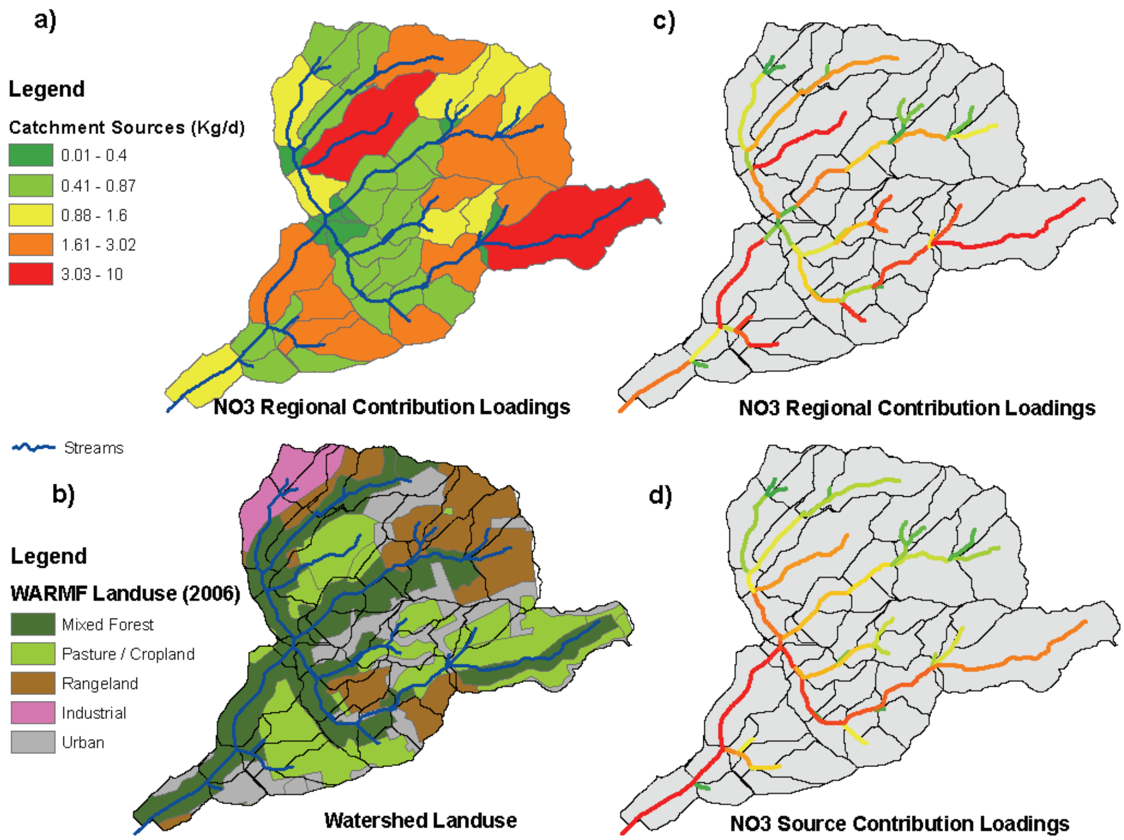
Figure 6.12 Example of WARMF's graphical GIS output for SW1



Bar Charts represent the average (over the simulation period) Nitrate regional loadings contributed by the interactively-user-defined sub-watersheds (shown in different colours) to streams. Bar Charts can be produced showing results of different scenarios when they have been run, for comparison purposes; here only the base scenario results are shown.

Although the graphical output presented in Figure 6.12 represents a very practical and attractive functionality of WARMF, reading results and making sense out of them can become difficult if many sub-watersheds are interactively defined by the user. However, it is possible to export output data and imported into a GIS for further analysis, or better presentation. Figure 6.13 presents an example of such endeavour.

Figure 6.13 GIS presentation of exported WARMF NO_3 loadings output for SW1



(**a**) Regional average NO_3 catchment generation of contributions are shown. (**b**) shows the landuse (in WARMF categories) for SW1 to provide analysis context for presented results. (**c**) Similar in nature to (a), but showing actual average regional NO_3 loadings received by streams (legend not provided). (**d**) presents each stream's average NO_3 contribution to downstream segments of the stream network. In other words this provides the means to quantitatively answer the question at the outlet: how much is coming from where?

From Figure 6.13 (a) NO_3 hotspot generating areas can be readily identified, in this case attributed to those sub-watersheds with predominant agricultural landuse. In a similar fashion (c) allow the quantification of the average amount of NO_3 generated in each sub-watershed which is actually reaching the stream.

Another capability provided by WARMF output presentation is to allow the user to answer the question at any point of the watershed, "What landuse is responsible for what amount of pollution generated and transported?" Table 6.10 provides an example of this output, produced from WARMF's graphical GIS output module (Figure 6.12) for a sub-watershed in SW1 for average Total Nitrogen.

Table 6.10 Attribution of average Total Nitrogen to landuses for a subcatchment of SW1

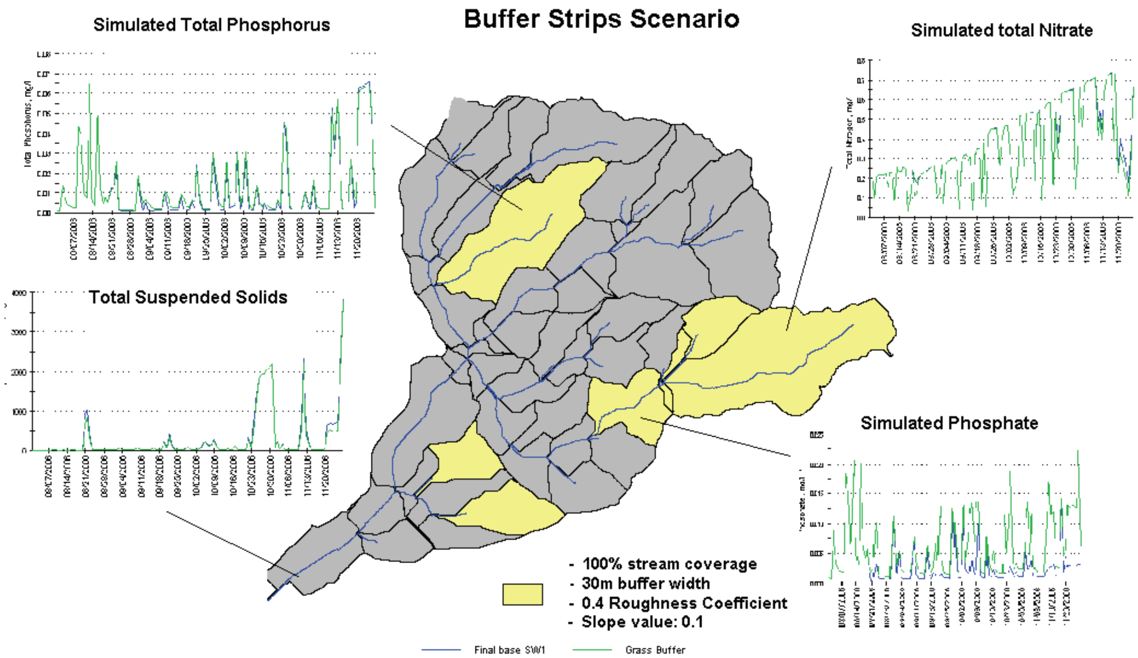
Landuse	Average Total Nitrogen Kg/d
Mixed Forest	0.391
Cropland / Pasture	2.53
Rangeland	0.16
Barren	0
Residential	0.306
Comm./Industrial	0
Total	**3.387**

6.8.2 Alternative Scenario Results

In relation to Cumming and Cockburn's (1006) recommendation for implementing grassed buffer strips for sediment and nutrient loadings control (Chapter 3), the subcatchments selected (Figure 6.14) for Grassed Buffer Strip implementation simulation where identified from (Figure 6.13) and other constituents' model output as those with highest source and regional sediment and nutrient contributions.

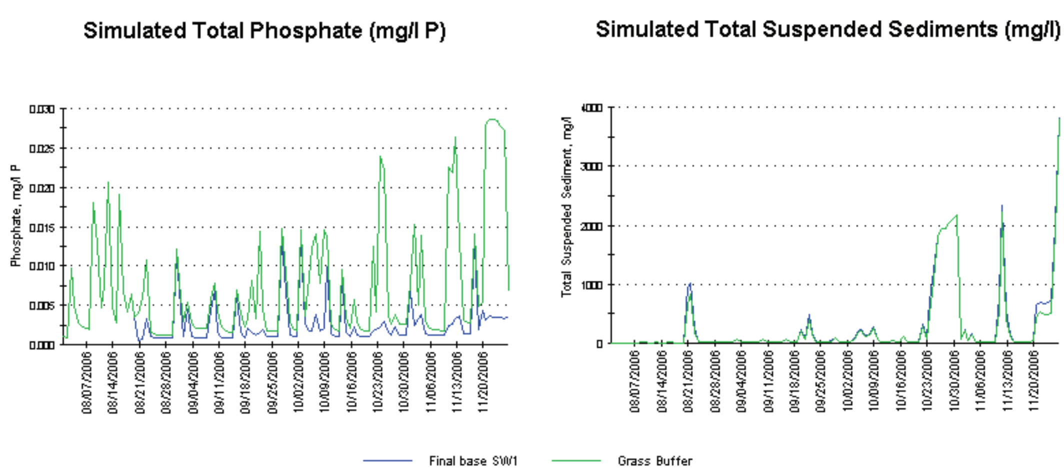
Following are presented the results for the grassed buffer strips scenario simulation. In each case, results presented are directly compared to "Base scenario" simulation results. Figure 6.14 provides an overview of buffer strip characteristics and locations of simulated implementation along with the results of selected output constituents. Figure 6.15 presents a more detailed view of 2 of the constituents presented in Figure 6.14.

Figure 6.14 Grassed Buffer Strips Scenario overview and results for SW1



Location of sub-watersheds selected for simulation of Grassed Buffer Strips as recommended by Cumming and Cockburn (1996). Along with selected output comparisons of base scenario and alternative measure scenario model outputs for different parts of the watershed, simulated buffer strips' characteristics are presented.

Figure 6.15 Selected Output comparisons of Grassed Buffer Strip effects for different areas of SW1



The presented results (excerpts from Figure 6.14) demonstrate that for different constituents alternative scenario simulation results may be positive, or negative in relation to the base scenario.

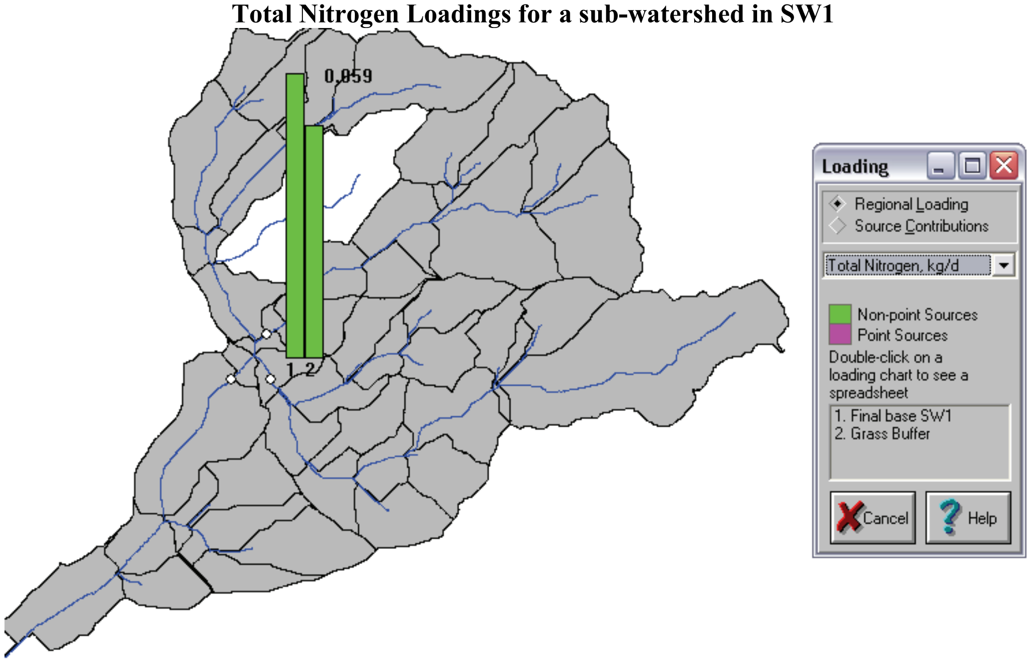
At the same time, WARMF is able to provide statistical output for scenario-run comparisons. Table presents the statistics pertaining to the graphical output presented in Figure 6.15.

Table 6.11 Statistical output of results from Figure 6.15

Phosphate (mg/l P)		
	Final base SW1	*Grass Buffer*
Mean	0.00398	0.0102
Minimum	0.000621	0.00094
Maximum	0.0293	0.0635
Total Suspended Solids (mg/l)		
	Final base SW1	*Grass Buffer*
Mean	287.7	261.6
Minimum	0	0
Maximum	3831	3819

Figure 6.16 presents a graphical representation of scenario comparisons for a "pollution hot-spot" sub-watershed summated to grass buffer strip simulation.

Figure 6.16 Graphical output of scenario comparisons of Grassed Buffer Strips' effect on Total Nitrogen Loadings for a sub-watershed in SW1



6.9 Conclusion:

WARMF offers a vast array of capabilities which may provide efficient and practical decision support for water quality protection and management. A comprehensive demonstration of all WARMF functionalities would be exhaustive, and is beyond the purposes of this thesis, in this regard the reader is directed to consult WARMF's documentation (Chen *et al.,* 2001) for further insight. It is important to re-iterate that the results of simulations here presented cannot be taken to be accurate representations of system realities in Barbados, as the models generating them have not been calibrated due to the lack of data unavailability and due to data in-accessibility for Barbados. In this light, very little analysis of the results produced has been presented, as besides being inaccurate, it is beyond the purposes of this thesis.

Further discussion of the results produced by the model simulations is presented in the final Chapter (7) to provide the context to consolidate overarching conclusions and recommendations derived from this thesis. The direction and focus of these last discussions inevitably highlight the importance of data availability and accessibility and the imminent need to establish a National Spatial Data Infrastructure programme, in the order to realize the presented potential benefits of implementing a decision support system (such as WARFM) for water quality management and protection purposes.

Chapter 7: Conclusions and Recommendations

7.1 Summary of Key points from previous chapters (Physical and Institutional)

For summarization and understanding, the system in Barbados as it relates to water quality protection and management through the use of DSS can be divided into two major realms: 1. the biophysical realm, which defines the dynamics governing water occurrence, water movement, water quantities, as well as pollutant loading, transport, and attenuation potentials; and 2. the institutional realm, which governs: land use activities, policies, and structural measures, affecting or protecting water quality; as well as the production and dissemination of data and tools used for water management. This data pertains to the representation, intersection and interaction of key elements affecting water quality from both the biophysical and institutional realms. A recapitulation of key aspects from both these realms serves to strengthen the above conceptualization and is provided hereafter.

7.1.1 Summary Key point From the physical realm:

Recharge to the aquifer in Barbados (Chapter 2) mainly occurs through the infiltration of surface water runoff, which is essentially limited to the wet season months, and is observed during major rainfall events. This recharge:

- is rapid, by discrete infiltration taking place through Karst features: cracks and fissures, channels, suck wells and sinkholes mainly occurring in dry valleys and gullies,
- constitutes of some diffuse, variant infiltration through the soil layer.
- Takes place only during the 1-3 wettest months of the year when precipitation occurs at 200mm/hr for a duration of at least one hour.
- Is higher by discrete infiltration through kartisc features occurring in the terrace above the Second High Cliff, and higher by diffuse infiltration occurring through soils in the terrace below the Second High Cliff.

Figure 5.1 (Chapter 5) provides a summary schematization of the physical system and its dynamics for Barbados.

Lastly, the estimation and measurement of surface water runoff plays an essential role in the evaluation of the movement of pollutants and their potential infiltration into the aquifer (Cumming and Cockburn, 1996).

7.1.2 Summary key points on the institutional realm:

In Barbados, there are multiple institutions involved in water resource management (Chapter 3), with mainly distinct, but with some overlapping mandates.

Various policy and legal frameworks (Chapter 3) exist and are in place, implemented by varied mechanisms, leading to a fragmented overarching institutional framework concerned with water resource management.

The groundwater protection plan (Chapter 3); the main policy frameworks concerned with water quality, has been defined on the basis of matrix flow (not suitable for Karstic systems) without major consideration of both, discrete infiltration through Karst features, and pollutant transport dynamics governed by hydrology of surface water.

In Barbados there is currently no formal institutional arrangement for the systematic collection, production and distribution of multidisciplinary data needed for environmental management purposes, and most of the data that has been compiled for these purpose and is presently available has been deemed outdated and unsuitable for meaningful analysis (Chapter 4 and 5).

The establishment of a National Spatial Data Infrastructure (Chapter 1) offers the most adequate, cost efficient and sustainable means for the acquisition, standardization, quality assurance and distribution of cross-disciplinary/multi-institutional data pertaining to environmental management.

7.2 Review of the pilot-DSS implementation experience

7.2.1 Physical realm: Data, modeling considerations, system dynamics

With reference to the presented demonstration of a DSS implementation for water quality protection and management (Chapter 6) further aspects pertaining to both the physical and institutional realms associated to the success of such implementation at a national level can be highlighted.

Karst features

An important overarching assumption adopted embedded the work presented in Chapter 6; is that the areas of internal drainage (sinks) present in the produced DEM , which are>1m^2 in area are actually sinkholes in reality. If these sinks, or at least the vast majority of those used as outlets/pour points to define subwatersheds, are in deed real sinkholes; nothing is knows about their status, whether they are blocked or filled with garbage, neither is anything known about their hydraulic properties (how much water can they absorb under different flow conditions and how much they will pass on to the downstream catchments). These aspects are clearly important for determining hydrologic dynamics and pollutant transport, translated to water quantities and qualities possibly recharged to the aquifer by means of discrete flow (Chapter 2). In light of this, **the importance of detailed mapping and characterization of sinkholes** becomes quite evident and highlighted.

Furthermore, the subwatershed delineations presented in Chapter 6 did not take into consideration neither the occurrence of suckwells and soakaways (which may be too small to have been captured in the topographic surveying conducted by Baird and Associates) nor the occurrence and extent of fissures. Depending on their locations, these features could potentially significantly alter surface hydrology, becoming important "recharge points" worthy of analyzing water quantities and qualities draining into them and possible means to mitigate pollution potential associated to these. In this context, **the importance of**

mapping and characterization of Karst features for better analysis is highlighted.

Surface water

Ideally it would serve to study all subwatersheds delineated for which reliable data is available for calibration and analysis. However, the available data (Tosic, 2007) is temporally and spatially limited for both quantity and quality observations, and in the case of observed surface water quantities it is insufficient for calibration purposes or any rigorous analysis. In light of this, **the necessity and importance of surface water quality and quantity observations** becomes emphasized.

Soils

The simulation of hydrology, and thus sediment and pollutant transport results can be largely affected by the soil properties used and defined in the model. While an apparent degree of acceptable adaptation lo local hydrology has been obtained, by extrapolating some critical soil parameters from nearby detailed data on soils available in the literature, no meaningful assessment of simulated hydrology has been possible by the lack of observed flow data. Therefore it hasn't been possible to assess the importance of localized soil characteristics data. However, it has been demonstrated that **detailed soil characteristics at some scale are a critical necessity for hydrologic modeling of Barbados.**

Land use practises and land cover:

Keeping in mind that WARMF's hydrology (to a smaller extent) and pollutant-fate (degradation, and attenuation) simulation characteristics are largely derived from various parameters associated to land use categories, **the importance of current accurate landuse categories and their location**s is thus emphasized.

To re-strengthen the above raised point, it should be noted that the presented "base scenario" represents a high agriculture landuse by some extent. This stems from the utilization of WARMF default non-point source "fertilization" values for all land uses in the absence of available data on fertilizer application rates for agricultural areas, and any estimate for other pollutant loadings associated to other land uses for Barbados. It thus becomes clear that **a degree of knowledge of non-point sources is crucial for surface water runoff quality assessments.**

Furthermore, modeling of the fate and transport of up to 3 user-defined pesticides could be provided by the paid-for version of WARMF. However, even if this version were available for this thesis, no information on pesticide application rates and locations has been available to be obtained. Clearly **the possible exploration of pesticide transport and fate, supported by knowledge of application rates and locations, would be of important relevance for water quality assessment, protection and management**.

In the case of the alternative scenario presented, it is possible that the effects of implementing grassed buffer strips at the edge of stream is being undermined by the "mixed forest" landuse category characteristics assigned to gullies. Considering the parameters assigned to this landuse category that are involved raises the possibility that gullies as defined in the simulation run may already be acting as natural buffers. While this is probably the case in reality, the parameters associated with "mixed forest" such as "litter fall" and nutrient reactions are based on North American coniferous and deciduous mixed forests, which are quite different in nature to the gully ecosystems found in Barbados. In light of this, **the necessity to define landuse parameters affecting hydrology and pollutant-fate that reflect the Barbadian realitie**s is emphasized.

Interesting insight into the physical realm of the system in Barbados has been gained through the presented modeling effort. As far as the physical realm is concerned, the presented demonstration cannot be guaranteed or assessed to provide an accurate representation of reality. The model has not yet been adopted locally by means of all necessary data input parameters, and calibration. Furthermore there are certain limitations in WARMF in areas of important interest for water quality protection and general water resource management in the Barbadian context. These have been presented in Section 7.4

7.2.2 Institutional realm (Improving data availability)

Landuse

As previously mentioned, accurate and current landuse mapping is an important element with potential effect on hydrology and pollutant transport and pollutant-fate simulations. In this regard, **it is imperative that land use mapping is kept current by periodical field revisions or other means**, if such an application of DSS as that presented is intended to be implemented in Barbados

DEM / DTM acquisition

In light of the work presented, and new insight gains derived from the use of high definition (1m) DEM for hydrologic modeling of Barbados' Karstic terrain conducted for the first **time**, **the importance of acquiring highest possible definition of topographic relief** becomes clearly imminent. Furthermore, given the small scale of watersheds and subwatersheds prevalent for most of Barbados, **the acquisition of a Digital Terrain Model (incorporating manmade structures affecting drainage** (if in deed its proclaimed existence is false, as suggested by material presented in this thesis) would provide more accuracy to the model, and could produce important information for flood management in Barbados.

Agricultural Census

As previously mentioned, agrochemical application rates are an important element for water quality simulations. In light of this, a regularly updated spatial agricultural census would provide more accurate water quality estimations, and would aid in future landuse planning by better informed scenario building.

One of the WARMF capabilities not demonstrated in the work presented relates to the area of standards compliance. The Demonstration of such capability was not possible as presently in Barbados there are no IWRM management plans in place at catchment level, an implementation of a DSS for water resources management such as that presented here could perhaps aid in the development of IWRM plans and measures.

7.3 Demonstrated potential capabilities of DSS implementation

The main capabilities of interest for water quality management offered and demonstrated by the work presented include the following:

The use of a DSS such as WARMF can provide, to a large extent, an assessment of the origins and amounts of pollutant loadings, and the evaluation of the management measures for reducing pollutant loadings in a shorter time period than that required for the approach previously suggested in this area by Cummings and Cockburn (1996), who have emphasised the importance of establishing an island wide surface water monitoring network. In the case of a DSS application, a substantial subset of data from the suggested surface runoff monitoring network would provide the means to calibrate the surface hydrology models (by surface runoff quantity), and the means to calibrate the models assessing impacts on water quality (by water quality monitoring results), allowing an accurate simulation applicable at a larger scale.

In other areas, it has been demonstrated that the WARMF DSS offers the capabilities to significantly contribute to the evaluation of effects of some suggestions previously made for implementing policy and structural measures to augment groundwater recharge by means of artificial recharge, or the capturing of surface runoff (Chapter 3). Since the potential threat posed by these recommendations to water quality are dependant on the quality and origin of the water to be used for recharge, both of these aspects can be simulated and examined within the DSS, while allowing for the creation of hypothetical scenarios for territorial planning.

The means of possibly evaluating and implementing some of these recommendations has may be aided by use of the WARMF DSS which has mainly demonstrated to be able to:

- Provide the means for the evaluation (by simulation) of different
- management (practical and policy) strategies that have been previously recommended / proposed (Chapter 3) by means of developing simulation scenarios.
- Provide the basis for the storage and analysis of the proposed monitoring and inventories data (Chapters 3 and 5) through the knowledge module which can accommodate the storage of external data, through the integration of monitoring results as observed data, and through the incorporation of inventory data into landuse parameters or characteristics, or as point sources.
- Provide the means for systemic identification of key areas, based on "pollution contributing, or receiving hotspots", for prioritizing enforcement, control, revising, management, monitoring and maintenance efforts.

In the above mentioned fashion, specific suggestions previously made for Barbados (Chapter 3) which can be evaluated by the use of WARMF DSS include the:

- Revising and updating zoning and land use controls (Klohn-Crippen Consultants, 1997b) by focusing on surface hydrology effects on water quality, which could subsequently be incorporated into more complex models to examine their interaction with subsurface hydrology and pollutant dynamics.
- Implementation of agricultural practices to reduce surface runoff and to maintain agricultural soakaways and suckwells (Cumming & Cockburn, 1996),
- Best management practices for storage, handling and application of agricultural chemicals (Cumming & Cockburn, 1996)*.

- Best management practices for the storage, handling and disposal of fuels and lubricants (Cumming & Cockburn, 1996)*.
- Maintenance of suckwells, particularly of the surface inlets to free them from refuse (Cumming & Cockburn, 1996).
- a qualitative risk assessment to identify suckwells that require blocking or filtering (WLS10)
- Improving the management of agricultural chemicals (storage, disposal and handling) (WLSX; Willms & Shier *et al.,* 1998d)*.
- Improving regulation and control of illegal solid waste dumps (WLSX; EMP)*
- Stricter control on suitable locations for heavy industry (WLSX, EMP)*.
- Forbidding fertilizers, pesticide and herbicide applications or strictly controlling their quantities and timing within Zone l [or other areas identified as receiving significant recharge after further studies are conducted] (Klohn-Crippen Consultants, 1997b).
- Providing protection from excessive nitrate loading on the groundwater by means of: nutrient management, manure application handling and storage controls and use of cover crops and rotations (Klohn-Crippen Consultants, 1997b).
- Directing runoff to grassed areas (fields, pastures, parks and golf courses) to provide a means of removing or reducing sediment picked-up from agricultural lands (Cumming & Cockburn, 1996).
- The incorporation of grassed buffer zones around the edges of fields to reduce sediment in the surface runoff (Cumming & Cockburn, 1996).
- Research into suckwell and stormwater detention pond designs to protect groundwater quality (by "burning" these into used DEMs) (BWA, 1997).
- Vegetation of critical slopes, drainage channels, swales and areas adjacent to suckwells, and/or reserving these as "no cultivation" areas in order to impede and/or remove silt which enters fissures (Cumming & Cockburn, 1996).
- Initiating a formal program for disposal of chemical containers; strictly prohibiting the disposal of chemical containers in suckwells and in open areas to avoid contamination of surface and groundwater.
- Revising proposed land uses within catchment areas of the quarries proposed for recharge to ensure no additional sources of contaminants are introduced into the area (i.e. locating fuel storage, vehicle maintenance and refueling outside the potential flood area) (Cumming & Cockburn, 1996).
- contingency planning to be triggered by monitoring [simulation] results

7.4 WARMF Limitations

Although in the presented application, WARMF has been demonstrated to provide a comprehensive set of promising capabilities for water quality protection and management, there are however certain limitations to its use and application, especially in the area of more generalized water resource management (i.e. concerned with water quantity as well as quality). These limitations include;

Outputs from mass balance elements (water balance) calculations, carried out for every subcatchment and "river segment" while carrying out the simulation, are not readily available. While the overall water balance is recorded for each catchment and each segment for every day of simulation, elements such as amounts lost to evaporation / evapotranspiration are not easily obtained. Of more importance, amounts of seepage into the soil layer is also not easily obtained, which would provide great insights into diffuse infiltration quantities and qualities, and could provide the means to integrate surface modeling with a sub-surface model simulating the unconfined Karst aquifer of Barbados (if ever developed).

One fundamental limitation in the work presented is the time step of the simulation, which has been set to 1 day as limited by the free version of WARMF. While WARMF is capable of carrying out simulations on a user defined time step, this requires meteorological data to be available, input accordingly, for and in the same time step scale. A more discrete time step simulation is possible for Barbados, given that some weather stations record data hourly or bi-hourly. A finer simulation time step is desirable for simulation in Barbados, given the role of 20mm/h precipitation for a duration of an hour previously (Chapter 2) estimated for recharge to occur. **A finer time-step simulation may shed light on interesting aspects of "recharge grade runoff generation".**

It should also be born in mind that WARMF has been developed mainly within the North American context, and many default values (and possibly embedded in the models) for processes simulated are representative of North American, large watershed ecosystems. Further research is needed to understand the extent to which this might affect simulations in the tropics. In this regard an application of WARMF still requires the adaptation to the local setting to be carried out.

Another limitation of the free WARMF version is the simulation of up to 100 subcatchments at one time. For the application presented in Chapter 6, 48 subwatersheds were generated for SW1 by BSINS. This number would certainly increase for the study of entire watersheds (as they have been previously defined not taking into consideration sinkholes as outlets). For a national scale implementation, the suitable spatial unit of study recommended is the “sinkhole-terminus subwatershed” given the computational demands required to prepare the high definition DEMs required for these models.

One other important limitation in WARMF is the lack of simulation of transport and fate of hydrocarbons, while a “proxy” measurement could be achieved by taking advantage of the 3 user defined “pesticides” capable of modeling in the paid-for version of WARMF, extensive research needs to be conducted to derive the right parameters to mimic hydrocarbons.

As previously alluded to, WARMF does not provide the easy means to integrate its output with sub-surface models (it does however for other surface models, mainly CE-QUAL). This poses complications if ever a fully integrated DSS is ever envisioned.

Perhaps the biggest limitation, WARMF does not and cannot account for, or provide output concerned with, discrete infiltration. The approach presented in this thesis seems to offer a readily available means to overcome this limitation. However, if all existing Karstic features were incorporated into the DEM (by means of a detailed mapping and characterization of these features) the numbers of subwatersheds generated could become overwhelming, and the working scale too large for practical decision making purposes.

Lastly the system is easily prone to substantial error generation and propagation easily incurred in model preparation and setup. The user documentation does not provide any warning or guidance in this regard, and good technical/computational capabilities, dedicated attention during model preparation, and analytical skills to tackle problems are required for a smooth model preparation.

While WARMF is a proprietary model, its code is not openly available for user modification (it is for revision). However, WARMF authors (Chen, *et al.*, 2000) have been very forthcoming in user forums, and it may be possible to come to an agreement to adapt the model for a designed application (i.e. integration with subsurface model, or extra output of data) as part of the model setup, adaptation and calibration service they provide.

7.5 Further possible applications of DSS use

It could be noted that the rest of "available data" (Chapter 4) has not been used directly in the presented DSS application in this thesis. However much of these data could be used to conduct further analysis in a GIS environment in conjunction with exported model outputs.

As previously alluded to, an enhanced surface monitoring system coupled with hydrological modeling could provide insights into the feasibility (amount and quality of water and treatment required) of impounding water for public supply purposes or artificial recharge.

Klohn-Crippen Consultants, (1997b) Indicated that bacteriological contamination exists at detectable levels in all four groundwater protection zones; however, in their study there was insufficient data to reliably distinguish the variations in concentration between each zone. They note that measured levels are likely attributable to specific local conditions rather than generalized zone location. This kind of question could be answered by WARMF if septic systems are simulated (and populated with data from the census), and the model were incorporated with a groundwater model.

Increased scenario complexity can offer the exploration of a great array of both policy and structural management measures, and can provide important information for landuse planning.

Full water quality protection and management can be provided by the integration or coupling of surface models such as those in WARMF with groundwater models or gained insights about Karst subsurface dynamics; such as those provided by Mayers *et al. 2005*.

Even though, costly tests are conducted at random in public water supplies in Barbados to test for pesticides; accurate simulation, with an enhanced knowledge of subsurface dynamics, could provide an efficient means to better target public supplies where vulnerability to high loadings of pesticides may be potentially recharging the aquifer.

7.6 Recommendations for future DSS implementations

If the presented potential benefits of implementing a DSS for water quality protection and management achieve to incite the pursuit of such an application in Barbados. It is imminent that the following considerations be closely contemplated and achieved to ensure and provide a successful effort. The following recommendations have been elaborated from previous recommendations Chapter 5 put forward to different governmental institutions concerned with water resource and environmental management in Barbados, In Chapter 5 they have been accompanied by the suggested institutional arrangements to fulfill their achievement and sustainable functioning. They mostly pertain to data gathering efforts, and establishment of institutional arrangements. They include:

- *Re-enforcing Data Accessibility / availability*

In making an assessment of existing datasets the issue and the reality of data accessibility (Chapter 5) it has been concluded that this is an aspect to which particular attention must be paid, as this can prove to be the biggest limiting factor for a successful and sustainable DSS application for water quality protection and management. Even if good quality (accurate and updated) data exists for use, it becomes useless if access is not granted to it.

If a more successful and insightful application of a Decision Support System for water quality protection than the work presented in Chapter 6 is sought, it imminently necessitates further data gathering efforts in order to fill the data gaps that presently exist in Barbados (Chapter 4, 5). Furthermore, accompanying data collection, it is also imminent that the appropriate institutional frameworks are established to ensure accessibility to data by the implementing government institution. This is further discussed later on.

- *The establishment of a reinforced weather station network and data collection and storage system*
- *The completion of a comprehensive contaminants inventory and spatial database including point sources and non-point sources*
- *Strengthening of information on soil and soil profiles*
- *Acquisition of a high resolution DEM*
- *Surface water data monitoring network*
- *Karst features mapping and characterization*
- *Establishment of an imminently needed NSDI*

Implementation of the proposed data gathering efforts would require the involvement of numerous government (as well as non-governmental) institutions and agencies including: Ministry of Health and Environment, Environmental Protection Department, the Ministry of Agriculture, the Drainage Unit, the Barbados Water Authority, Costal Zone Management Unit, CIMH, Lands and Surveys Department, and the CIMH. However, the successful implementation of these efforts would greatly benefit from the involvement of participation of the public, public involvement and the support of the major commercial interests in Barbados such as the agricultural sector, the tourism sector and corporations such as Barbados National Oil Company, who all have the potential to influence quality of the groundwater and the environment by their activities. At the same they all share a stake in protecting that environment to ensure long term sustainability.

In sight of such multi-, and cross disciplinary stakeholder involvement, the establishment of a NSDI (Chapter 1) offers the most appropriate means to secure the successful achievement of data collection efforts while providing for a formalized framework for data standardization, security, access and updating.

While the benefits derived from the use of spatial data, GIS and associated tools, such as DSS, are substantial, the budget and personnel allocations required to build these also are substantial. Therefore, sharing the cost burden amongst stakeholders through a NSDI provides the means to reap the benefits of spatial data use, while minimizing costs for all parties involved.

However, the successful establishment of a NSDI is directly related to the level of stakeholder involvement as well as the level of senior government commitment to oversee and endorse its implementation.

7.7 Final Summary

In summary this thesis has fulfilled its stated objectives by:

1. Providing a comprehensive literature review on the development, application and adoption of DSS for the management of water resources provided in Chapter 1
2. Providing an overall review of the physical makeup of the island of Barbados and how it relates to the water resources regime with a specific focus on water quality, presented in Chapter 2
3. Providing an overview of the current institutional arrangements in place for the management of water resources in Barbados in Chapters 1 and 3
4. Having identified, and rationalized, the main factors/components to be considered by the DSS in Chapter 5.
5. Providing an inventory, and assessment of the state of, as well as the functionality of data needed for a DSS application for water quality protection and management presented in Chapter 4.

6. Having identified which institutions / individuals are custodians of presently available datasets, and which would be the most suitable custodians for proposed future data collection/production initiatives, provided in Chapters 4, and 5.
7. Having suggested technical and conceptual design for possible applications of a spatial decision support system achieved by tight or loose coupling of hydrologic models and GIS for the purposes of water resource management, in Chapters 6 and 7.
8. Highlighting the importance of the crucial establishment of a NSDI to best achieve a sustainable DSS implementation implicitly throughout its entirety, and explicitly in Chapters 5 and 7.
9. Providing an implementation of a DSS for water quality protection and management protection, demonstrative of the potential it offers within the Barbadian context (Chapter 6).

7.8 Concluding Remarks:

If the portrayed potential benefits are to be reaped in Barbados, a DSS needs to be built tailored to the physical and institutional context of Barbados. Such a DSS should mainly take account of:

- Karst topography and recharge dynamics unique to the island
- the socio-economic reality of the island, and future development prospects and how these relate to the protection of the water resource.
- The institutional dimension as it pertains to:
  - data collection and provision to feed the system,
  - decision-making, and
  - responsibilities for assessment and enforcement of devised alternatives.

Such as DSS would best be implemented through the establishment of the proposed Water Resources Board, or would best be administered by some other high-level governmental multidisciplinary entity (such as the Ministry of Environment), in collaboration with a cross-disciplinary institutional body such as the National Commission for Sustainable Development. The success of the implementation of a DSS for water resource management in Barbados is largely dependent on the existence and establishment of a NSDI as has been described in this thesis.

While a preliminary demonstrative application of a DSS for water quality protection and management has been achieved in an academic setting (Chapter 6) by using some of the datasets available in Barbados, it should be noted that, under the prevailing circumstances, as they relate to institutional aspects and data availability and accessibility; such application in a larger scale to be employed for real water quality protection and management decision making is not deemed possible in Barbados at the time.

However, it should be clearly stated that the potential for embarking on the use of DSS and GIS for water quality protection and management, as well as for other aspects of water resource, and environmental management in general in Barbados clearly exists. Within various governmental institutions concerned with environmental management (i.e. CZMU, DU, MOHE, and BWA) there already exist technical expertise in the field of GIS and a keen interest and desire to use it along with other related technologies like DSS to enhance environmental analysis and decision making. Much of this impetus has been blocked and frustrated by the lack of a formalized national spatial data infrastructure which would mainly serve government agencies to share cost burdens, ensure data reliability, standardization, and mainly, accessibility and dissemination. A careful review of the fate of efforts to establish a NSDI previously pursued should therefore be carefully considered. An impetus for the revival of such initiative is highly recommended to be seen and carried through, culminating in the establishment of a NSDI (at least for environmental management purposes) in Barbados.

While the detailed exploration and technical discussions about modeling a Karstic system such as that of Barbados is worthy of the entire focus and research of an entire thesis; in this thesis they have been limited to the final two chapters. This has been done under the premise that: in the context of a pragmatic approach for implementing a DSS for water quality protection and management in a national setting; the importance of attaining the necessary institutional frameworks, and provision of necessary “data bases” [not databases] for achieving modeling efforts efficiently, take precedence over the in-depth conceptual and practical technicalities associated with hydrological modeling and decision support. However, these practical and conceptual technicalities cannot be left out of sight, as they in turn shape the nature of the “data bases” and, to a certain degree, the institutional characteristics required for a meaningful and successful DSS application as this thesis aims to demonstrate.

> *“Having the information does not provide easy answers; however, to make the tough decisions that are needed to balance conservation and use, it is critical that there be a clear assessment of the conditions of the natural resources and an understanding of the consequences of decisions. Without a solid understanding of consequences, it is virtually impossible to design policies or projects and to implement the effective mitigation measures needed to claim sustainability” (EMLAP 2 p4)*

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Appendix 1: Canadian and Caribbean Examples of NSDIs

Examples of Canadian NSDIs

Canada has been recognized as being exemplary in the successful development and implementation of SDI's (Rajabifard et al, 2002). According to the Canadian geospatial data infrastructure (CGDI) vision, "the CGDI initiative aims to facilitate the sharing of geographic databases, provide mechanisms which transcend the copyright and licensing restrictions, permits data exchange among agencies, and includes funding mechanisms and defines the databases" (Turnbull and Loukes, 1997). This initiative has five inter-related technical components, namely data access, geospatial framework, standards, partnerships, and supportive policy environment (Labonte et al, 1998). The most notable examples of Canadian SDI's are presented below.

GeoConnections (2008)

GeoConnections, a national partnership program led by Natural Resources Canada, helps decision-makers use online geospatial information, such as maps and satellite images, to tackle some of Canada's most pressing challenges. The program focuses on working with partners in public health, public safety and security, the environment and sustainable development, Aboriginal matters, and geomatics technology development.

Although GeoConnections acts as a catalyst in creating solutions for decision-makers in its four priority areas, the program also relies heavily on its partners therefore, partners play a vital role in GeoConnections. These partners can be private companies, government agencies at all levels, non-government organizations, academic institutions, or sometimes a combination of the above. Ample time and energy are devoted to establishing and nurturing partnerships because they anchor the success of the Canadian Geospatial Data Infrastructure as an online resource to support decision making.

"Recognized around the world for its prominent role in building the Canadian Geospatial Data Infrastructure, GeoConnections can serve as a model for other countries to emulate in creating their own national geospatial data infrastructure".

CNLWIS (AAFF, 2008)

"The National Land and Water Information Service is an Internet-based service being developed ... to provide on-line access to agri-environmental information to help Canadians make responsible land-use decisions".

The National Land and Water Information Service is being built on a foundation of partnerships and collaboration. The project is led by Agriculture and Agri-Food Canada (AAFC). The success of this service relies on the close collaboration with other federal departments, provincial, territorial and municipal governments, non-government organizations, producer and industry groups, and academic institutions. The National Land and Water Information Service will link agri-environmental information from these dispersed sources and make it available through the Internet.

The project is based on GIS technology following national standards and specifications, as well as federal geomatics policies and practices, to achieve an approach that will be responsive to clients' needs and coordinated across Canada's geographic information community.

By providing geospatial information, decision-support tools and improvements in national data collection, analysis and reporting, the National Land and Water Information Service will support a number of environmental programs under the Agricultural Policy Framework. Included in these programs are: Environmental Farm Plans and Environmental Assessments, Greencover, National Farm Stewardship, National Water Supply Expansion and Water Quality Surveillance. This Service will benefit the agricultural sector and all Canadians by contributing to the development of better agri-environmental policies, increasing public awareness of the relationship between agriculture and the environment, and improving land-use decision making and risk management.

When the project is completed in 2009, the National Land and Water Information Service will be recognized as Canada's source of information, analysis and interpretation of agri-environmental data on land use, soil, water, climate and biodiversity to assist land-use decision makers. These land-use decision makers include governments, community groups, researchers, producers and industry

Development of the National Land and Water Information Service will build on other efforts to reduce agricultural risks and better use Canada's land, soil, water and biodiversity resources.

RésEau (GC, 2008)

RésEau is a Government On-Line demonstration initiative that focuses on water information. RésEau supports clean, safe, and secure water for all Canadians and ecosystems. Specifically, RésEau establishes partnerships and projects to demonstrate the sharing, discovery, access, and use of water information over the Internet. The initiative is led by Environment Canada in partnership with Natural Resources Canada and Health Canada. Its user-driven focus targets information for a wide range of generalists and specialists; from high school-level youth to water resource managers.

An interactive Web portal forms the dynamic focal point of RésEau. The portal includes data, interpreted information, tools, and services to facilitate the interconnection of water information from distributed sources to promote a greater understanding of complex water issues for enhanced decision making.

Scientific integrity is a key pillar of RésEau starting with credible water quality, quantity and use data. Standards and specifications endorsed by the Canadian Geospatial Data Infrastructure (GeoConnections) and the Open Geospatial Consortium (OGC) are an essential foundation of RésEau projects.

RésEau plays a leadership role in pulling together existing data and information (including water quality, quantity, and use) from distributed networks of partners across numerous Canadian jurisdictions. Water stakeholders in many levels of government, nongovernment organizations, and community groups are being engaged through this national partnership initiative. These partnerships demonstrate how information can effectively be shared, discovered, accessed, and used when common technical and scientific standards are adopted. RésEau builds on Environment Canada's data integration successes achieved through the strategy outlined in the Canadian Information System for the Environment (CISE). Collaboration with other national environmental information initiatives is instrumental, including the following: National Land and Water Information Service National Hydro Network (NHN) GeoConnections RésEau is a key step in the complex task of providing Canadians with timely access to credible water information, data, and tools.

Caribbean

The most notable projects in the Caribbean promoting the development of national and regional SDI's are the following:

CRMI

Caribbean Risk Management Initiative's (CRMI) main objectives and activities are:

- Increased Capacity for climate risk management
- Risk reduction and climate change adaptation integrated into development
- Increase in investments in climate risk management

To support these objectives, the project recognizes that sharing Geographical Information is a key factor, due to the transversal nature of this information across the Caribbean.

IWCAM

The Global Environmental Funds (GEF) -funded Integrating Watershed and Coastal Areas Management in Caribbean Small Island Developing States (IWCAM) Project has as its overall objective to strengthen the commitment and capacity of all participating countries to implement an integrated approach to the management of watersheds and coastal areas (CATHALAC & UWI, 2007).

IWCAM undertakes a Roadmap for Effective Mainstreaming of GIS for Watershed Management in the Caribbean based on the following framework issues:

- Comprehensive needs and requirements assessment
- Acquisition and management of data and databases
- Acquisition and management of technological resources
- Development and management of human capacity
- Development and management of institutional environment
- Development of end-user applications, products and services
- Continuous monitoring and evaluation of the system

The Project recognizes the important role of GIS-technology as a tool for integrating data analysis and management. It also recognizes the need to incorporate GIS technology at various components of the project and aims to expand and improve GIS capacity and use GIS technology in all participating countries (Small Island Developing States) (CATHALAC & UWI, 2007).

Appendix 2 WARMF Simulation Supplemental Data

LINKNC	DSLINK	USLINK	USLINK	DSNODEID	Order_	Length	Magnitu	DS_Cont_Ar	Drop	Slope	Straight_L	US_Cont_Ar	WSNO	DOUT_END
1	-1	47	48	1.0	4	406.0	24	1703080.0	10.89	2.682462745900	373.0	1652531.0	1	0.0
48	1	-1	-1	-1.0	1	87.7	1	22738.0	22.94	26.168628904600	76.0	18116.0	48	406.0
47	1	42	46	-1.0	4	202.9	23	1629791.0	7.24	3.567182265400	192.0	1606143.0	2	406.0
46	47	45	36	-1.0	2	71.3	3	132826.0	12.76	17.904221300700	64.0	121361.0	43	608.8
36	46	-1	-1	-1.0	1	89.4	1	30623.0	11.34	12.678761069700	87.0	21446.0	47	680.1
45	46	43	44	-1.0	2	99.3	2	90736.0	10.00	10.070852013400	86.0	63119.0	44	680.1
44	45	-1	-1	-1.0	1	10.2	1	20495.0	0.00	0.000000000000	9.0	18949.0	46	779.4
43	45	-1	-1	-1.0	1	124.6	1	42623.0	10.57	8.482571292700	118.0	19957.0	45	779.4
42	47	41	-1	-1.0	4	480.8	20	1473278.0	12.76	2.654668555900	424.0	1390753.0	3	608.8
41	42	24	40	2.0	4	87.5	20	1390722.0	5.00	5.711733043300	83.0	1383743.0	4	1089.6
40	41	30	39	-1.0	3	125.5	9	580219.0	3.02	2.404352089100	111.0	564396.0	26	1177.1
39	40	38	35	-1.0	2	232.9	6	444398.0	11.98	5.144647368600	210.0	418773.0	32	1302.7
35	39	-1	-1	-1.0	1	41.8	1	26776.0	0.00	0.000000000000	38.0	21350.0	42	1535.6
38	39	34	37	-1.0	2	147.5	5	391992.0	0.00	0.000000000000	133.0	368901.0	33	1535.6
37	38	-1	-1	-1.0	1	142.8	1	32816.0	10.00	7.003034232800	133.0	18950.0	41	1683.0
34	38	32	33	-1.0	2	166.4	4	336070.0	5.00	3.005339068300	149.0	317359.0	34	1683.0
33	34	-1	-1	-1.0	1	43.0	1	29099.0	5.00	11.635872746800	38.0	24741.0	40	1849.4
32	34	26	31	-1.0	2	351.3	3	288211.0	10.00	2.846779198300	298.0	241193.0	35	1849.4
31	32	-1	-1	-1.0	1	80.0	1	20396.0	1.41	1.767615810600	65.0	18925.0	39	2200.7
26	32	21	25	-1.0	2	18.7	2	220578.0	0.00	0.000000000000	17.0	212636.0	36	2200.7
25	26	-1	-1	-1.0	1	227.7	1	32959.0	11.14	4.893349278000	206.0	19586.0	38	2219.4
21	26	-1	-1	-1.0	1	762.9	1	179671.0	20.00	2.621474315900	670.0	18069.0	37	2219.4
30	40	29	27	-1.0	2	222.5	3	119997.0	6.98	3.138490895400	174.0	94951.0	27	1302.7
27	30	-1	-1	-1.0	1	81.4	1	23203.0	5.00	6.142734825800	75.0	18162.0	31	1525.1
29	30	20	28	-1.0	2	191.6	2	71747.0	10.00	5.218549711600	169.0	57277.0	28	1525.1
28	29	-1	-1	-1.0	1	83.3	1	27614.0	5.00	6.005657281400	76.0	19096.0	30	1716.7
20	29	-1	-1	-1.0	1	164.6	1	29662.0	15.00	9.115698345700	149.0	18436.0	29	1716.7
24	41	14	23	-1.0	4	38.9	11	803523.0	0.00	0.000000000000	36.0	798305.0	5	1177.1
23	24	19	22	-1.0	3	103.8	6	390196.0	5.00	4.817802933600	96.0	383820.0	15	1216.0
22	23	-1	-1	-1.0	1	3.0	1	19660.0	0.57	19.099934895800	3.0	19581.0	25	1319.8
19	23	17	18	-1.0	3	296.5	5	364158.0	10.00	3.372628760100	255.0	334380.0	16	1319.8
18	19	-1	-1	-1.0	1	3.4	1	18098.0	0.00	0.000000000000	3.0	18068.0	24	1616.3
17	19	11	16	-1.0	3	243.7	4	316262.0	5.00	2.051370184500	221.0	280722.0	17	1616.3
16	17	12	15	-1.0	2	287.2	2	198540.0	5.39	1.876874517200	246.0	114463.0	21	1860.0
15	16	-1	-1	-1.0	1	235.7	1	76116.0	9.61	4.077038828200	214.0	18205.0	23	2147.2
12	16	-1	-1	-1.0	1	196.5	1	38306.0	9.61	4.891818301400	171.0	23341.0	22	2147.2
11	17	9	10	-1.0	2	116.0	2	82181.0	5.00	4.309438856600	106.0	78053.0	18	1860.0
10	11	-1	-1	-1.0	1	119.9	1	36462.0	12.71	10.603895585300	104.0	18970.0	20	1976.1
9	11	-1	-1	-1.0	1	117.4	1	41585.0	6.52	5.553978657100	98.0	18107.0	19	1976.1
14	24	8	13	-1.0	3	261.5	5	408108.0	10.00	3.824202569700	236.0	377591.0	6	1216.0
13	14	-1	-1	-1.0	1	540.6	1	122413.0	20.00	3.699492175500	468.0	18238.0	14	1477.5
8	14	5	7	-1.0	3	93.8	4	255074.0	5.00	5.332221238300	83.0	244898.0	7	1477.5
7	8	2	6	-1.0	2	409.2	2	106706.0	15.00	3.666011950800	346.0	49642.0	11	1571.3
6	7	-1	-1	-1.0	1	97.1	1	26294.0	5.00	5.150218423100	86.0	19019.0	13	1980.4
2	7	-1	-1	-1.0	1	83.6	1	23346.0	5.00	5.981005779300	74.0	18064.0	12	1980.4
5	8	3	4	-1.0	2	353.8	2	137965.0	10.00	2.826088568400	330.0	104834.0	8	1571.3
4	5	-1	-1	-1.0	1	209.1	1	28916.0	10.00	4.782899172900	172.0	18804.0	10	1925.1
3	5	-1	-1	-1.0	1	494.6	1	75914.0	15.00	3.032572809700	441.0	18409.0	9	1925.1

Annex 2

Hilaby Meteorological File used for SW1 simulations

DATE	TIME	PRECIP	MIN TEMP	MAX TEMP	CLOUDCOV	DEWPOINT	BAR	WINDSPEI	DATASOURCE
04082006	0000	0.2	25.2	31.9	0.7	21	1014.108	7.791667	
05082006	0000	0.3	22.7	32.2	0.9	22	1013.867	5.566667	
06082006	0000	1.3	24.8	31.1	0.8	23	1013.671	10.2	HILABY
07082006	0000	0.1	26.6	31.1	0.9	23	1012.942	20.5125	HILABY
08082006	0000	0.1	26.4	31.5	0.8	23	1012.988	13.2125	HILABY
09082006	0000	0.4	25.8	30	0.2	23	1012.763	8.775	HILABY
10082006	0000	0.6	24.9	32.2	0.7	24	1013.383	9.45	HILABY
11082006	0000	0.2	26.3	31.6	0.9	23	1013.754	13.74583	HILABY
12082006	0000	1.1	24.7	30.9	0.8	23	1013.7	12.3375	HILABY
13082006	0000	0.7	25.2	30.6	0.1	24	1013.167	3.804167	HILABY
14082006	0000	0	25.2	32.8	1.0	24	1013.146	5.608333	HILABY
15082006	0000	1.5	25.4	32.1	0.8	24	1013.467	12.3875	HILABY
16082006	0000	0.4	26.6	31.1	0.5	24	1013.258	11.51667	HILABY
17082006	0000	0	25.6	31.6	0.7	22	1013.471	9.516667	HILABY
18082006	0000	0.2	24.9	32.1	0.8	22	1013.488	7.383333	HILABY
19082006	0000	0.9	24.2	31.4	0.7	23	1014.325	10.875	HILABY
20082006	0000	0.1	25.2	31.9	0.9	23	1015.063	10.8	HILABY
21082006	0000	2.1	25.7	30.7	0.4	24	1015.488	12.425	HILABY
22082006	0000	1	25.8	31.2	0.4	24	1014.908	14.2875	HILABY
23082006	0000	0.2	27.8	31.2	0.7	24	1013.808	17.68333	HILABY
24082006	0000	10.2	23.7	28.5	0.0	23	1012.75	17.96667	HILABY
25082006	0000	1.1	24.7	30.8	0.6	23	1013.588	12.06667	HILABY
26082006	0000	0.3	23.8	31.5	1.0	22	1013.608	8.845833	HILABY
27082006	0000	0	24.5	31.1	1.0	22	1013.054	9.379167	HILABY
28082006	0000	0.1	24.1	34.1	0.9	23	1013.363	2.408333	HILABY
29082006	0000	0.1	25.3	36.6	0.8	24	1014.275	0.804167	HILABY
30082006	0000	0	25.3	32.1	0.9	24	1014.458	4.6875	HILABY
31082006	0000	0	24.8	32.3	0.8	23	1014.438	6.575	HILABY
01092006	0000	0	23.9	32.6	0.8	23	1013.05	6.1	HILABY
02092006	0000	0.5	24.1	30.6	0.4	24	1011.792	4.541667	HILABY
03092006	0000	1.6	24.3	31.6	0.4	24	1010.838	7.6375	HILABY
04092006	0000	1	24.9	32.1	0.3	24	1011.663	7.225	HILABY
05092006	0000	0.1	24.7	33.1	0.5	24	1013.183	3.804167	HILABY
06092006	0000	1.5	24.9	31.4	0.7	24	1013.771	5.15	HILABY
07092006	0000	0	24.3	32.6	1.0	23	1012.971	3.866667	HILABY
08092006	0000	0.2	26.2	31.6	1.0	23	1012.913	5.358333	HILABY
09092006	0000	0	25.2	32.6	0.8	23	1013.713	5.145833	HILABY
10092006	0000	0	25.3	32.8	0.9	22	1013.875	7.241667	HILABY
11092006	0000	0.3	23.7	31.4	0.8	23	1013.729	7.5	HILABY
12092006	0000	0.7	24.4	32.1	0.8	23	1013.208	6.370833	HILABY
13092006	0000	2.4	24.4	28.1	0.1	23	1014.233	3.9375	HILABY
14092006	0000	0.2	24.5	32	0.6	24	1014.875	8.845833	HILABY
15092006	0000	0.3	26.5	31.5	0.8	23	1014.521	15.3625	HILABY
16092006	0000	0	27.2	31.6	0.9	23	1013.717	11.39167	HILABY
17092006	0000	0	25.1	31.7	0.9	22	1012.979	6.4375	HILABY
18092006	0000	0	24.5	33.1	0.9	23	1014.546	4.6125	HILABY
19092006	0000	2.6	25.1	32.4	0.6	24	1015.183	5.7	HILABY
20092006	0000	0.1	24.5	33.1	0.8	23	1014.167	4.466667	HILABY
21092006	0000	0	24.5	32.6	0.9	22	1014.088	6.2375	HILABY
22092006	0000	0.8	25.2	32	0.8	23	1013.688	8.720833	HILABY
23092006	0000	2.5	24.3	31.6	0.5	24	1012.788	6.770833	HILABY
24092006	0000	0.2	25.4	32.4	0.7	23	1013.308	6.370833	HILABY
25092006	0000	2.8	23.4	30.8	0.4	23	1014.558	5.691667	HILABY
26092006	0000	0	24	31.9	0.8	23	1014.825	6.229167	HILABY
27092006	0000	0	22.7	33.2	0.9	22	1014.3	4.1375	HILABY
28092006	0000	0.3	24.6	32.1	0.8	23	1013.442	8.104167	HILABY
29092006	0000	0.5	24.5	31.7	0.7	23	1013.558	8.766667	HILABY
30092006	0000	0.4	25.2	31.6	0.6	23	1013.483	8.704167	HILABY
01102006	0000	1.2	24.6	31.6	0.6	23	1013.35	7.566667	HILABY
02102006	0000	0.8	24.7	31.6	0.6	23	1012.663	8.441667	HILABY
03102006	0000	0.2	25.4	31.7	0.8	23	1012.138	7.845833	HILABY
04102006	0000	0.2	24.9	31.7	0.9	23	1011.571	10.45417	HILABY
05102006	0000	0.2	27.2	32	0.9	23	1011.983	16.41667	HILABY
06102006	0000	0.9	25.1	31.6	0.6	24	1013.104	14.2875	HILABY
07102006	0000	1.3	24.4	30	0.3	24	1013.763	16.16667	HILABY
08102006	0000	1.3	26.8	31.2	0.7	24	1012.408	14.34167	HILABY
09102006	0000	1	23.3	30.7	0.2	24	1013.146	6.158333	HILABY
10102006	0000	0.5	25.3	31.6	0.4	24	1013.125	7.375	HILABY
11102006	0000	0.5	24.2	27.6	0.5	23	1012.833	5.9625	HILABY
12102006	0000	1.1	25.4	31.2	0.5	23	1012.675	8.441667	HILABY
13102006	0000	0.3	24.4	31.6	0.8	23	1011.133	5.766667	HILABY
14102006	0000	0	24.4	31.6	0.8	23	1011.038	5.429167	HILABY
15102006	0000	0	25.1	32.1	0.8	23	1011.4	6.1625	HILABY
16102006	0000	0.5	24.9	32.4	0.8	24	1011.592	5.55	HILABY
17102006	0000	1.3	24.3	31.7	0.8	23	1010.846	4.1375	HILABY
18102006	0000	0	24.6	32.1	0.8	23	1009.933	3.879167	HILABY
19102006	0000	0	24.9	32.9	0.9	23	1009.492	4.6	HILABY
20102006	0000	2.2	23.4	31.3	0.5	23	1010.717	7.845833	HILABY
21102006	0000	0	25.7	32.2	0.9	23	1013.633	7.9125	HILABY
22102006	0000	0.2	25.4	31.2	0.9	24	1013.583	8.245833	HILABY
23102006	0000	0	25.8	30.9	0.9	23	1012.479	9.391667	HILABY
24102006	0000	0.4	24.3	31.2	0.7	24	1012.138	5.291667	HILABY
25102006	0000	2.7	24.7	31.7	0.6	24	1013.096	5.679167	HILABY
26102006	0000	0	25.2	32	0.8	23	1013.05	5.208333	HILABY
27102006	0000	4.2	24.9	30.7	0.4	24	1011.788	3.070833	HILABY
28102006	0000	0.1	24.9	30.8	0.7	23	1012.513	13.54583	HILABY
29102006	0000	0	27.5	30.6	0.7	23	1012.717	15.55417	HILABY
30102006	0000	0.2	25.1	30.6	0.8	23	1010.875	13.8875	HILABY
31102006	0000	0.5	24.9	30.4	0.8	23	1010.492	10.65417	HILABY
01112006	0000	0	24.5	30.4	0.9	23	1010.896	8.1875	HILABY
02112006	0000	0.3	23.7	30.4	0.7	23	1011.95	8.770833	HILABY
03112006	0000	0.2	24.6	31.4	0.9	23	1012.096	8.320833	HILABY
04112006	0000	2.3	24.4	30.4	0.7	23	1011.571	8.975	HILABY
05112006	0000	1	23.5	29.4	0.4	22	1010.775	7.770833	HILABY
06112006	0000	0.3	24.2	30.3	0.9	22	1011.117	7.570833	HILABY
07112006	0000	0.8	25.1	30.8	0.7	23	1011.1	15.08333	HILABY
08112006	0000	0.1	26.6	30.7	0.9	22	1011.242	17.02917	HILABY
09112006	0000	0	25.4	30.3	0.9	22	1012.696	9.845833	HILABY
10112006	0000	0.3	24.6	31.4	0.9	22	1012.879	6.433333	HILABY
11112006	0000	0.1	24.5	30.6	0.9	23	1012.246	10.05833	HILABY
12112006	0000	0	24.9	30	0.9	22	1012.204	6.495833	HILABY
13112006	0000	0	23.8	30.3	0.8	22	1011.646	6.175	HILABY
14112006	0000	5.4	23.7	30.4	0.6	23	1010.6	7.508333	HILABY
15112006	0000	0.5	24.7	30.7	0.9	23	1011.138	7.4375	HILABY
16112006	0000	1.1	23.4	31.1	0.7	22	1011.458	7.8375	HILABY
17112006	0000	0	24.9	31.6	0.7	23	1012.275	6.6125	HILABY
18112006	0000	0	25.2	30	0.7	23	1012.875	8.4375	HILABY
19112006	0000	0	25.1	30.4	0.8	23	1013.908	7.970833	HILABY
20112006	0000	0.4	25.9	30.4	0.8	23	1013.925	11.1875	HILABY
21112006	0000	0.9	24.9	30.4	0.7	23	1013.867	12.2625	HILABY
22112006	0000	0.2	25.2	29.7	0.8	23	1012.496	10.45833	HILABY
23112006	0000	1.1	20.3	28.5	0.1	23	1010.913	8.3	HILABY
24112006	0000	2.9	23.3	28.8	0.1	23	1011.817	4.216667	HILABY
25112006	0000	1.3	24.4	30	0.7	23	1012.217	7.7	HILABY
26112006	0000	1.6	24.4	30.8	0.4	24	1012.288	5.020833	HILABY
27112006	0000	2.1	24.3	30.2	0.6	23	1011.088	6.2375	HILABY
28112006	0000	3.7	23.9	30.9	0.2	23	1011.588	5.616667	HILABY
29112006	0000	0.4	24.3	30.3	0.1	23	1012.804	3.745833	HILABY
30112006	0000	0	24.6	29.8	0.8	23	1012.046	9.1125	HILABY

POLYGONID	STREAMLIN	STREAMLEN	DSNODEID	DSWSID	US1WSID	US2WSID	AREA_M	AREA_ACRE	AREA_SQMI	AVESLOPE	POLYID	TRUE_ASPEC
12	2	83.0	-1.0	11	-1	-1	23345.875001000000	5.768882442100	0.009013878800	11.5017353774635000	12	153.73300170900
13	6	97.0	-1.0	11	-1	-1	26294.000001000000	6.497378870300	0.010152154400	6.7584378010474100	13	123.38400268600
10	4	209.0	-1.0	8	-1	-1	28915.874999000000	7.145257291600	0.011164464500	13.5869173962010000	10	174.24600219700
9	3	494.0	-1.0	8	-1	-1	75913.875000000000	18.758698081000	0.029310465700	20.2769870855985000	9	141.87300109900
20	10	119.0	-1.0	18	-1	-1	36461.999999000000	9.009942509800	0.014078035100	10.2103690264652000	20	180.96299743700
19	9	117.0	-1.0	18	-1	-1	41585.124996999900	10.275892312000	0.016056081700	14.5549021721070000	19	297.10779953000
11	7	409.0	-1.0	7	12	13	57065.875000000000	14.101263041000	0.022033223500	17.4713540761303000	11	147.03100585900
22	12	196.0	-1.0	21	-1	-1	38305.750000000000	9.465542353900	0.014789909900	16.9848998139642000	22	263.56900024400
14	13	540.0	-1.0	6	-1	-1	122412.999990000000	30.248864364000	0.047263850500	11.8770521373868000	14	139.52099609400
8	5	353.0	-1.0	7	9	10	33135.250002000000	8.187885951800	0.012793571800	18.3829456434067000	8	95.50579833980
21	16	287.0	-1.0	17	22	23	84118.375000000000	20.786071054000	0.032478236000	16.0040080733200000	21	106.39600372300
23	15	235.0	-1.0	21	-1	-1	76116.000000000000	18.808644180000	0.029388506500	16.7345257550577000	23	115.82399749800
17	17	243.0	-1.0	16	18	21	35540.875000000000	8.782327917000	0.013722387300	23.6053353065057000	17	326.45690155030
18	11	116.0	-1.0	17	19	20	4133.875000100000	1.021501181900	0.001596095500	20.4670161617533000	18	319.99860000610
7	8	93.0	-1.0	6	8	11	10402.999999000000	2.570633314800	0.004016614500	25.3241296108753000	7	95.05069732670
16	19	296.0	-1.0	15	17	24	29798.000000000000	7.363234790000	0.011505054300	38.7396932680750000	16	80.24169921880
24	18	3.0	-1.0	16	-1	-1	18097.874999000000	4.472075401700	0.006987617800	23.6420142359013000	24	126.44400024400
6	14	261.0	-1.0	5	7	14	30621.124999000000	7.566633092900	0.011822864200	30.7195408477915000	6	120.94699859600
29	20	164.0	-1.0	28	-1	-1	29662.000000000000	7.329628510200	0.011452544500	13.9758422441114000	29	149.88299560500
38	25	227.0	-1.0	36	-1	-1	32959.000000000000	8.144333695000	0.012725521300	16.5456296014852000	38	171.81500244100
31	27	81.0	-1.0	27	-1	-1	23202.874999000000	5.733546426700	0.008958666200	17.6783689985173000	31	301.41730117800
37	21	762.0	-1.0	36	-1	-1	179670.875000000000	44.397571567000	0.069371205500	23.8887496973959000	37	155.94400024400
39	31	80.0	-1.0	35	-1	-1	20395.875001000000	5.039922692100	0.007874879200	13.0744365837994000	39	214.63200378400
28	29	191.0	-1.0	27	29	30	14470.875000000000	3.575825567000	0.005587227400	30.6591865310600000	28	139.55000305200
25	22	3.0	-1.0	15	-1	-1	19660.250000000000	4.858146076200	0.007590853200	20.5226983267033000	25	145.34800720200
15	23	103.0	-1.0	5	16	25	6377.875000000000	1.576004801800	0.002462507500	35.6840187838467000	15	182.33700561500
30	28	83.0	-1.0	28	-1	-1	27613.999999000000	6.823557469700	0.010661808500	21.4818238124594000	30	131.73425420258
36	26	18.0	-1.0	35	37	38	7947.874999700000	1.963959651800	0.003068686900	16.1461303622999000	36	284.76529693600
5	24	38.0	-1.0	4	6	15	5218.874998400000	1.289610106400	0.002015015700	36.0695515579147000	5	127.61000061000
4	41	87.0	2.0	3	5	26	6980.000002100000	1.724792900500	0.002694988900	52.4327819058822000	4	123.18299865700
26	40	125.0	-1.0	4	27	32	15823.999999000000	3.910189519800	0.006109671100	37.3349010135431000	26	159.35899353000
3	42	480.0	-1.0	2	4	-1	82556.125000000000	20.400031268000	0.031875048800	36.3973553116386000	3	153.31199646000
27	30	222.0	-1.0	26	28	31	25046.874999000000	6.189208046600	0.009670637500	29.1415023909241000	27	170.27900695800
35	32	351.0	-1.0	34	36	39	47237.250001000000	11.672560661000	0.018238376000	19.4767829918041000	35	113.89900207500
42	35	41.0	-1.0	32	-1	-1	26776.000000000000	6.616483480100	0.010338255400	10.2432329030279000	42	140.68200683600
32	39	232.0	-1.0	26	33	42	25629.750000000000	6.333239373900	0.009895686500	27.1592219834587000	32	72.05680084230
34	34	166.0	-1.0	33	35	40	18760.000000000000	4.635689800200	0.007243265300	20.6309361428251000	34	132.85800170900
47	36	89.0	-1.0	43	-1	-1	30622.999999000000	7.567096414900	0.011823588100	10.9140869251098000	47	212.17900085400
40	33	43.0	-1.0	34	-1	-1	29098.874996999900	7.190477506400	0.011235121100	18.1422408647467000	40	151.18899536100
33	38	147.0	-1.0	32	34	41	23106.249999000000	5.709669906100	0.008921359200	15.7699150837838000	33	87.87740325930
43	46	71.0	-1.0	2	44	47	11466.874999000000	2.833522146600	0.004427378300	20.7314999355664000	43	241.23599243200
41	37	142.0	-1.0	33	-1	-1	32815.874996999900	8.108966791600	0.012670260600	17.0744345007901000	41	94.72779846190
44	45	99.0	-1.0	43	45	46	27618.124994999900	6.824576777300	0.010663401200	11.3286269816786000	44	174.27999877900
2	47	202.0	-1.0	1	3	43	23687.125002000000	5.853207023600	0.009145635900	44.7316290919850000	2	108.83000183100
45	43	124.0	-1.0	44	-1	-1	42622.750000000000	10.532294638000	0.016456710300	7.5015381712092900	45	194.07899475100
1	1	406.0	1.0	-1	2	48	50551.749999000000	12.491590183000	0.019518109600	44.3712057121350000	1	280.30609893800
46	44	10.0	-1.0	44	-1	-1	20494.875001000000	5.064386087300	0.007913103200	7.6208042593589700	46	171.66999816900
48	48	87.0	-1.0	1	-1	-1	22737.874999000000	5.618642601600	0.008779129000	15.1766896492207000	48	197.47900390600

Annex 2 Attribute Table for BASINS SW1 and sub-basins output

DOUT_START	DOUT_MID	ElevLow	Elevhigh	MeanWidth	MeanDepth	DSAreaAcre	DSAreaSqMi	USAreaAcre	USAreaSqMi
406.0	203.0	199.1098000000	209.9994000000	0.215194628600	0.039394702900	420.839583400000	0.657561849000	408.348672750000	0.638044801100
493.6	449.8	209.9994000000	232.9412000000	0.133241537300	0.028618265000	5.618673490000	0.008779177300	4.476554180000	0.006994615900
608.8	507.4	209.9994000000	217.2364000000	0.136551703200	0.029090306200	402.729505050000	0.629264851600	396.885966010000	0.620134321800
680.1	644.5	217.2364000000	229.9993000000	0.088360213600	0.021763131300	32.821968730000	0.051284326100	29.988909905000	0.046857671700
769.6	724.8	229.9993000000	241.1506000000	0.159300944500	0.032237580900	7.567096415000	0.011823588100	5.299413830000	0.008280334100
779.4	729.8	229.9993000000	239.9993000000	0.149729103600	0.030932927800	22.421319280000	0.035033311300	15.597020495000	0.024370344500
789.7	784.5	239.9993000000	239.9993000000	0.125192085600	0.027453736500	5.064416975000	0.007913151500	4.682392645000	0.007316238500
904.0	841.7	239.9993000000	250.5709000000	0.194256066400	0.036795943100	10.532356415000	0.016456806800	4.931474485000	0.007705428800
1089.6	849.2	217.2364000000	229.9993000000	0.288827998200	0.047933933800	364.054360190000	0.568834937700	343.662020060000	0.536971906300
1177.1	1133.4	229.9993000000	234.9993000000	0.065599867700	0.017843724900	343.654359810000	0.536959937200	341.929814010000	0.534265334300
1302.7	1239.9	234.9993000000	238.0177000000	0.107196220800	0.024755395000	143.375015990000	0.224023462400	139.465073580000	0.217914177400
1535.6	1419.1	238.0177000000	249.9993000000	0.143164826800	0.030022102200	109.812967790000	0.171582762100	103.480902160000	0.161688909600
1577.3	1556.4	249.9993000000	249.9993000000	0.146972854700	0.030552139700	6.616483480000	0.010338255400	5.275691750000	0.008243268300
1683.0	1609.3	249.9993000000	249.9993000000	0.134532555200	0.028802828500	96.863183160000	0.151348723600	91.157281605000	0.142433252500
1825.8	1754.4	249.9993000000	259.9992000000	0.166050467800	0.033141865200	8.108997680000	0.012670308800	4.682639750000	0.007316624600
1849.4	1766.2	249.9993000000	254.9992000000	0.118721509700	0.026499427100	83.044577350000	0.129757152100	78.420995695000	0.122532805700
1892.4	1870.9	254.9992000000	259.9992000000	0.154495356000	0.031585941800	7.190508395000	0.011235169300	6.113624805000	0.009552538700
2200.7	2025.0	254.9992000000	264.9992000000	0.206614346600	0.038340449000	71.218379155000	0.111278717400	59.599996265000	0.093124994100
2280.7	2240.7	264.9992000000	266.3474000000	0.124828891800	0.027400613600	5.039953580000	0.007874927400	4.676462125000	0.007306972000
2219.4	2210.0	264.9992000000	264.9992000000	0.070915362400	0.018795062000	54.505926690000	0.085165510400	52.543418780000	0.082099091800
2447.1	2333.2	264.9992000000	276.0134000000	0.166484622600	0.033199608500	8.144333695000	0.012725521300	4.839798530000	0.007562185200
2982.4	2600.9	264.9992000000	284.9991000000	0.460549505100	0.065423598100	44.397602455000	0.069371253800	4.464940245000	0.006976469100
1525.1	1413.9	238.0177000000	244.9993000000	0.141202322200	0.029747109400	29.651858685000	0.046331029100	23.462866855000	0.036660729400
1606.5	1565.8	244.9993000000	249.9993000000	0.134869823900	0.028850946900	5.733577315000	0.008958714500	4.487921010000	0.007012376500
1716.7	1620.9	244.9993000000	254.9992000000	0.101598333700	0.023885881200	17.729042435000	0.027701628800	14.153433085000	0.022114739100
1800.0	1758.4	254.9992000000	259.9992000000	0.149715685300	0.030931079700	6.823557470000	0.010661808500	4.718717080000	0.007372995400
1881.3	1799.0	254.9992000000	269.9992000000	0.156282362800	0.031829038800	7.329628510000	0.011452544500	4.555627780000	0.007118168400
1216.0	1196.6	234.9993000000	234.9993000000	0.055098001500	0.015884520500	198.554550910000	0.310241485800	197.265157020000	0.308226807800
1319.8	1267.9	234.9993000000	239.9993000000	0.062143443100	0.017211303100	96.419382580000	0.150655285200	94.843841100000	0.148193501700
1322.8	1321.3	239.9993000000	240.3230000000	0.122107722700	0.027000945100	4.858084300000	0.007590756700	4.838563005000	0.007560254600
1616.3	1468.1	239.9993000000	249.9993000000	0.156711901300	0.031887333100	89.985262590000	0.140601972700	82.626969900000	0.129104640400
1619.7	1618.0	249.9993000000	249.9993000000	0.116189333600	0.026121275800	4.472106290000	0.006987666000	4.464693140000	0.006976083000
1860.0	1738.2	249.9993000000	254.9992000000	0.174191347800	0.034216422300	78.149921510000	0.122109252300	69.367809810000	0.108387202800
2147.2	2003.6	254.9992000000	260.2797000000	0.292095075300	0.048294725500	49.060226700000	0.076656604200	28.284379615000	0.044194343100
2382.9	2265.1	260.3892000000	269.9992000000	0.275090304900	0.046401683200	18.808644180000	0.029388506500	4.498546525000	0.007028978900
2343.7	2245.5	260.3892000000	269.9992000000	0.182199882300	0.035257291000	9.465604130000	0.014790006400	5.767677805000	0.009011996500
1976.1	1918.1	254.9992000000	259.9992000000	0.047907566800	0.014470591600	20.307336005000	0.031730212500	19.287286565000	0.030136385200
2096.0	2036.0	259.9992000000	272.7114000000	0.176886220400	0.034568421300	9.009942510000	0.014078035100	4.687581850000	0.007324346600
2093.5	2034.8	259.9992000000	266.5194000000	0.191404664400	0.036434981700	10.275861425000	0.016056033400	4.474330235000	0.006991140900
1477.5	1346.8	234.9993000000	244.9993000000	0.159295092200	0.032236791400	100.845527340000	0.157571136400	93.304624055000	0.145788475000
2018.1	1747.8	244.9993000000	264.9992000000	0.365835827500	0.056114405800	30.248864365000	0.047263850500	4.506700990000	0.007041720200
1571.3	1524.4	244.9993000000	249.9993000000	0.083346020600	0.020931810300	63.030060770000	0.098484469900	60.515520290000	0.094555500400
1980.4	1775.9	249.9993000000	264.9992000000	0.231427838300	0.041351754800	26.367586130000	0.041199353300	12.266786410000	0.019166853700
2077.5	2029.0	264.9992000000	269.9992000000	0.145379678900	0.030330950100	6.497378870000	0.010152154400	4.699689995000	0.007343265600
2064.0	2022.2	264.9992000000	269.9992000000	0.135367934900	0.028921939500	5.768913330000	0.009013927000	4.463704720000	0.006974538600
1925.1	1748.2	249.9993000000	259.9992000000	0.167018224000	0.033270509600	34.091841325000	0.053268502000	25.905005570000	0.040476571200
2134.2	2029.7	259.9992000000	269.9992000000	0.153911656800	0.031506335000	7.145288180000	0.011164512700	4.646562420000	0.007260253700
2419.8	2172.5	259.9992000000	274.9992000000	0.274651772700	0.046352356300	18.758728970000	0.029310514000	4.548955945000	0.007107743600