10-28-1999

Groundwater nutrient loading in Biscayne Bay, Biscayne National Park, Florida

Michael James Byrne
Florida International University

DOI: 10.25148/etd.FI14052511

FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

GROUNDWATER NUTRIENT LOADING IN BISCAYNE BAY, BISCAYNE NATIONAL PARK, FLORIDA

A thesis submitted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE

in

ENVIRNONMENTAL STUDIES

by

Michael James Byrne

1999

To: Dean Arthur W. Herriott
College of Arts and Sciences

This thesis, written by Michael James Byrne, and entitled Groundwater Nutrient Loading In Biscayne Bay, Biscayne National Park, Florida, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

Krishnaswamy Jayachandran

Christian Langevin

John Meeder, Major Professor

Date of Defense: October 28, 1999

The thesis of Michael James Byrne is approved.

Dean Arthur W. Herriott
College of Arts and Sciences

Dean Richard L. Campbell
Division of Graduate Studies

Florida International University, 1999

DEDICATION

I dedicate this thesis to my sister and a friend, Eileen Byrne Brady and Tom Stewart. They touched and enriched so many lives in the short time they were here. They inspire me everyday.

ACKNOWLDGEMENTS

I would like to thank my major professor, John Meeder. Dr. Meeder provided an opportunity to test any theory and was always willing to assist me. He also provided me with two excellent helpers, Jen Alvord and Amy Renshaw. Jen and Amy helped me collect all my water-quality samples. Jen conducted a companion project on the benthic community within my study area that added a great deal of importance to my thesis results.

I would also like to thank my two committee members, Chris Langevin and "Jay" Krishnaswamy Jayachandran. Chris provided pressure transducers and many hours analyzing my methodologies for determining discharge.

I would like to thank the many hydrologic technicians, especially Liz Debiak, from the U.S. Geological Survey who spent time in the bay with me collecting seepage meter measurements. In addition to the technicians, I would like to thank Bob Mooney, Jon Passehl, Vincente Quinones, Eric Swain, Carolyn Price and Barbara Howie for their help in completing my research.

I would also like to thank everyone at Biscayne National Park, especially Max Flandorfer and Richard Curry. I wish to thank the lab people of S.E.R.C., especially, Pete, Elaine and Nancy. Finaly, thanks to all the scientists who allowed me to ask questions and never shut me out, especially, Anne Cox, Phil Stoddard, Mike Ross, Tom Smith, Suzanne Kopter, Jim Fourqurean and Joe Boyer.

ABSTRACT OF THE THESIS

GROUNDWATER NUTRIENT LOADING IN BISCAYNE BAY, BISCAYNE NATIONAL PARK, FLORIDA

By

Michael James Byrne

Florida International University, 1999

Miami, Florida

Professor John Meeder, Major Professor

This research documents submarine groundwater discharge along the shore of Biscayne Bay. Seepage meters and groundwater monitoring wells, between the outlets of Mowry and Military Canals, were used to quantify groundwater discharge, nutrient concentration and loading. Discharge is greatest 185 m offshore and then decreases to zero 400 m offshore. Total discharge is 20.6 m^3 m^{-1} d^{-1}. The location of discharge is controlled by distance from shore and sediment characteristics. Generally, nutrient concentrations were highest in groundwater flowing through seepage meters, followed in decreasing order; shallow groundwater, deep groundwater and surface water. The ratios of Mowry Canal nutrient loading and groundwater nutrient loading is 6:1, 7:1, and 14:1 for carbon, nitrogen and phosphorous, respectively.

Groundwater nutrient loading calculations indicate a negative impact on the Biscayne Bay estuary. Managers should address the source of the elevated nutrient concentrations and determine effective ways to reduce the negative effects of groundwater discharge.

TABLE OF CONTENTS

CHAPTER PAGE

CHAPTER PAGE

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

CHAPTER I

Introduction

The National Park Service recognizes Biscayne Bay as an important natural estuary because it hosts a wide variety of marine life and living corals. Over the past century, the ecosystem of Biscayne Bay has been threatened by a number of factors that are directly related to urban development and agriculture. Two of the most important factors relate to the chemical quality of the water discharging to Biscayne Bay and quantity of water discharging to Biscayne Bay. The quality of surface water and groundwater has diminished because of nutrient loading and pollution. In, addition the timing and delivery of freshwater flows to Biscayne Bay has been severely altered. Surface water flow occurs mainly through canals with control structures regulated by the South Florida Water Management District.

The Surface Water Improvement and Management Plan for Biscayne Bay (SWIM, South Florida Water Management District 1995) addresses the problems associated with water quality in the bay. The National Park Service, South Florida Water Management District and Miami-Dade County Environmental Resource Management agree to improve water quality by reestablishing sheet flow to the coastal estuarine zone. Groundwater discharge and nutrient loading to Biscayne Bay is considered insignificant because no data exists to suggest otherwise.

This research determines the importance of nearshore groundwater discharge and nutrient loading to Biscayne Bay. This is the first attempt to quantify total groundwater discharge to Biscayne Bay. Previous research, conducted over 30 years

ago, determined only fresh groundwater discharge to the estuary (Kohout, 1960, 1964, 1967). Therefore, this is the first study to determine groundwater nutrient loading to Biscayne Bay factoring in the nutrient rich brackish groundwater.

1.1 Previous Groundwater Studies

Submarine groundwater discharge occurs along many coasts and is often a significant source of nutrients in an estuary. In a summary of groundwater investigations in coastal estuaries, Johannes (1980) estimates submarine groundwater discharge contributes 3 to 5 times as much nitrogen to the estuarine environment than does surface water discharge. This relationship exists even though submarine groundwater discharge is often between 1 and 10 percent of surface water discharge. Groundwater high in nutrients can have a significant impact on the quality of water in a shallow estuary. The significance of groundwater nutrient loading of an estuary is summarized in several papers (Valiela et al. 1980; Spalding and Exner 1993; Winter 1995). They conclude groundwater nutrient loading may be far more significant than previously thought. Valiela et al. (1980) suggests that coastal wetlands might contribute significantly to groundwater nutrients. The latter conclusion was due to finding higher concentrations of nutrients in the uppermost groundwater in the aquifer when compared with lower depths.

Valiela et al (1978) document nutrient export from coastal groundwater and find most groundwater discharge close to shore. The contribution of groundwater to coastal waters is considered to be important to nutrient budgets (Capone and Bautista

1985; Giblin and Gaines 1990; Turner 1990; Matson 1993; Drexler et al.1999). In Guam, terrestrial nitrate and other solutes leach rapidly into the karst limestone and discharge within 1000 m of shore (Matson 1993). In the Florida Keys, groundwater nutrients are elevated by human activities and may pose loading problems to nearshore ecosystems (LaPointe et al. 1990; Shinn et al. 1994). Johannes (1980) concludes that nutrient loading by way of groundwater to bays and estuaries has increased because of the decreased groundwater quality associated with agricultural, municipal, and industrial land use.

Several researchers predict the rate of groundwater discharge from the zone of diffusion rapidly decreases offshore (Hubbert 1940; Harr 1962). Bokuniewiscz (1980) substantiates this prediction and documents discharge decreases nearly exponentially with distance from shore, and 40 to 98 percent of discharge occurs within 100 m of shore. However, Kohout (1960) documents fresh groundwater discharge to Biscayne Bay, 2000 m off shore.

Physical and numerical methods have been used to describe groundwater discharge into coastal estuaries and lakes. Anderson (1976) uses a Dupuit-Forcheimer (DF) approximation to simulate discharge beneath a strip oceanic island. Langevin et al. (1998) uses a Dupuit Gyhben Herzberg model to estimate the movement and location of a freshwater lens on a coastal island in Florida.

Lee (1977) developed a seepage meter to study groundwater surface water interaction. His main study was performed on Lake Sallie in Minnesota, where he found seepage rates ranged from 8.6×10^{-4} to 0.22 $m^3 m^{-2} d^{-1}$ and discharge decreased exponentially offshore. Lee's research inspires many studies incorporating the

inexpensive seepage meters as a methodology to determine discharge (Bokuniewicz 1980; Belanger and Montgomery 1992; Matson 1993; Cable et al. 1997).

Belanger and Montgomery (1992) evaluated the seepage meter in a test tank to determine potential errors associated with flow field deflection, friction and head loss within the seepage meter. By pre-filling bags, they were able to establish a measured to actual inseepage ratio of 0.77. Shaw and Prepas (1990) and Cable et al. (1997) also found the importance of pre-filling bags before installation. An empty bag forms a vacuum that increases flow into the bag, causing an overestimation of discharge.

1.2 Physical Characteristics of Southeast Florida

Southeast Florida is a low area with little relief. The Atlantic Coastal Ridge is 3 to 10 km (kilometers) wide and roughly parallel to the coast. The elevation of the ridge is 5 to 7 m (relative to the National Geodetic Vertical Datum of 1929) along the northern edge of the bay, 2 to 5 m along the central edge of the bay, and 1 to 3 m along the southern edge of the bay (Parker et al. 1955). The belt of coastal wetlands increases in width to the south as the coastal ridge decreases in elevation and trends westward away from the coast. The coastal ridge forces most of the drainage in the Everglades to the south and west, rather than toward the east. The coastal ridge has several breaks or topographic low areas, called the transverse glades, which allow surface water to flow from the Everglades to Biscayne Bay. These transverse glades furnish water to the bay as sheet flow across the broad marl prairie and fed tidal creeks (Perrine-Terra 1952; Ceia-Pennsuco U.S. Department of Agriculture 1996). In

addition to overland flow, large quantities of fresh groundwater were once known to flow to the bay through the Biscayne aquifer (Parker 1975).

The climate of south Florida is warm due to the proximity of the equator and the Gulf Stream. This subtropical region averages 180 cm yr^{-1} (centimeters per year) of rainfall and 150 cm yr^{-1} loss due to evapotranspiration. Most rain percolates through shallow soils and into the Biscayne aquifer (Parker et al. 1955).

The Biscayne aquifer is unconfined and consists mainly of limestone with some sandstones and clays. The aquifer increases in thickness from west to east and south to north, with an average thickness of 40 m at the coast. The hydraulic conductivity ranges from 6 to 16 km d^{-1} (Fish and Stewart 1990).

Biscayne Bay was once a shallow estuary with an average depth of 1-3 m (South Florida Water Management District 1995). Sediment composition included: exposed limestone, carbonate muds, quartz sands, skeletal carbonate sands, and mangrove muds (Wanless 1984). In all, Wanless described 11 sediment types in Biscayne Bay. Development has changed many of the physical and chemical characteristics of the bay.

1.3 Alterations to Biscayne Bay

The volume, timing of delivery, manner of delivery, and quality of freshwater discharge to Biscayne Bay have been highly altered (Parker et al. 1955). The tidal exchange or the amount of water exchanged between the bay and the ocean during a tidal cycle has increased. Increased tidal exchange has occurred in the last century

because of sea level rise (approximately 20 cm) and the construction of deepwater navigation channels (Haulover and Government Cuts) and the Intracoastal Waterway. In addition, the volume of groundwater discharge to the bay is assumed to have decreased in response to the decrease in water table elevation of approximately 1.3 m (Parker 1975).

The circulation pattern of the bay was first modified in 1896 with the construction of the Miami River-Cape Florida Channel (original control depth 3 m, increased to 4 m in 1897) (U. S. Army Corps of Engineers 1900) to permit access to larger ships. By 1905, the second ship channel was dredged through Norris Cut (4 m control depth). Construction of the Florida East Coast (FEC) Railway Channel (control depth 3 m) was completed in 1903. The present Miami Ship Channel was built in 1917 (Smiley 1973), increased to a depth of 8 m by 1929, to 10 m by 1935 and 13 m in the 1970's (Harlem 1979). The construction of Haulover Inlet in 1925 (Harlem 1979) led to the decline of the estuarine condition of north Biscayne Bay and produced significant ecological changes to the bay (Michel 1976; Teas 1976; Wanless 1976). The construction of these deep-water channels into the northern portion of the bay has increased tidal exchange (the amount of water exchanged during a tidal cycle due to increased velocities), and decreased the bay water resonance times resulting in increased salinities. This increased tidal exchange may be somewhat beneficial, although it has probably reduced the estuarine nature of the bay, by serving as a direct outlet for the more rapid export of the poor quality waters from the Miami River and Port of Miami. Coastal drainage for land recovery for agricultural use and mosquito control was complete along the west coast of the bay from the Deering Estate

southward to Homestead by 1928 (observations from 1928 aerial photography). These activities reduced the distribution of wetlands considerably. These wetlands must have exported both organic carbon, and freshwater through the narrow mangrove swamp fringe to the nearshore bay, maintaining a nearshore estuarine environment.

Historically, the coastal mangroves were a narrow fringe along the coastline and have expanded westward with the loss of sheet flow (Meeder et al. 1996). Fossil oyster bars, indicative of a past estuarine system, are frequently found at the mouths of old tidal creeks that no longer function as freshwater sources. Most of the oyster bars are buried by only a few centimeters to decimeters of soil suggesting that they were functional in the recent past (John Meeder, Florida International University, oral commun., 1999). The loss of oyster bars is probably a response to loss of a coastal, brackish estuarine zone that was maintained by freshwater sheet flow toward the bay. Saltwater encroachment curtailed further agricultural development in many areas until a series of water control structures implemented in the 1960's as recommended by the predecessor of the South Florida Water Management District, the Central and Southern Florida Flood Control Project (C&SF Project) (Parker et al. 1955). In addition, the L-31E Levee and Canal was constructed parallel to the coast to prevent saltwater encroachment and reduce impact from storm tides. The construction of the L-31E Levee and Canal system essentially eliminated any remaining sheet flow to the bay. Results of this loss of sheet flow have been the continued saltwater encroachment to the foot of the levee, loss of a slow steady source of freshwater along the Bay's shoreline and reduction in the flushing of freshwater marsh and mangrove

detritus. In place of sheet flow, canals now discharge large qualities of poor quality freshwater into the bay during the wet season.

The change from sheet flow to canal flow has had other effects on the bay. The abundance of nearshore benthic biomass declines as summer approaches because of the increasing cover by filamentous algae. The growth of algal biomass is triggered by increased load of nutrients delivered to the bay. Winds prevailing from the southeast tend to force surface water that is discharged from canals to flow northward along the shoreline. *Thalassia testudinum* is not abundant within 400 m of shore, which probably is a reflection of increased nutrient load and reduced salinities produced by canal point discharge (Meeder et al. 1996). In addition, as population density and agricultural chemical use increased since the 1940's, nutrient concentrations in groundwater have also presumably increased.

1.4 Restoring Biscayne Bay

The Surface Water Improvement and Management Plan (SWIM) for Biscayne Bay divided the bay into three segments based on geographic location, hydrologic input and hydrodynamics characteristics of the estuary (South Florida Water Management District 1995). North Bay is located between Dumbfoundling Bay and the Port of Miami; Central Bay is located between the Port of Miami and Featherbed Bank, and South Bay is located between the Featherbed Bank and stretches south to the Card Sound and Manatee Bay.

Salinities in North Bay were relatively low because freshwater discharge extended to the shoreline in several places. North Bay supported an active oyster fishery until the 1920's when Baker's Haulover Inlet was constructed (Harlem 1979). In the North Bay, two main inlets control the flow to tide: Baker's Haulover Inlet and Government Cut. Residence times average 3.2 days for Baker's Haulover Inlet and 13.2 days for Government Cut (van de Kreeke and Wang 1984).

The shoreline of Central Bay is a transitional shoreline from a rock cliff in the north to a broad prairie in the south. The coastal area along Central Bay varies from a rocky outcrop with 6 m of relief in the north, to coastal wetlands in the south.

The coastal zone along the shore of South Bay was broader than the Central and North Bays and historically received the least freshwater because of its distal location in the watershed and the low relief. No extensive fossil oyster bars have been located in this area. However, this is not to imply that there was a lack of freshwater. Marl soils indicative of a freshwater environment extend within 100 m of the shoreline (Meeder et al. 1996). The coastal freshwater, in South Bay, has been reduced more than elsewhere, resulting in 3,000 meters of saltwater encroachment in the last 30 to 50 years (Meeder et al. 1996).

Kohout (1960) calculated the rate of freshwater flow from the Biscayne aquifer into Biscayne Bay. He predicted fresh groundwater discharge, to be 45 m^3 m^{-1} d^{-1} in the Central Bay area. Kohout and Kolipinski (1967) documented a relationship between the distribution of benthic communities and groundwater discharge along the Biscayne Bay coastline.

The recalculation of nearshore groundwater discharge to Biscayne Bay is essential to understanding the sources of nutrients to the estuary. This is the first discharge study in 30 years and several major changes to the system have been made: 1) lowered groundwater table, 2) decreased groundwater quality, and 3) coastal water tables and saltwater encroachment has been controlled by water management structures and coastal protection levee (L-31E). This study is also the first attempt to estimate groundwater nutrient loading to Biscayne Bay.

The nutrient load entering Biscayne Bay by way of groundwater is calculated for the area between the outlets of Mowry and Military Canals as a component of the L-31E Freshwater Re-diversion Project for South Florida Water Management District (Ross and Meeder 1995). This thesis focuses on three areas: 1) documentation of the spatial and temporal distribution of groundwater salinity and nutrient levels, 2) measurement of groundwater discharge, and 3) estimation of groundwater nutrient load to nearshore Biscayne Bay.

1.5 Hypotheses

The following four hypotheses will address the importance of groundwater nutrient loading to Biscayne Bay.

1. Concentrations of nutrients in the nearshore groundwater are higher than bay and canal waters.
2. Groundwater is discharging into the bay.
3. Nutrient loading by way of groundwater is a significant source of nutrients to the

bay.

4. Water quality in Biscayne Bay would be altered if groundwater discharge increased.
   a. Increased groundwater discharge would reduce salinity, thereby returning the nearshore environment to a more estuarine community.
   b. Increased groundwater discharge would elevate nutrient concentrations and increase algae growth and reduce dissolved oxygen.

CHAPTER II

Materials and Methods

2.1 Study Area

The study area is located along the western shore of south Biscayne Bay between the outlets of Mowry and Military Canals (Figure 1). The western boundary of the study area is L-31E Canal and storm protection levee which is usually 600 m west of the shoreline. Black Point landfill is north of the study area. Turkey Point nuclear power plant is south of the study area.

2.1.1 Geologic Setting and Well Installation

The Quaternary-aged limestone of south Florida is subdivided into five units Q1-Q5 (Perkins 1977). The upper portion of the Q3 unit is freshwater limestone with lower permeability than the surrounding layers (Perkins 1977; Shinn et al. 1996). The Q3 layer is located between 3 to 5 m below land surface near the shoreline (Shinn et al. 1996). The lower permeability reduces vertical flow and encourages lateral flow.

Seven pairs of wells, 1 above and 1 below the unconformity, were drilled in Biscayne Bay in April and May, 1996. Well pairs are located along two transects, one 500 m south of Military Canal and the other 500 m north of the Mowry Canal (Figure 2). The wells on the Mowry transect (south) are located approximately 50, 300, 500 and 800 m offshore. An additional pair of wells was drilled 50 m offshore and 50 m

south of the Mowry Canal transect. The Military Canal transect has two sites located 50 and 300 m offshore.

The wells are 3.81 cm outside diameter, schedule 40 polyvinyl chloride (PVC) with a 1.5 m screen interval located at the bottom. The wells were installed according to standard operating procedure (MacIntyre 1975; Shinn et al. 1994) by member of the U. S. Geological Survey. Well heads were finished approximately 30 cm above the substrate. Well location was determined by Global Positional Satellites ((GPS) Table 1).

2.1.2 Seepage Meter Location and Sampling

Seepage meters were installed to measure groundwater discharge. The seepage meters were constructed from 208-liter steel drums cut into thirds. The center rings were discarded and the two ends were fitted with a PVC coupling in the top. This yields two seepage meters (Lee 1977). Seepage meters were installed in the field by gently pressing and rotating the meters into the sediment. The PVC vent and top of the seepage meter were kept slightly elevated above the sediment to allow for proper ventilation (Figure 3). The seepage meter "N3" was installed in 15 to 20 cm of sediment, and concrete was poured along the outside to prevent surface water from entering the meter (Chris Reich, U.S. Geological Survey, oral commun., 1998).

Two seepage meters were installed approximately 300 to 350 m offshore during well construction. No discharge was observed in these meters; it was determined that they were too far offshore. A total of 15 seepage meters were placed

along three transects - south, central and north with two seepage meters at 25 m from shore, and one at 50, 185, 300 m from shore along the transects. South and north transects are located adjacent to the well transects. The central transect is located parallel to a benthic vegetation transect (Meeder et al. 1996).

Seepage meters (S3, S4, C4) were moved later in the study to allow further experimentation on the northern transect. Sediment was removed to allow direct access to the aquifer in order to test for the effect of surface sediments on discharge. Two seepage meters were installed 25 and 50 m (NF1, NF2) from shore. In addition, a meter was installed at 80 m (N2.5) from shore to test if discharge increases as sediment decreases (Figure 4).

Sediment thickness on each transect was determined by direct measurement. Three random measurements were done at each site and an average thickness determined. Sediment thickness was measured from shore to 330 m offshore at 5 m increments.

2.2 Groundwater Discharge

Groundwater discharge was determined using two different and independent methodologies: seepage meters and Darcy's Law. Flow measurements in the seepage meters were initiated in February 1998 and continued through August 1999. Pressure transducers were used in January 1999 and again in July 1999. The pressure transducers installed in July 1999 failed to operate correctly and therefore, those measurements were not used to determine discharge.

2.2.1 Discharge from Seepage Meters

Discharge measurements in the seepage meters followed a standard procedure (Cable et al. 1997). Reynolds Oven bags were wrapped around a small piece of PVC pipe (10 cm in length and 3.8 cm in diameter) and attached with rubber bands. Before attaching a bag, 1 liter of bay water was poured into the bag in order to prevent a vacuum from developing (Shaw and Prepas 1991; Belanger and Montgomery 1992; Cable et al. 1997). A typical seepage measurement lasted between 20 and 60 minutes. The main concern was to receive enough water to measure a difference +/- 0.05 liter. The seepage meters were measured many times throughout different tidal cycles. In order to calculate seepage flux, measured water volumes collected in the bag over a known time and area (0.255 m^2) yielded a seepage flux for that location.

2.2.2 Pressure Transducers and Head Measurements

Three submersible pressure transducers were installed on the north transect for 3 weeks in January 1998 (Global Water WL 14). The pressure transducers were installed in the shallow and deep 50 m wells and in the shallow 300 m well (A1B, A1A, A2B). These pressure transducer record the difference in pressure between surface water and groundwater. This pressure difference can be converted to a head difference. Pressure data were collected every 15 minutes.

Difference in hydraulic head was also measured directly by extending the well head above the water surface with a PVC pipe. Water was removed from the inside of the casing and enough time was allowed to reach equilibrium (approximately 1 minute). The PVC pipe was measured inside and outside with a chalked steel tape and the surface water elevation was subtracted from groundwater head to determine net head difference (Fetter 1994).

The form of Darcy's law used to estimate groundwater discharge is:

$q = k\ (dh/dl)$

q = discharge (flux) [m d^{-1}]or [m^3 m^{-2} d^{-1}]

k= hydraulic conductivity of the sediments [m d^{-1}]

dh/dl = Difference in hydraulic head divided by sediment thickness.

The hydraulic conductivity of the sediments range between 0.00864 to 0.864 m d^{-1}(Fetter 1994). A value of 0.0864 m d^{-1}, which is toward the middle of this range, is used for all of the Darcy's Law calculations in this study. Sediment thickness was measured in the field. The head difference was measured with the pressure transducers.

An exponential line is computed using the mean difference in hydraulic head at 50 and 300 m offshore. The exponential equation is used to define the difference in hydraulic head, in 1 meter intervals, from 0 to 400 m offshore. Discharge per square meter is computed in 1 meter intervals and total discharge in cubic meters (per linear m) d^{-1} was determined by adding the 1 meter increments from 0 to 400 m offshore.

2.2.3 Well Flow Measurements

The groundwater wells flow positively when the PVC cap is removed and in order to measure the artesian flow from the groundwater wells, a PVC collar, with a 2 liter plastic bag, is attached to the well head. The bag is attached for 1 minute or until it becomes full, whichever comes first. Three measurements were made and an average flow rate was determined. These measurements were only used in a qualitative manner.

2.3 Nutrients

Well caps were removed and a watertight PVC fitting with two hoses attached were placed on top of each well. Three to five well volumes were purged with a centrifugal pump. A peristaltic pump was then used to collect samples from the surface water, upper and lower ground water and placed in 60 and 120 milliliter Nalgene bottles. The samples were filtered in the field and the 60 milliliter bottles were chilled immediately, in accordance with the Southeast Environmental Research Center (SERC) Laboratory Comprehensive Quality Assurance Plan. Samples were delivered to the lab within 24 hours. Specific conductivity and temperature were measured in the field using an Orion conductivity meter, and pH was measured with an Orion pH meter. Specific conductivity was transformed to salinity through the two step computation as follows: 1) y (chloride) = 0.4225 X - 2142, where X = conductivity) and 2) salinity = 1.825 X + 443.43, where X = chloride (R.S. Reese,

U.S. Geological Survey, oral commun., 1997). The samples were analyzed for the following nutrients: NO_2 (nitrite) + NO_3 (nitrate), NO_2, NH_4^+(ammonium), TP (total phosphorous), chlorophyll, TOC (total organic carbon), TN (total nitrogen), SRP (soluble reactive phosphorus), and APA (alkaline phosphatase activity). NH_4^+, NO_2 and NO_3 were combined as dissolved inorganic nitrogen (DIN) for analyses. Organic nitrogen (ON) was calculated by subtracting DIN from TN.

Water quality samples were collected from all 15 wells and surface water sites (Figure 1) a total of seven times: June 1996, September 1996, January 1997, May 1997, June 1997, April 1998, and August 1998. In addition to water quality samples, salinity and pH were also measured.

The seepage meters were also sampled for the same suite of nutrients during the last two sampling dates. The seepage meters were sampled by attaching new empty bags to the 15 seepage meters. The seepage meters discharged into the bags until we could return to remove the bags, approximately three hours.

2.4 Nutrient Loading

Groundwater nutrient load (nutrient species concentration/ area/ time unit) is the product of discharge (volume/area/time unit) and nutrient concentration (weight/volume). Load was calculated by multiplying the average concentration and average discharge at 25, 50, 185 and 300 m from shore. Shallow groundwater nutrient concentration and discharge were estimated at 25 and 185 m from shore by using an exponential curve.

The four different loading curves are the product of discharge (Darcy's Law, seepage meter) and nutrient concentration (shallow groundwater, seepage meter) in one meter steps. The sum of the one meter steps using Darcy's Law discharge were added from zero to 400 m (approximate limit of groundwater discharge) and the one meter steps for seepage meter discharge were added from 11 to 356 m off shore (positive values). Total loading, per day for the study area, is the product of the above sum and 2,100 m, the length of the shoreline between Mowry and Military Canals (g d^{-1}).

2.5 Statistical analysis

Wells were divided into three categories based on distance from shore and depth; shallow (above the Q3 boundary), and deep (below the Q3 boundary), and season. A total of 13 sites were used for the statistical analysis. The following sites were used to describe shallow wells: A1B, M1B, and M4B (50 m), A2B, and M1.5B (300 m), M2B (500 m) and M3B (800 m). The following sites were used to describe deep wells: A1A, M1A, M4A (50 m), A2A, M1.5A (300 m), Sites M2A (500 m) and M3A (800 m).

The seepage meters on the north transect used for nutrient analysis were N1, NC1 (25 m), N2 (50 m), N3 (185 m), N4 (300 m). The seepage meters on the central transect are C1, CC1 (25 m), C2 (50 m), C3 (185 m), C4 (300 m). The seepage meters on the south transect are S1, SC1 (25 m), S2 (50 m), S3 (185 m), S4 (300 m). All locator labels ending in "S" indicate surface water samples collected at the well site.

A two-way ANOVA and Tukey's post hoc test were used to test for statistical significance between sites and well depths (Iman and Conover 1983).

CHAPTER III

Results

3.1 Discharge

The average value, per linear meter of shoreline, of discharge recorded at the seepage meters is 20.6 m^3 d^{-1}. The average value made with the Darcy's Law calculation is10.5 m^3 m^{-1} d^{-1}. This is the average value that would occur over a 1-year period. Most of the groundwater discharge to the bay occurs between 50 to 250 m offshore.

3.1.1 Seepage Meter Discharge

Measured discharge to the seepage meters ranges from –0.07 to 1.48 m^3 m^{-2} d^{-1}. Discharge in "N1", the 25-m seepage meter, ranges from -0.01 to 0.15 m^3 m^{-2} d^{-1} (mean 0.017 m^3 m^2 d^{-1}). Discharge in "N2", the 50-m seepage meter, ranges from –0.006 to 0.13 m^3 m^{-2} d^{-1} (mean 0.031 m^3 m^{-2} d^{-1}). Discharge in "N2.5", the 85-m seepage meter, ranges from –0.04 to 0.12 m^3 m^{-2} d^{-1} (mean 0.054 m^3 m^{-2} d^{-1}). Discharge in "N3", the 185-m seepage meter, ranges from –0.016 to 0.27 m^3 m^{-2} d^{-1} (mean 0.10 m^3 m^{-2} d^{-1}). Discharge in "N4", the 300-m seepage meter, ranges from –0.005 to 0.10 m^3 m^{-2} d^{-1} (mean 0.031 m^3 m^{-2} d^{-1}). Discharge in "S3", the 185-m seepage meter located on the south transect, is the highest with a mean .35 m^3 m^{-2} d^{-1}.

Discharge measurements made along the north transect were used to compute a polynomial to quantify discharge as a function of distance from shore. The north transect was measured the most frequent, with 511 of 743 measurements. Discharge was defined by, the best fit line, a polynomial equation $y = -3 \times 10^{-6} x^2 + 0.0011x - 0.0113$. Discharge estimates were made in 1 meter increments and the sum of those measurements from 11 to 356 m offshore. Discharge through a 1 meter wide section of shoreline, from the shoreline to 356 m offshore is equal to 20.6 m^{-1} m^2 d^{-1} (Figure 5). The seepage meter data indicates little discharge in the nearshore area and the greatest discharge at 185 m offshore ((approximately 0.075 m^3 m^{-2} d^{-1}) Figure 6).

NF1, the free flowing seepage meter, with the sediment removed, at 25-m from shore, had statistically greater discharge than N1 and N1C in January 1999. The seepage meter NF1 ranged from 0.026 to 0.43 m^3 m^{-2} d^{-1} (mean 0.11 m^3 m^{-2} d^{-1}), and the means for N1 and N1C were 0.011 and 0.015 m^3 m^{-2} d^{-1}, respectively. However, in July 1999, the discharge from NF1 was less than N1 and N1C. In July, the seepage meter NF1 ranged from -0.011 to 0.026 m^3 m^{-2} d^{-1} (mean 0.11 m^3 m^{-2} d^{-1}), and the mean discharges for N1 and N1C were 0.015 and 0.011 m^3 m^{-2} d^{-1}, respectively. NF2, the free flowing seepage meter 50 m from shore mean discharge, was lower than N2. The mean discharges for NF2 and N2 during January 1999 were 0.012 and 0.030 m^3 m^{-2} d^{-1}, respectively. The mean discharges for NF2 and N2 during July 1999 were 0.011 and 0.062 m^3 m^{-2} d^{-1}, respectively.

The seepage meter (N2.5), on the north transect, located 80 m offshore had greater discharge than the other seepage meters located closer to shore. The mean discharges for January 1999 and July 1999 were 0.051 and 0.062 m^3 m^{-1} d^{-1},

respectively. Discharge from N2.5 was greater in the summer than winter, however, the difference was not statistically significant.

3.1.2 Darcy's Law Discharge

The discharge estimate computed using the pressure transducer and Darcy's Law, was much lower (8.2 $m^3\ m^{-1}\ d^{-1}$) than the seepage meter estimate (20.6 $m^3\ m^{-1}\ d^{-1}$). This discharge estimate is two times lower than the seepage meter estimate. Discharge is greatest 150 m offshore with a large increase beginning 80 m offshore as sediment thins.

The discharge estimate for summer is 36 percent higher than the estimate for winter. Summer discharge was 12.82 $m^3\ m^{-1}\ d^{-1}$. The annual discharge estimate using Darcy's Law is 10.49 $m^3\ m^{-2}\ d^{-1}$ (Figure 7).

3.2 Nutrients

Data were tested for temporal (seasonal) and spatial (distance from shore) variation. Each of the parameters had significant variance based on location. Nutrient concentrations were higher in the seepage meters than in groundwater. Shallow groundwater nutrient concentrations were also elevated, decreasing offshore (Table 3). Six seepage meters, collectively called "25-m seepage meter samples", are used to describe the seepage meter nutrient concentration 25 meters offshore.

3.2.1 Nitrogen

Concentration of ammonium (NH_4^+) in the 25-m seepage meter samples was significantly higher than surface water and deep groundwater. NH_4^+ concentration in the 25-m seepage meter samples range from 0.16 to 6.00 mg liter^{-1} (mean 1.489 mg liter^{-1}). Shallow nearshore groundwater ranged from 0.03 to 1.05 mg liter^{-1} (mean 0.665 mg liter^{-1}). Ammonium concentrations in the groundwater samples collected from shallow wells nearshore were significantly higher (approximately by a factor of 20) than the ammonia concentrations in surface water 50 m offshore (mean 0.034 mg liter^{-1}). Ammonium concentrations decrease as distance from shore increases (Figure 8). The mean concentrations in the shallow and deep groundwater were higher than the mean concentrations of the surface water (by a factor of between 10 and 15). This was expected because ammonium is found in anoxic environments. Ammonium concentrations did not vary significantly seasonally.

Concentration of dissolved inorganic nitrogen (DIN) in the 25-m seepage meter samples was significantly higher than surface water and deep groundwater. DIN concentrations in the 25-m seepage meter samples ranged from 0.70 to 6.01 mg liter^{-1} (mean 1.498 mg liter^{-1}). Groundwater samples collected from shallow wells nearshore ranged from 0.037 to 1.06 mg liter^{-1} (mean concentration of 0.673 mg liter^{-1}). The highest concentrations of DIN were found in the nearshore decreasing offshore (Figure 9).

Concentration of organic nitrogen (ON) concentration in the 25-m seepage meter samples was significantly higher than all the other groundwater and surface

water samples. The ON concentrations in the 25-m seepage meter samples range from 0.12 to 9.28 mg liter^{-1} (mean 2.93 mg liter^{-1}). Groundwater samples collected from shallow wells nearshore ranged between 0.07 to 0.82 mg liter^{-1} (mean 0.41 mg liter^{-1}). The ON concentrations decrease as distance from shore increases (Figure 10).

Concentration of total nitrogen (TN), the sum of inorganic nitrogen (ammonia, nitrate, nitrite) and organic nitrogen, in the 25-m seepage meter samples ranged from 0.74 to 9.49 mg liter^{-1} (mean 2.87 mg liter^{-1}). The TN concentrations in the 25-m seepage meter samples were significantly higher than all surface and groundwater. Groundwater samples collected from shallow wells nearshore ranged from 0.48 to 1.53 mg liter^{-1} (mean 1.04 mg liter^{-1}). All concentrations decrease as distance from shore increases (Figure 11).

3.2.2 Phosphorus

Concentration of total phosphorous (TP) in the 25-m seepage meter samples ranged from 0.005 to 0.031 mg liter^{-1} (mean 0.013 mg liter^{-1}). The TP concentrations in the groundwater samples collected from shallow wells nearshore were significantly higher than the all the surface water samples. The TP concentrations in the shallow nearshore groundwater samples ranged from 0.017 to 0.040 mg liter^{-1} (Figure 12).

3.2.3 Organic Carbon

Concentration of total organic carbon (TOC) in the 25-m seepage meter samples was significantly higher than all the surface water and groundwater samples. The TOC concentrations in the 25-m seepage meter samples ranged from 9.28 to 48.52 mg $liter^{-1}$ (mean 35.40 mg $liter^{-1}$). The TOC concentrations in the groundwater samples collected from shallow wells nearshore were significantly higher than the deep groundwater samples 300 m offshore. The TOC concentrations in the shallow groundwater samples ranged from 7.37 to 13.46 mg $liter^{-1}$ (mean 10.72 mg $liter^{-1}$ Figure 13).

3.2.4 Salinity

Salinity concentrations in the 50-m nearshore shallow groundwater were significantly lower than all the other groundwater samples. The nearshore shallow groundwater ranged from 14.9 to 20.4 parts per thousand (ppt) (mean 16.8 ppt). Salinity concentrations in the 50-m deep nearshore groundwater range were 17 to 37 ppt (mean 25.5 ppt) and were significantly lower than the deep groundwater offshore 300 m 28 to 37 ppt (mean 35 ppt). Surface water salinity at 50 m ranged from 2 to 37 ppt (mean 15 ppt). Mean salinity for all surface water sites at 25, 185, 300 and 800 m were 13, 14, 18, 25 ppt, respectively. All salinity concentrations increase as distance from shore increases (Figure 14).

3.3 Nutrient Loading

Loading calculations from seepage meter discharge (SMQ) and seepage meters nutrient concentration (SMC) and are highest for the following nutrients: TN, TOC, and ON. The NH_4^+ loading is 10.23 g (per linear m) d^{-1}, 7,841 kg yr^{-1} (Figures 15, 16) The TN loading is 31.99 g m^{-1} d^{-1}, 24,520 kg yr^{-1} (Figures 17, 18). The DIN loading is 10.75 g m^{-1} d^{-1}, 8,240 kg yr^{-1} (Figures 19, 20) The ON loading is 26 g m^{-1} d^{-1}, 19,929 kg yr^{-1} (Figures 21, 22). The TP loading is low relative to the other loading calculation 0.131 g m^{-1} d^{-1}, 100 kg yr^{-1} (Figures 23, 24). The TOC loading is 492 g m^{-1} d^{-1}, 377,118 kg yr^{-1} (Figures 25, 26).

Loading calculations from SMQ and shallow groundwater nutrient concentration (SGC) are much higher than SMC x SMQ for TP; 0.559 g m^{-1} d^{-1}, 428 kg yr^{-1}. Loading estimates are similar for the following parameters: NH_4^+ 8,838 kg yr^{-1}, and DIN 8,960 kg yr^{-1}. The TOC loading estimates for SMQ x SGC are 112,107 kg yr^{-1} is three times lower than estimates for SMQ x SMC. All other loading calculations can be found in Table 5.

CHAPTER IV

Discussion and Conclusions

4.1 Impact of Groundwater Discharge

This research documents groundwater, rich in nutrients, is discharging to Biscayne Bay along the nearshore. Excess nutrients will increase algal growth and reduce available light and ecosystem productivity. Major findings include:

1. Nutrient loading by way of groundwater is significant.
2. Greatest discharge rate is found approximately 185 meters offshore.
3. Groundwater discharge extends 400 meters offshore.
4. The sediment exports nitrogen and carbon and acts as a phosphorous sink.
5. The ratio of Mowry Canal discharge to groundwater discharge is 12:1.
6. The ratio of Mowry Canal nutrient loading to groundwater nutrient loading is 6:1, 7:1, 14:1 for Total Organic Carbon (Figure 29), Total Nitrogen (Figure 30), and Total Phosphorous (Figure 31), respectively.

4.2 Discharge

Discharge estimates are calculated using two methodologies: seepage meters and well pressure transducers. Seepage meters directly measure discharge, but require many measurements to get a representative discharge. Pressure transducers calculations use Darcy's Law to determine discharge. These calculations rely on sediment homogeneity and accurate pressure readings.

4.2.1 Seepage Meter Discharge

Groundwater discharge to Biscayne Bay, as measured with the seepage meters, is relatively low nearshore but increases offshore as sediment thins. The sediment thins from an average of 60 cm at the shoreline to approximately 20 cm, 80 meters from shore. The near shore sediment is composed of mud, carbonate skeletal matrix and flocculent matter. The sediment contains little mud at 80 meters from shore, most is carbonate skeletal matrix. Sediment thickness, hydraulic conductivity and hydraulic gradient govern discharge. Highest discharge is located 185 m from the shoreline. Discharge increases from a low rate at the coast to the highest rate 185 m offshore, the flow rate is much lower 300 m offshore. The second-order polynomial is a very effective way to represent this discharge.

Seepage meter discharge does not correlate tidally and seasonally (Figure 32). Water discharges in pulses and the pulses are independent to each seepage meter. There is a lag time between groundwater seepage and tide and it is dependent on sediment composition. In addition, hydraulic gradient affects groundwater discharge in the coastal zone. The coastal control structure on Mowry Canal (S20F) opens whenever canal water stage rises and exceeds the regulated elevation and closed when stage drop below the regulate elevation. The gate openings occur throughout the day, and these openings reduce the elevation of the L-31E Canal. A reduction in L-31E Canal will lower the hydraulic gradient and reduce overall discharge. Fluctuations in

hydraulic gradient will cause unsteady groundwater flow in the coastal zone. There was also no detectable reduction in discharge from summer to winter. The higher summer discharge may have occurred outside the main area of focus, 0 to 80 m.

Measurements from the meters located 185 and 300 meters were not continued after September 1998. It was assumed most discharge would be found closer to the shoreline. Several researchers predict groundwater discharge decreases exponentially from shore (Lee 1977; Bokuniewicz 1980; Fellow and Bezonik 1980; Belanger et al. 1985; Reay et al. 1992; Robinson et al. 1998).

Sediment, distance from shore and hydraulic gradient control groundwater flow. Two meters NF1 and NF2 were installed on bare rock 25 and 50 m offshore to test for the effect sediment had on discharge. In January, NF1 flow was very high with the initial measurements, however, NF2 did not have greater discharge. To explain the low flow in NF2 it was assumed that mud was trapped under the seepage meter, reducing the permeability. Therefore, before measuring for the summer discharge, NF2 was moved to a different location with a similar result. In July, flows from NF1 and NF2 were lower than the surrounding seepage meters. Layers of mud cover the limestone surface and low permeability sediments overlie certain other areas. If NF2 was installed over another layer of mud, it may have impacted the flow. NF1 might have filled with flocculent material in the six months it was exposed.

4.2.2 Well Flow Measurements

Well flow data documents the potential for exponentially decreasing hydraulic conductivity. Well flow measurements are very high and they are useful for documenting groundwater potential and groundwater flows (Table 2, Figure 33). The measurements might be used to represent historic groundwater springs. If the volumetric flows can be converted to discharge, then, these data would be of greater use. This methodology to collect flow measurements and compute discharge is not supported by the literature.

4.2.3 Pressure Transducer Discharge

Groundwater discharge estimate by pressure transducers and Darcy's Law calculations is approximately 50 percent of seepage meter discharge estimate. In order to compute discharge using Darcy's Law calculations certain assumptions are made; sediment composition is constant, hydraulic gradient decreases exponentially, and difference in pressure from the pressure transducers was accurate.

Sediment composition, thickness and hydraulic gradient govern the location of discharge. The sediment hydraulic conductivity is difficult to measure accurately, therefore, an estimate was used (Fetter 1994). Sediment hydraulic conductivity is probably within an order of magnitude of this estimate. Hydraulic potential does decrease exponentially as shown with the well flow data (Figure 33). The pressure transducers used were not very accurate and can be off by several centimeters and the

after laboratory tests, these pressure transducers were returned for calibration.

4.2.4 Predicted Discharge Increase

A Darcy's Law calculation was used to predict the impact of future increases in groundwater elevation as a result of Everglades restoration. An annual increase of 30 cm was used for the calculations. Winter discharge, based on a theoretical increase of the L-31E Canal from 0.43 to 0.73 m, would equal 13.2 m^3 m^{-1} d^{-1}. It was assumed an increase in elevation of the L-31E Canal would increase difference in groundwater pressure by the same ratio. Summer discharge, with an increase of the L-31E canal from 0.67 to 0.97 m, would equal 17.8 m^3 m^{-1} d^{-1}. Therefore, based on a 30 cm rise in canal elevation, annual discharge is 15.5 m^3 m^{-1} d^{-1}. The 30 cm estimate is based on plans of increasing groundwater elevation by 60 cm in western Miami-Dade County (U.S. Army Corps of Engineers 1999).

4.2.5 Groundwater Discharge in Other Estuaries and Lakes

The groundwater seepage rates found in other estuaries are comparable to the rates found in Biscayne Bay with seepage meters and pressure transducers (Table 5). Belanger et al. (1985) found discharge using seepage meters were a magnitude higher in Indian River Lagoon than the discharges found using a Galerkin finite element model (Pandit and El-Khazen 1988). Models and mass balance equations tend to underestimate discharge into coastal estuaries (Lee 1977; Johannes 1980).

Groundwater flow to estuaries is often underestimated because the researcher is focussed on the fresh water contribution. However, the total discharge that includes saltwater mixing can be more than a magnitude greater (Cable et al 1999). The predictive models often lack important variables like wind speed and direction, tidal height, and offshore sediment thickness and composition.

4.2.6 Previous Groundwater Studies in Biscayne Bay

Kohout studied groundwater flow, near the Deering Estate located in Central Biscayne Bay, from the late 1950's until the mid 1960's (1960, 1964, 1967). Kohout estimated the movement and position of the saltwater front after a large rain event. In addition a relationship between groundwater flow and benthic communities was documented (Kohout and Kolipinski 1967).

Kohout (1960) first used physical parameters in the field to estimate groundwater discharge. An average velocity of 21 m d^{-1}, aquifer thickness 10.5 m and effective porosity of the limestone of 0.2 was determined. The predicted discharge, using Darcy's Law and the above parameters, was 46 m^3 m^{-1} d^{-1} (Kohout 1960). This estimate is twice the estimate based on seepage meters and 4 times the estimate based on pressure transducers.

Kohout (1967) second method is no longer in use by hydrologists estimating groundwater contribution into estuaries and lakes. Kohout made certain assumptions, concerning Biscayne Bay, which cannot be made today. The assumptions are; all fresh water components in Biscayne Bay came from groundwater flow, negligible

horizontal flow of coastal waters existed and he used a mass balance equation. At the time of this study, there was no surface water canal within 8 km. Therefore, negligible overland flow was assumed and no net change due rainfall and evapotranspiration. Alterations to Biscayne Bay, make these estimations impossible to test. Kohout predicted a net freshwater discharge of 11.4 $m^3\ m^{-1}\ d^{-1}$.

Kohout's predicted discharge estimates should not be compared to the estimates of this study. The conditions in the bay have been altered and the discharge he predicted was fresh groundwater, whereas, the discharge found by this study includes saline groundwater discharge.

4.3 Groundwater Nutrient Concentrations

Groundwater discharge to estuaries and lakes is important because nutrient concentrations are often higher than surface water. Increased nutrient concentrations often change benthic community dynamics and structures. The two elements that have the greatest potential for changing an ecosystem are nitrogen and phosphorus. Nitrogen is found in the atmosphere as a stable compound N_2 and usually requires microbial activity in soils to convert it to NH_3. All forms of N dissolve in water and are transported by overland and groundwater flows. Phosphorous is often found as PO_4^-, and is hydrophobic. The element is usually added to the ecosystem with fertilizers. Plants require very little phosphorous, therefore, small concentrations can have a negative impact. Phosphorous was found to be the limiting nutrient in Florida Bay (Fourqueren 1992).

Two methodologies were used to measure nutrient concentration; direct measurement of groundwater nutrient concentrations in groundwater wells and measurement of groundwater seepage through seepage meters, which includes nutrient export from the sediment. In addition to nutrient concentration, salinity is critical to an ecosystem. Therefore, along with groundwater nutrient concentration salinity was also measured. Seepage meter salinity was measured, but due to the methodology used to collect discharge, an estimate of salinity could contain too much error to get an accurate concentration. The seepage bag was filled with 1 liter of surface water and the seepage meter would usually discharge 0.10 liter and the net change in volume was not great enough to get an accurate estimate of seepage salinity.

4.3.1 NH_4^+ Groundwater and Seepage Meter Concentrations

The NH_4^+ is found in anaerobic environments and is often negligible in most surface waters. The concentration of NH_4^+decreases exponentially from the shoreline and approaches local marine concentrations 0.4 mg liter^{-1} at 800 m from shore. The average concentration from 25-m seepage meters (1.5 mg liter^{-1}) is almost 3 times higher than the nearshore shallow groundwater (0.67 mg liter^{-1}). Water discharge through the seepage meter includes nitrogen exported from the sediment. Seepage meter concentration decreases to background levels (0.24 mg liter^{-1}) at 185 m from shore, and this is probably due to thinning sediment and greater biologic activity.

Most groundwater studies focus on levels of NO_3^- rather than NH_4^+ (Capone

and Bautista 1985; Matson 1993). The high levels of NH_4^+ in the Biscayne Aquifer are due to rainfall that percolates through the thin south Florida soils and carrying organic materials into the groundwater prior to the decomposition process. This results in the anaerobic breakdown of organic material into NH_4^+ in the shallow aquifer rather than NO_3^-, which is produced by aerobic decomposition process in the soil profile. In many systems NH_4^+ would be trapped in the soils until converted into NO_3^-. However, high groundwater NH_4^+ concentrations were measured entering a Florida lake 3.2 mg liter^{-1} (Belanger et al 1985). An investigation in groundwater quality in Miami-Dade County found NH_4^+ levels ranged between 0.02 to 1.9 mg liter^{-1} and a mean 0.47 mg liter^{-1} (Sonntag 1987). Levels in the bay range from 0 to 0.09 mg liter^{-1} and in the nearby canals from 0.10 to 0.30 mg liter^{-1} (South Florida Water Management District 1995).

4.3.2 Total Nitrogen Groundwater and Seepage Meter Concentrations

The TN concentrations in the groundwater and the seepage meters are very high when compared with the near shore marine surface water TN. The average concentration in the 25-m seepage meters (2.7 mg liter^{-1}) is about three times as high as the near shore shallow groundwater (1 mg liter^{-1}) and it is 4.5 times higher than the marine concentration (0.6 mg liter^{-1}) found 0 to 800 m offshore. The elevated nitrogen concentration in the seepage meter exists 300 m offshore (1.5 mg liter^{-1}). Although the sediment thins, and aerobic activity increases there is still a great deal of organic nitrogen available (1.1 mg liter^{-1}).

Sediment exports high concentrations of organic nitrogen and dissolved inorganic nitrogen near the coast and high concentration of organic nitrogen 300 m from shore (Figure 30). Estuarine groundwater rich in nitrogen has been associated with agriculture as reported by several authors (Valiela et al. 1978; Capone and Bautista 1985). Three springs flowing from agriculture lands in upstate N.Y. had elevated DIN concentrations of 7.8, 1.5 and 3.1 mg liter^{-1} (Drexler et al. 1999). A study, in coastal Massachusetts, found a direct link between development and DIN enrichment of groundwater entering a marsh fringed estuary; concentrations for background levels, a moderately developed area and a highly developed area were 0.08, 1.5, 2.8 mg liter^{-1}, respectively (Portnoy et al. 1998). Mean total nitrogen concentrations in Biscayne aquifer are 1.0 mg liter^{-1} (Sonntag, 1987).

4.3.3 TP Concentrations in Groundwater and Seepage Meters

Total phosphorus concentrations are highest in nearshore shallow groundwater (0.031 mg liter^{-1}) are similar to the concentrations found in Mowry Canal 0.032 mg liter^{-1} (Meeder unpublished data). The concentration found flowing through the seepage meters (0.013 mg liter^{-1}) may be low due to assimilation by biologic activity and the attraction phosphorus has to sediment. The clays found in the nearshore sediment can attract the free phosphorus. Therefore, the sediment is probably high in phosphorus and the water exiting through sediment would be less. However, the rusting metallic surface of the seepage meter could adsorb free phosphorus and lead to anomalous low readings (Ron Jones, Florida International University, personal

communication 1999). Background bay water concentrations are 0.007 mg liter^{-1} and nearby canals concentrations range between 0.008-0.020 mg liter^{-1} (South Florida Water Management District 1995). Mean total phosphorus concentrations in Biscayne aquifer are 0.020 mg liter^{-1} (Sonntag 1987).

4.3.4 TOC Concentrations in Groundwater and Seepage Meters

There are high levels of organic carbon found in both surface and groundwater due to the peat soils. Highest concentrations are found flowing through the sediment and into the 25 m seepage meter (35.4 mg liter^{-1}). The concentration shallow nearshore groundwater, 10.72 mg liter^{-1}, was similar to the mean concentration found in the Biscayne aquifer, 11.7 mg liter^{-1} (Sonntag 1987). High levels of organic carbon are common around marsh fringed estuaries, therefore, organic carbon is rarely a limiting nutrient in these systems (Valiela et al. 1978).

4.3.5 Salinity in Groundwater and Surface Water

Increased groundwater discharge would mean a return to a more estuarine environment. The mean salinity in the nearshore shallow groundwater is 16.8 ppt, whereas, the mean salinity in the mouth of Mowry Canal is 25 ppt (South Florida Water Management District 1995). Salinity in the nearshore surface water trends higher further offshore. At 25 m offshore mean salinity is 13 ppt, whereas, at 800 m offshore mean salinity is 25 ppt. Enhanced groundwater flow would lower the salinity

concentrations in the nearshore shallow groundwater and thereby lower the mean concentration in the nearshore surface water. Groundwater flow helps to mediate the extreme changes in salinity in the nearshore surface water such as the ranges found by this study, 2 to 37 ppt.

4.4 Nutrient Loading

Loading was calculated using several different methodologies and comparisons. Seepage meter discharge (SMQ) x seepage meter nutrient concentrations (SMC) represents the net loading to the bay water. SMQ x shallow groundwater nutrient concentrations (SGC) represent the net loading of the sediment. Whereas, Darcy's Law discharge (DLQ) x SGC and DLQ x SMC alter true location of loading by overestimating nearshore discharge and underestimating loading 185 m off shore. The sediment is a potential source of nitrogen and organic carbon and a phosphorus sink.

4.4.1 Nitrogen Loading

Total groundwater nitrogen loading, for the study area, to the bay is (SMQ x SMC) 24,520 kg yr^{-1} and total loading to the sediment is (SMQ x SGC) 13,184 kg yr^{-1}. Sediment doubles the amount of nitrogen available to the estuary. Therefore, it is unlikely that nitrogen is a limiting nutrient to this system.

4.4.2 Phosphorus Loading

Total groundwater phosphorus loading, for the study area, to the bay is (SMQ x SMC) 100 kg yr^{-1} and total loading to the sediment is (SMQ x SGC) 428 kg yr^{-1}. Therefore, the sediment is a phosphorus sink. Approximately 75 percent of the phosphorus is trapped in the sediment, however, the trapped phosphorus is still available to benthic plants and algae with root structures.

4.4.3 Total Organic Carbon Loading

Total groundwater organic carbon loading, for the study area, to the bay is (SMQ x SMC) 377,118 kg yr^{-1} and total loading to the sediment is (SMQ x SGC) 121,107 kg yr^{-1}.

4.4.4 Groundwater Loading Compared with Mowry Canal

Mowry Canal borders the southern boundary of the study area, the canal has a drainage basin of 105 km^2 mainly comprised of agriculture. This canal discharges 36 percent of the canal flow to south Biscayne Bay (SFWMD 1995). This is a nutrient rich canal with mean concentrations; 0.92 TN mg $liter^{-1}$, 0.032 TP mg $liter^{-1}$ and 12.5 TC mg $liter^{-1}$, calculated by sampling ten days in a row in June 1996 (Meeder unpublished data). Loading calculations for Mowry Canal are the product of mean annual discharge 191,439,200 m^3 yr^{-1} and the above nutrient concentrations.

Mowry Canal discharge water extends beyond the study area and any comparison should be considered qualitative. The groundwater discharge represents discharge along 2,100 meters of shoreline. The ratio of Mowry Canal discharge to groundwater discharge (SMQ) is 12:1. However, because of elevated nutrient concentrations, in groundwater and sediment, the nutrient loading ratio of Mowry Canal to groundwater discharge is 6:1, 7:1 and 14:1 for carbon, nitrogen and phosphorous, respectively.

Increased groundwater discharge, by way of higher groundwater elevation and without a reduction in nutrient concentrations, will enrich Biscayne Bay at a greater rate than increased canal flows. Increased groundwater discharge will drive the saltwater interface further offshore, allowing fresher water to discharge in the nearshore. Fresh water is higher in nutrient concentration than brackish water, therefore, an increase of groundwater will increase loading by a greater ratio.

4.4.5 Groundwater Loading Estimates by Others

Chesapeake Bay nutrient concentrations and discharge has been intensively studied and best management practices have been implemented (Reay et al. 1992; Staver and Brinsfield 1996). Nitrate levels, in a main stem inlet, were up to 20 times greater due to groundwater discharge, which indicates groundwater is of significant ecological importance. The management practices produced greater discharge by way of groundwater (Reay et al. 1992). Staver and Brinsfield (1996) found annual nitrogen groundwater discharge to be 1.2 kg m^{-1}.

Several authors have discussed the importance of ground nutrient loading to lakes (Loeb and Goldman 1979; Belanger et al 1985). Ward Valley, in Lake Tahoe, delivers 49 percent of the nitrogen and 44 percent of the phosphorus by way of groundwater, even though groundwater flow comprises a small percent of the major inputs; overland flow (16 percent) and precipitation (10 percent) (Loeb and Goldman 1979). East Lake Tohopekaliga, in Florida, receives 8.7 and 17.6 percent of the annual phosphorous and nitrogen, respectively, from groundwater loading (Belanger et al 1985).

High rates of groundwater discharge and elevated nutrient loading been found in association with island coastal waters with limestone aquifers (Lapoint et al. 1990; Matson 1993). Nitrogen concentrations, in the Florida Keys, are elevated in the groundwater and coupled with high discharge velocities, (mean 0.75 m^3 m^2 d^{-1}) make groundwater nutrient loading a significant problem (Lapoint et al. 1990). Guam also receives elevated nutrients via groundwater loading with an average discharge, 5.1 m^3 m^{-1} d^{-1}, similar to those found in this study (Matson 1993).

4.5 Implications to Managers

Everglades restoration will raise groundwater elevation, which will increase groundwater discharge and nutrient loading and decrease salinity in the nearshore estuary. Managers should address the sources of the excess nutrients and determine ways to reduce the sources of elevated nutrient concentration in the groundwater. The source of the elevated nutrient concentrations was not determined by this study. The

coastal wetland is underlain by a marl substrate, which reduces the vertical hydraulic conductivity. This aquaclude makes the coastal wetlands an unlikely source of nutrients. In addition, salinity and hydraulic gradients govern the groundwater flow in the coastal area, therefore, flow perpendicular to the shore is in an upward direction.

Alterations to the sediment composition, by dredging or filling, will impact the nearshore environment with unattended consequences. Any dredging of the nearshore coastal area could create a conduit for nutrient rich groundwater. Nearshore sediment mediates the loading of phosphorous and would increase groundwater discharge close to the coast. Sediment also reduces saltwater intrusion by restricting the vertical flow in the nearshore shallow groundwater. Dredging of canals would create a flow path, allowing groundwater to transmit directly to the canals, thereby, limiting the overall groundwater discharge along the shoreline.

4.6 Conclusions

Groundwater discharge is much less than the surface water discharge by way of canals, however, nutrient concentration is much greater. Therefore, increased groundwater discharge, without reducing nutrient concentrations in the aquifer, would impact nearshore communities negatively by increasing algal growth and reducing productivity. However, the nearshore environment would benefit from increased discharge by reducing salinity and moderating the affects of the point discharge from Mowry Canal.

This study documents elevated groundwater nutrient concentrations in both the nearshore shallow groundwater and the sediment, as measured in seepage meters. The ratios of nutrient contributions from Mowry Canal are greater than groundwater by 6:1, 7:1, 14:1 for carbon, nitrogen and phosphorous, respectively.

This study area has a low hydraulic gradient along the coastal shore, whereas, north and central Biscayne Bay have a higher gradients and increased hydraulic potential. Therefore, groundwater discharges along the coast are greater in the northern areas of the bay. Further research should quantify this discharge and determine the groundwater quality in the northern areas of the bay.

Table 1. Location for Groundwater Wells Drilled in Biscayne Bay.

USGS Well name and Location	Site Name	GPS Coordinates	Well Depth and Screen Interval	Driller's Notes
G-3629 50 m from shore	M1A	25-28.436N 080-20.399W	13 m 10-11.5 m	
G-3630 50 m from shore	M1B	25-28.436N 080-20.243W	2.75 m 1.25-2.75 m	Rock beneath 1-1.2 m soft sediment, Holocene rubble or top of Q5. Soilstone crust 2.75 m
G-3631 300 m from shore	M1.5A	25-28.465N 080-20.243W	6 m 4.5-6.0 m	30 cm soft sediment. Possible unconformity 1 m & 4 m.
G-3632 300 m from shore	M1.5B	25-28.465N 080-20.243W	3.35 m 1.85-3.35 m	30 cm soft sediment.
G-3633 300 m from shore	M1.5C	25-28.465N 080-20.243W	1.2 m 0.45-1.2	30 cm soft sediment.
G-3634 500 m from shore	M2A	25-28.477N 080-20.110W	6 m 4.5-6.0 m	
G-3635 500 m from shore	M2B	25-28.477N 080-20.110W	3.4 m 1.9-3.4 m	
G-3636 800 m from shore	M3A	25-28.490N 080-19.990W	6 m 4.5-1.2 m	30 cm Soft sediment.
G-3637 800 m from shore	M3B	25-28.490N 080-19.990W	3.4 m 1.9-3.4 m	30 cm Soft sediment.
G-3638 150' from shore	M4A	25-28.384N 080-20.411W	20.0' 15.0-20.0	
G-3639 150' from shore	M4B	25-28.384N 080-20.411W	11.0' 6.0-11.0	
G-3640 150' from shore	A1A	25-29.110N 080-20.365W	20.0' 15.0-20.0	
G-3641 150' from shore	A1B	25-29.110N 080-20.365W	11.0' 6.0-11.0	
G-3642 600' from shore	A2A	25-29.181N 080-10.193W	22.0 17.0-22.0	Unconformity at 15.0'
G-3643 600' from shore	A2B	25-29.181N 080-10.193W	13.0' 8.0-13.0	Caliche crust Observed at 5.0

Table 2. Well flow Measurements

Well name	Distance (m)	Date	Vol/min(l)
M1A	50	7/8/97	0.03
M1A	50	8/13/97	0.1
M1.5B	300	7/8/97	0.11
M1A	50	8/13/97	0.12
M1.5A	300	7/8/97	0.14
M1.5A	300	7/8/97	0.3
M1B	50	7/8/97	0.5
M1.5B	300	7/8/97	0.5
M4B	50	7/8/97	1
M4A	50	7/8/97	1
M1B	50	8/13/97	1
M4A	50	8/13/97	1.25
M4B	50	7/8/97	1.5
M4A	50	7/8/97	1.5
M1B	50	8/13/97	1.5
M4B	50	7/8/97	2
M4A	50	7/8/97	2
A1B	50	7/8/97	2
M1B	50	7/8/97	2
M1A	50	7/8/97	2
M4A	50	8/13/97	2
A1B	50	7/8/97	2.4
A1B	50	7/8/97	3
A1A	50	7/8/97	4
A1A	50	7/8/97	6
A1A	50	7/8/97	6

Table 3. Groundwater Nutrients and Salinity in Biscayne Bay

Location	n	NH_4^+	TN	TOC (1)	TP	ON	DIN	Salinity (ppt)
Seepage Meter 25 m	9	1.489 (1.791)	2.715 (2.871)	35.40 (15.82)	0.013 (0.009)	2.931 (3.32)	1.498 (1.79)	
Seepage Meter 50 m	6	1.133 (1.629)	1.909 (1.513)	40.38 (18.25)	0.011 (0.007)	1.632 (1.35)	1.138 (1.63)	
Seepage Meter 185 m	5	0.236 (0.110)	1.348 (0.601)	20.55 (9.34)	0.006 (0.001)	1.091 (0.53)	0.257 (0.10)	
Seepage Meter 300 m	5	0.365 (0.446)	1.543 (1.878)	15.49 (11.28)	0.004 (0.001)	1.121 (1.40)	0.421 (0.50)	
Shallow Groundwater 50 m	18	0.665 (0.258)	1.035 (0.301)	10.72 (1.65)	0.031 (0.008)	0.408 (0.17)	0.673 (0.26)	16.8
Shallow Groundwater 300 m	14	0.468 (0.294)	0.658 (0.144)	4.96 (0.94)	0.023 (0.009)	0.256 (0.14)	0.484 (0.29)	33.0
Shallow Groundwater 500 m	7	0.533 (0.141)	0.673 (0.131)	4.58 (1.27)	0.021 (0.003)	0.239 (0.17)	0.543 (0.14)	33.0
Shallow Groundwater 800 m	7	0.499 (0.094)	0.606 (0.114)	4.33 (1.24)	0.015 (0.004)	0.202 (0.10)	0.506 (0.10)	32.0
Deep Groundwater 50 m	20	0.481 (0.247)	0.795 (0.327)	8.21 (2.89)	0.026 (0.013)	0.324 (0.19)	0.491 (0.24)	25.5
Deep Groundwater 300 m	14	0.332 (0.145)	0.587 (0.115)	4.51 (1.20)	0.018 (0.010)	0.238 (0.13)	0.349 (0.13)	33.0
Deep Groundwater 500 m	7	0.403 (0.157)	0.597 (0.123)	4.26 (0.93)	0.014 (0.005)	0.237 (0.08)	0.415 (0.16)	33.8
Deep Groundwater 800 m	7	0.417 (0.122)	0.625 (0.232)	4.02 (1.07)	0.012 (0.006)	0.230 (0.20)	0.428 (0.12)	34.9
Surface Water 50 m	20	0.034 (0.029)	0.648 (0.359)	6.91 (1.37)	0.008 (0.004)	0.433 (0.10)	0.216 (0.35)	15.3
Surface Water 300 m	14	0.029 (0.018)	0.604 (0.243)	6.44 (1.24)	0.006 (0.003)	0.389 (0.10)	0.201 (0.27)	17.6
Surface Water 500 m	7	0.037 (0.026)	0.567 (0.238)	6.66 (1.48)	0.006 (0.002)	0.314 (0.12)	0.253 (0.28)	24.7
Surface Water 800 m	7	0.035 (0.027)	0.597 (0.261)	5.88 (0.64)	0.006 (0.002)	0.329 (0.13)	0.269 (0.32)	25.4

(1) TOC results for groundwater and seepage meters were not reported by the lab for the last sample, therefore, samples size is less for TOC. Listed in order is the adjusted sample size; "SM 25" 5, "SM 50" 3, "SM 185" 2, "SM 300" 3, "ShGW 50" 16, "ShGW 30

Table 4. Nutrient Loading Table

Nutrient Load	load g m^{-1} d^{-1}	Site kg $month^{-1}$	Site kg yr^{-1}
NH_4^+ SMQ x SMC	10.23	644.49	7841
NH_4^+ SMQ x SGC	11.53	726.39	8838
NH_4^+ DLQ x SGC	5.59	352.17	4285
NH_4^+ DLQ x SMC	5.90	371.7	4522
NH_4^+ "Proj" DLQ x SGC	8.72	549.36	6684
NH_4^+ "Proj" DLQ x SMC	9.21	580.23	7059
TN SMQ x SMC	31.99	2015.37	24520
TN SMQ x SGC	17.2	1083.6	13184
TN DLQ x SGC	8.28	521.64	6347
TN DLQ x SMC	16.72	1053.36	12816
TN "Proj" DLQ x SGC	12.91	813.33	9896
TN "Proj" DLQ x SMC	26.07	1642.41	19983
TP SMQ x SMC	0.131	8.253	100
TP SMQ x SGC	0.559	35.217	428
TP DLQ x SGC	0.269	16.947	206
TP DLQ x SMC	0.066	4.158	51
TP "Proj" DLQ x SGC	0.42	26.46	322
TP "Proj" DLQ x SMC	0.1	6.3	77
TOC SMQ x SMC	492	30996	377118
TOC SMQ x SGC	158	9954	121107
TOC DLQ x SGC	76.8	4838.4	58867
TOC DLQ x SMC	238	14994	182427
TOC "Proj" DLQ x SGC	119	7497	91214
TOC "Proj" DLQ x SMC	371	23373	284372
DIN SMQ x SMC	10.75	677.25	8240
DIN SMQ x SGC	11.69	736.47	8960
DIN DLQ x SGC	5.69	358.47	4361
DIN DLQ x SMC	6.19	389.97	4745
DIN "Proj" DLQ x SGC	8.87	558.81	6799
DIN "Proj" DLQ x SMC	9.66	608.58	7404
ON SMQ x SMC	26	1638	19929
ON SMQ x SGC	6.79	427.77	5205
ON DLQ x SGC	3.28	206.64	2514
ON DLQ x SMC	14.07	886.41	10785
ON "Proj" DLQ x SGC	5.12	322.56	3924
ON "Proj" DLQ x SMC	21.94	1382.22	16817
Abreviations are; SMQ = Seepage Meter Discharge, SMC= Seepage Meter Nutrient Concentration, DLQ= Darcy's Law Discharge, SGC = Shallow Groundwater Nutrient Concentration, "Proj"= Predicted increase in nutrient loading due to raising of the L-31E Canal			

Table 5. Groundwater Discharge in Lakes and Estuaries

Author	Location	Discharge measurements	Seepage Rate (mean or range) $m^3\ m^{-2}\ d^{-1}$
This Study	Biscayne Bay	Seepage meters	0 to 0.10
This Study	Biscayne Bay	Pressure Transducers	0 to 2.4×10^{-2}
Belanger, T.V. et al. 1985	E Lake Tohopekaliga, FL	Seepage meters	1.6×10^{-4} to 7.0×10^{-3}
Belanger, T.V. and Walker, R. B. 1990	Indian River Lagoon, FL	Seepage meters	6.0×10^{-3} to 1.33 mean discharge 0.12
Bokuniewicz, H. 1980	Great South Bay, N.Y.	Seepage meters	1.0×10^{-2} to 4.0×10^{-2}
Cherkauer and McBride 1988	Lake Michigan, WS	Seepage meters	3.5×10^{-5}
Connor and Belanger 1981	Lake Washington, FL	Seepage meters	-3.5×10^{-3} to 4.3×10^{-2}
Downing and Peterka 1978	Lake Metigoshe, ND	Seepage meters	5.2×10^{-3} to 1.7×10^{-2}
Fellows and Brezonik 1980	Lakes Conway and Apoka, FL	Seepage meters	0 to 8.6×10^{-2}
Krabbenhoft and Anderson 1986	Lake Trout, WS	Seepage meters	8.6×10^{-3} to 4.3×10^{-2}
Lee 1977	Lake Mendota, WS	Seepage meters	2.6×10^{-2} to 4.3×10^{-2}
Lee 1977	Lake Movil, MN	Seepage meters	6.9×10^{-2}
Lee 1977	Lake Sallie, Mn	Seepage meters	8.6 X 10-3 to 0.22
Lewis, J. B.	Barbados	Seepage meters	0.73 to 1.2
Lock and John 1978	Lake Taupo, New Zealand	Seepage meters	1.3 X 10-3 to 0.52
Pandit and El-Khazen	Indian River Lagoon, FL	Galerkin Finite element model	3×10^{-3} to 2.0×10^{-2}
Robinson, M. et al. 1983	Chesapeake Bay	Dupuit (Darcy's Law)	6.1×10^{-3} to 3.8×10^{-2}
Robinson, M et al. 1983	Chesapeake Bay	Seepage meters	1.2×10^{-2} to 7.9×10^{-2}
Shaw, R.D. and Prepas E.E. 1990	Lake Sallie and Narrow Lake, Mn	Seepage meters	-1.7×10^{-5} to -1.7×10^{-4}
Shaw, R.D. and Prepas E.E. 1990	Lake Sallie and Narrow Lake, Mn	Seepage meters	2.6×10^{-5} to 1.7×10^{-2}

Figure 1. Site map and location of wells, seepage meters and transects.

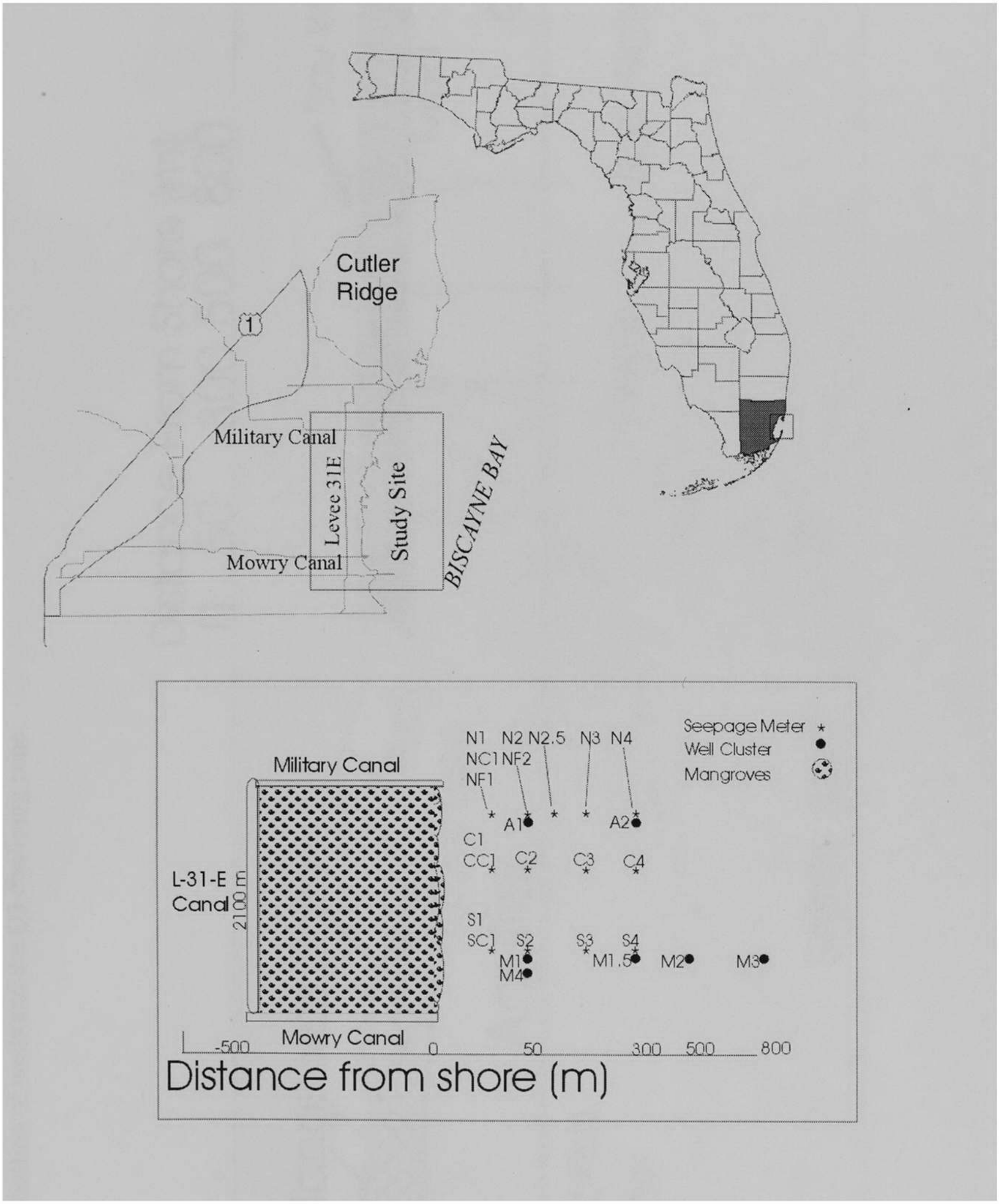


Figure 2. Location of wells and the Q3 confining zone

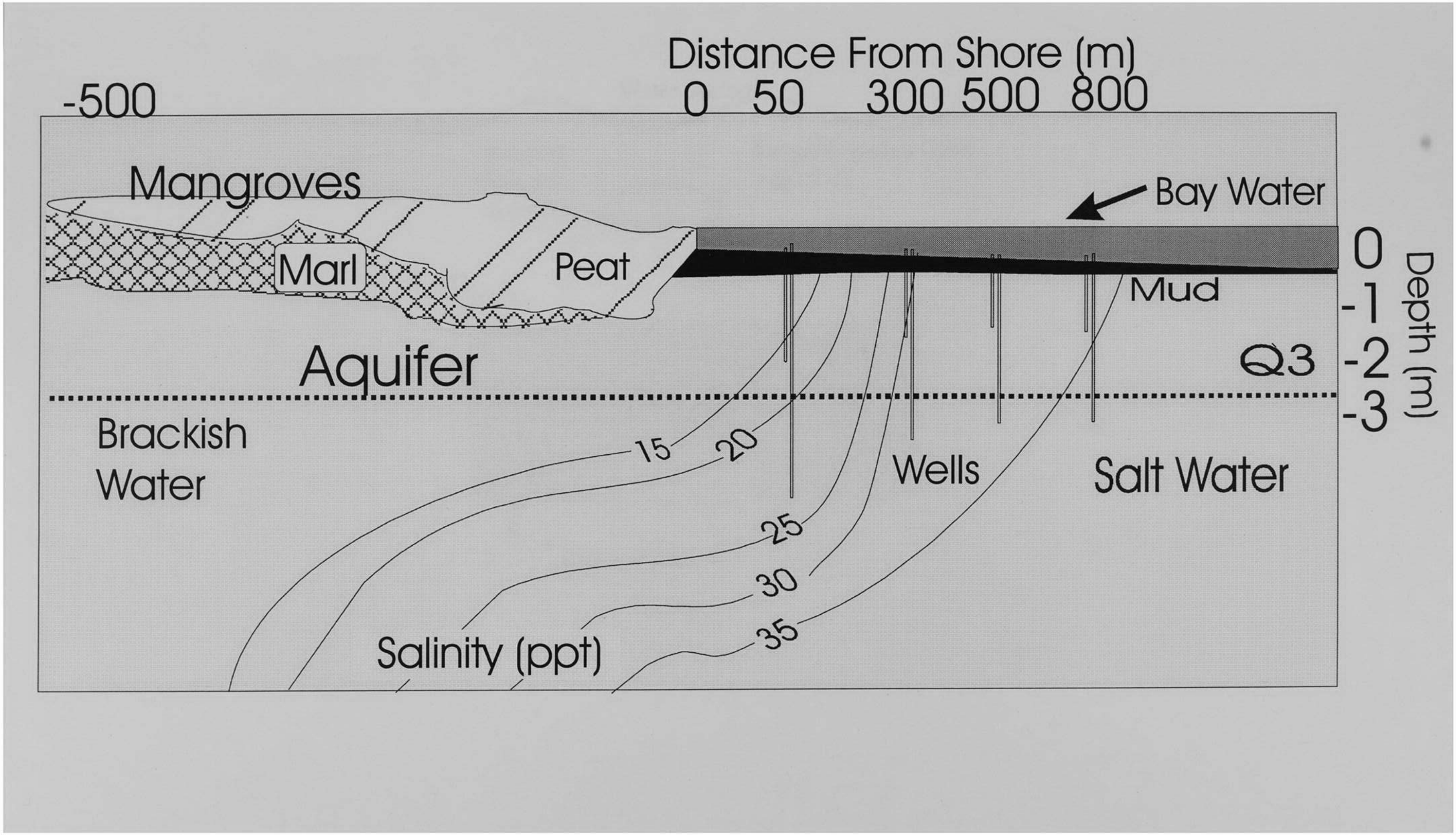


Figure 3. Schematic of a typical seepage meter and location for study.

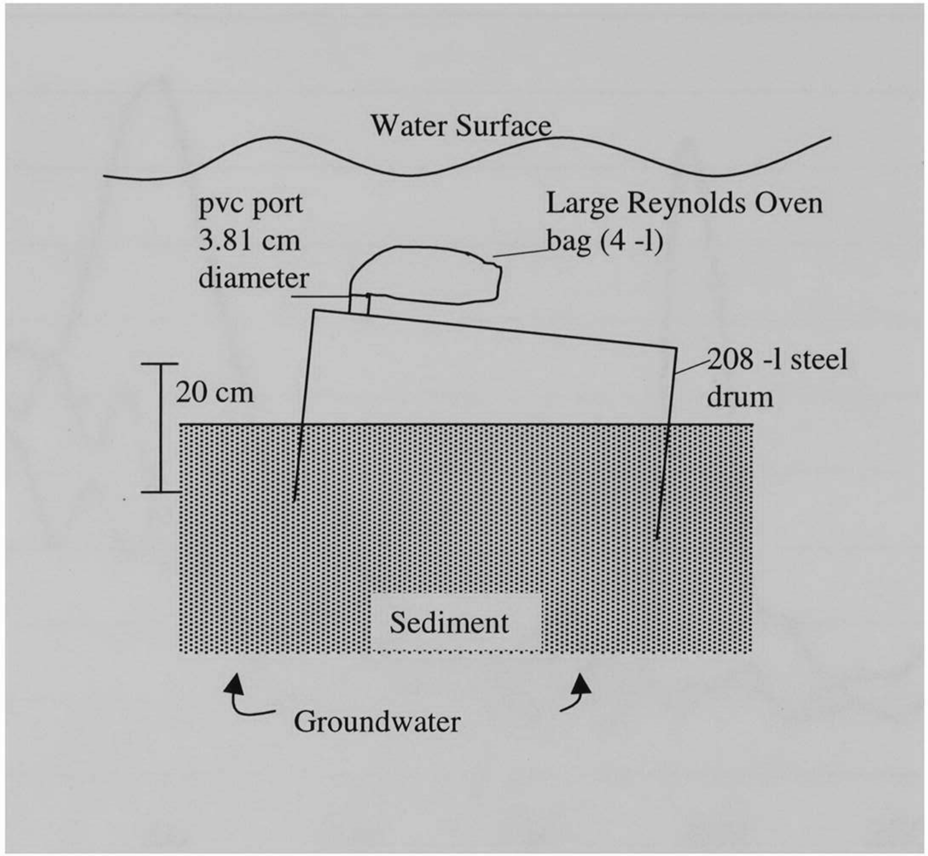


Figure 4. Sediment thickness versus distance

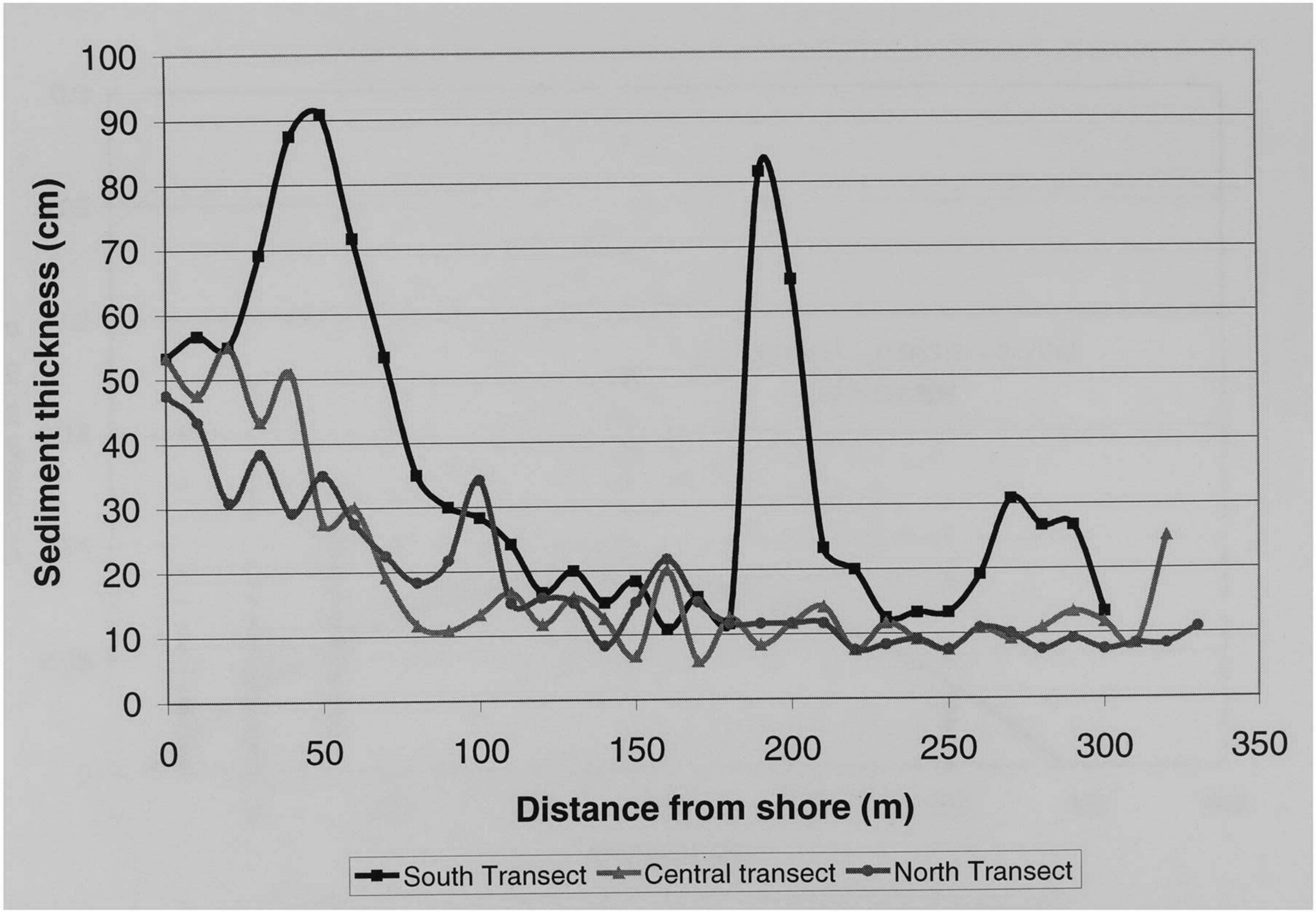


Figure 5. Discharge Polynomial Curve

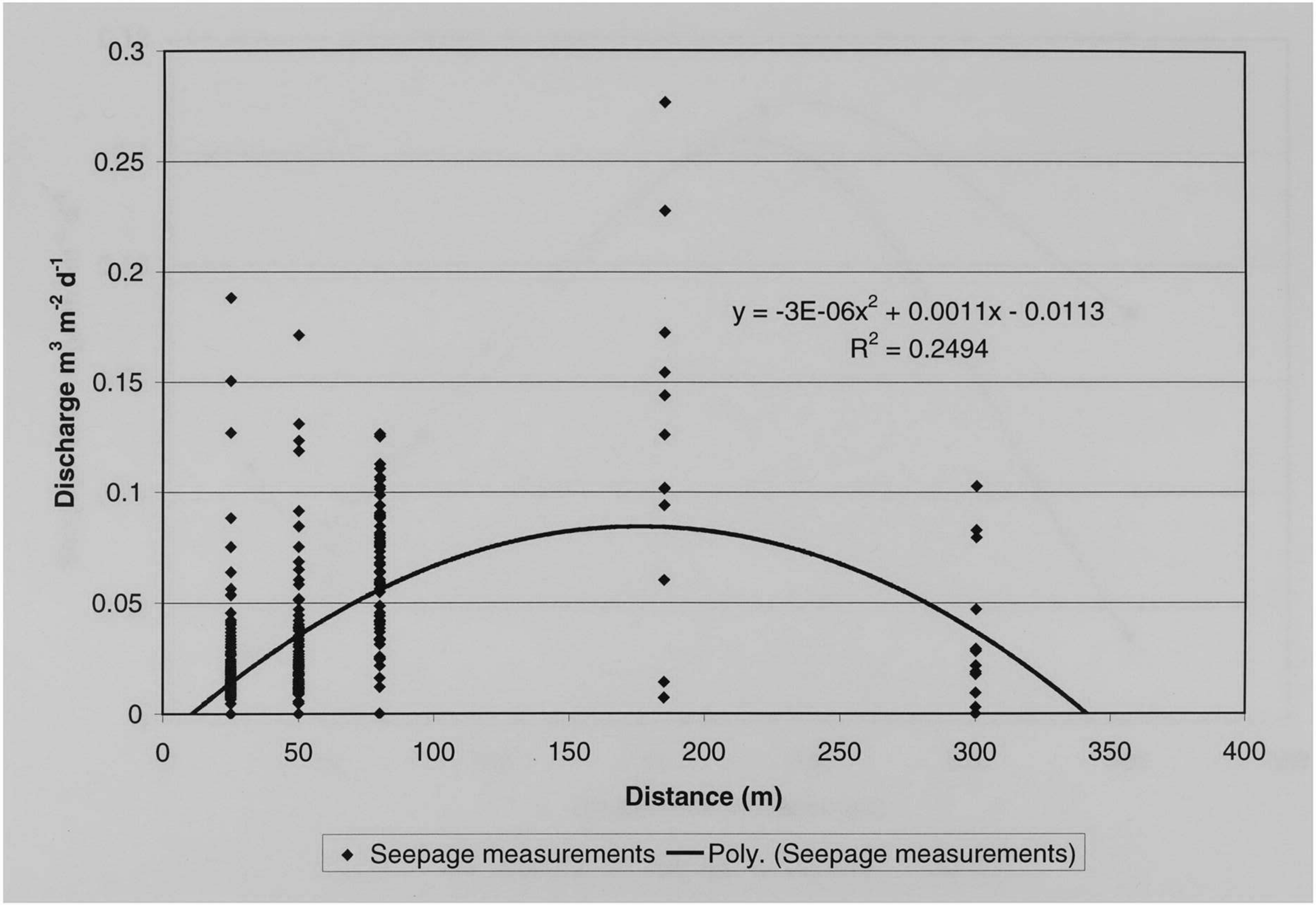


Figure 6. Seasonal variation in groundwater seepage

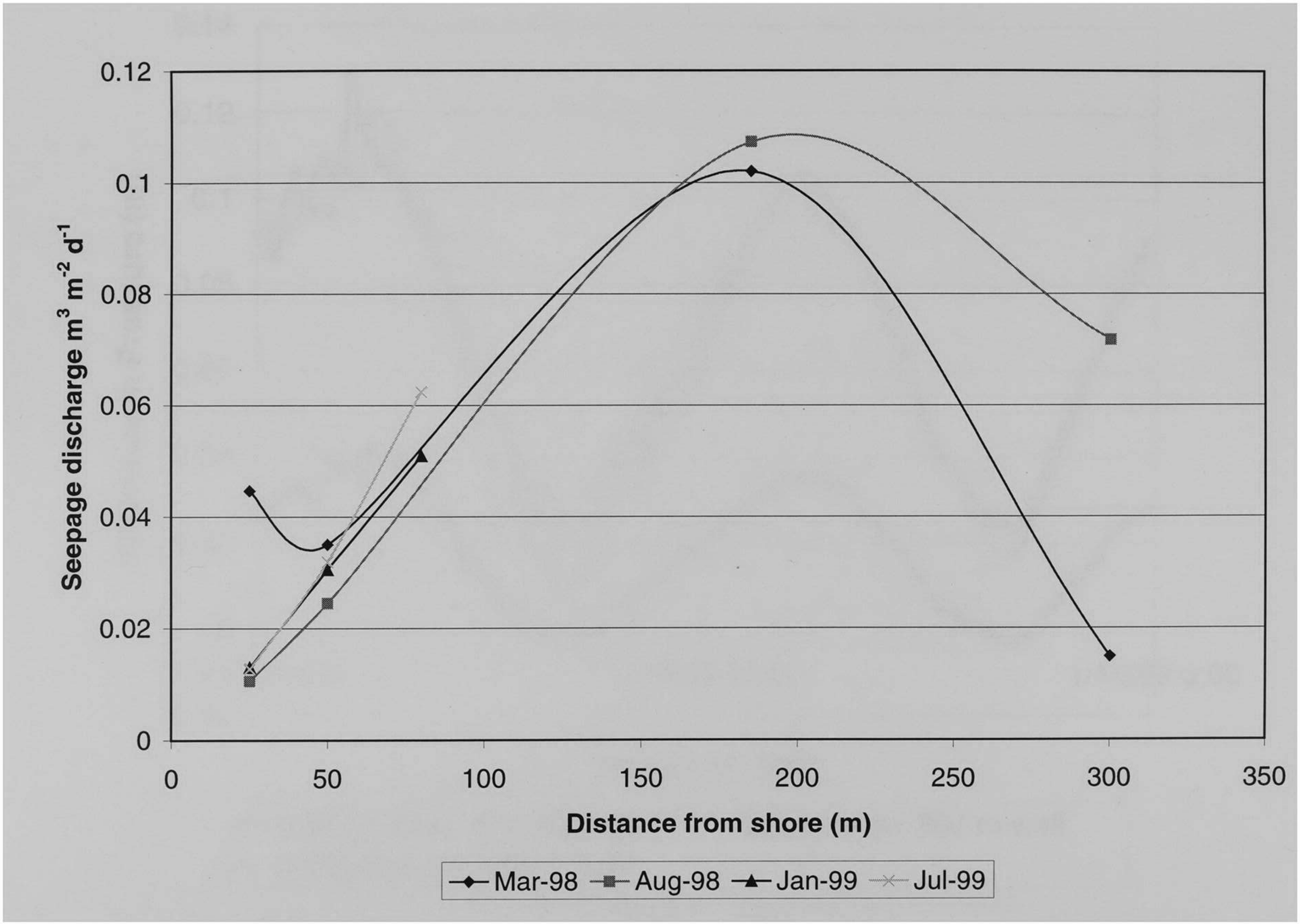


Figure 7. Difference in pressure head

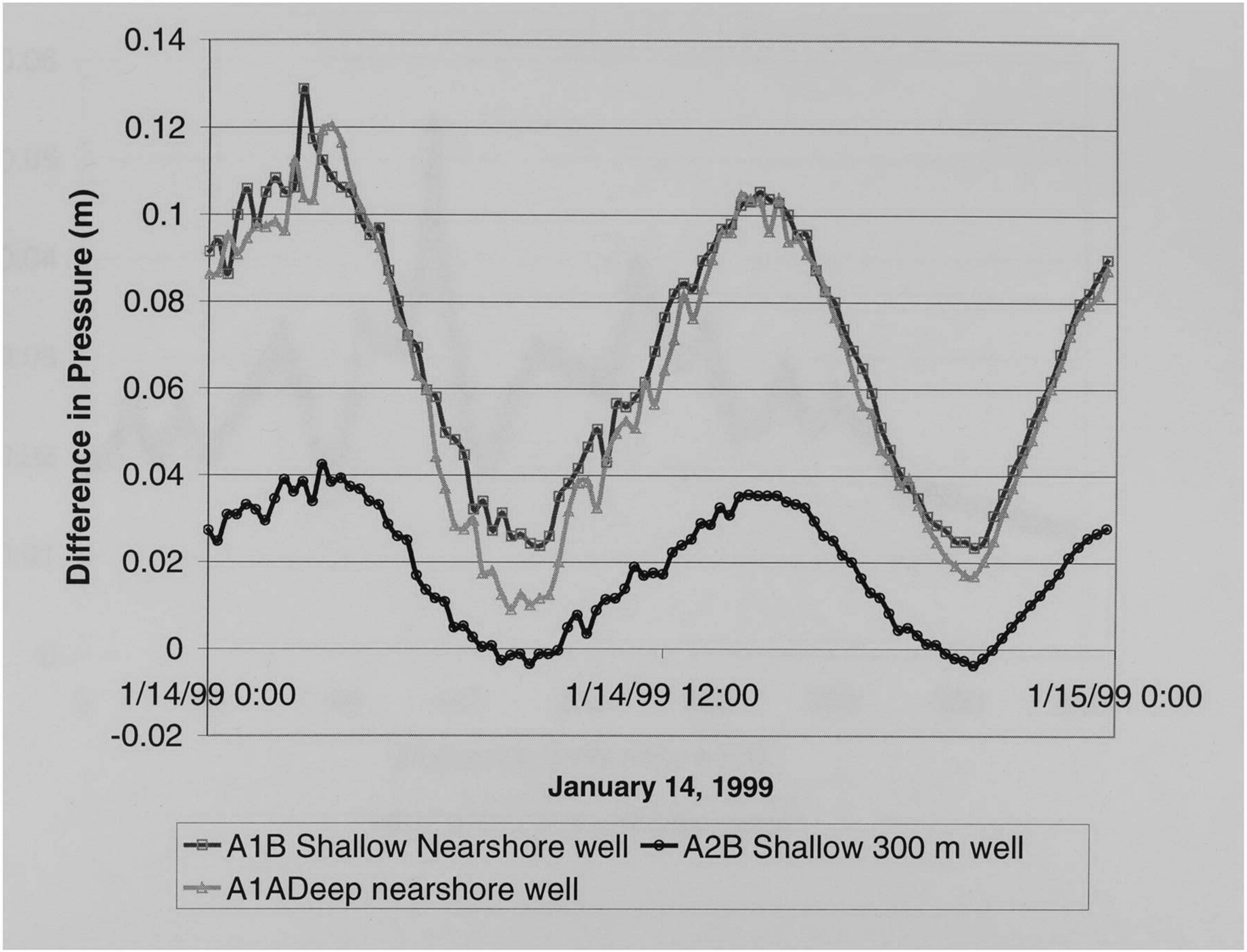


Figure 8. Darcy's Law Discharge

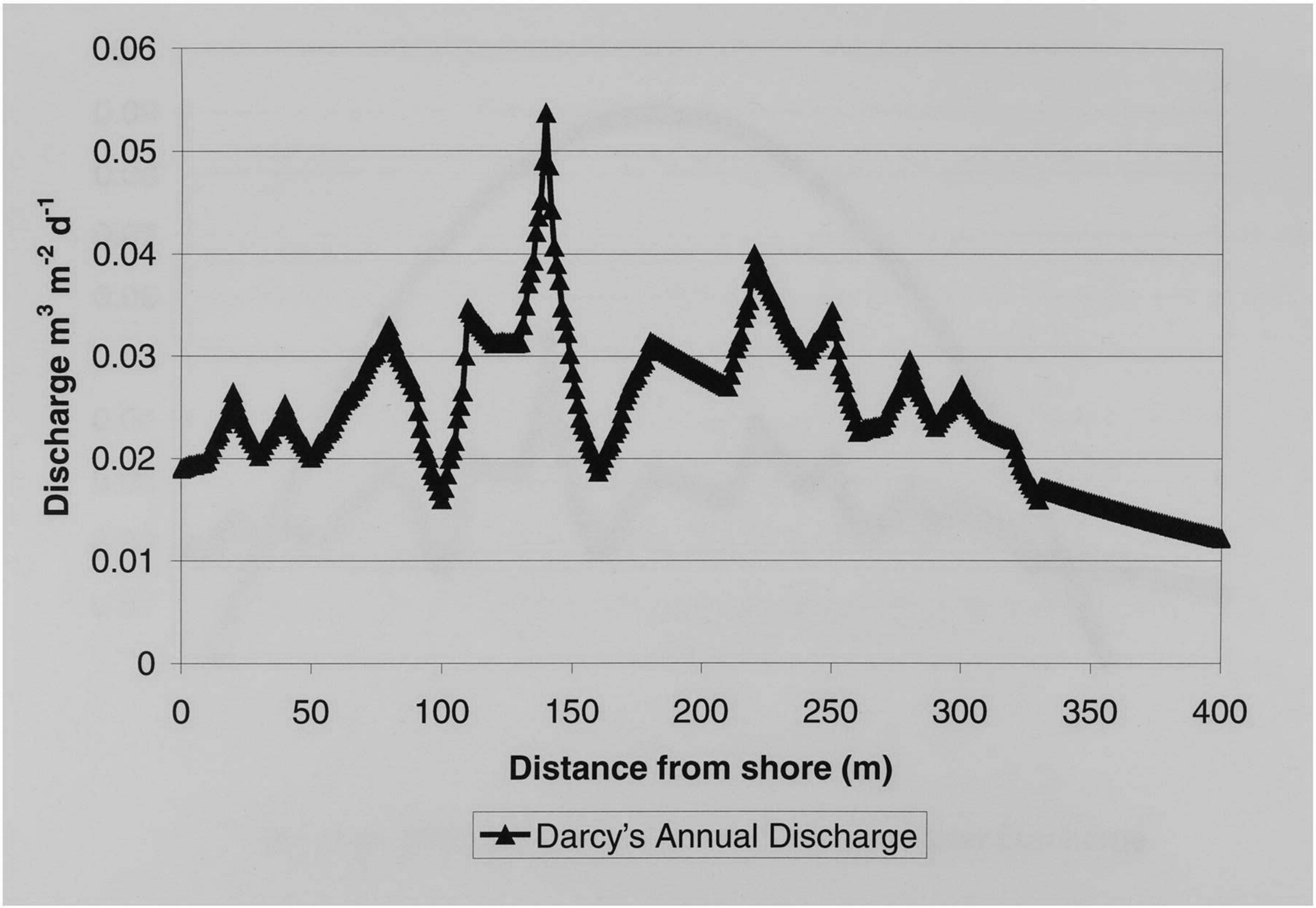


Figure 9. Comparison plot with Darcy's Law Discharge and Seepage Meter Discharge

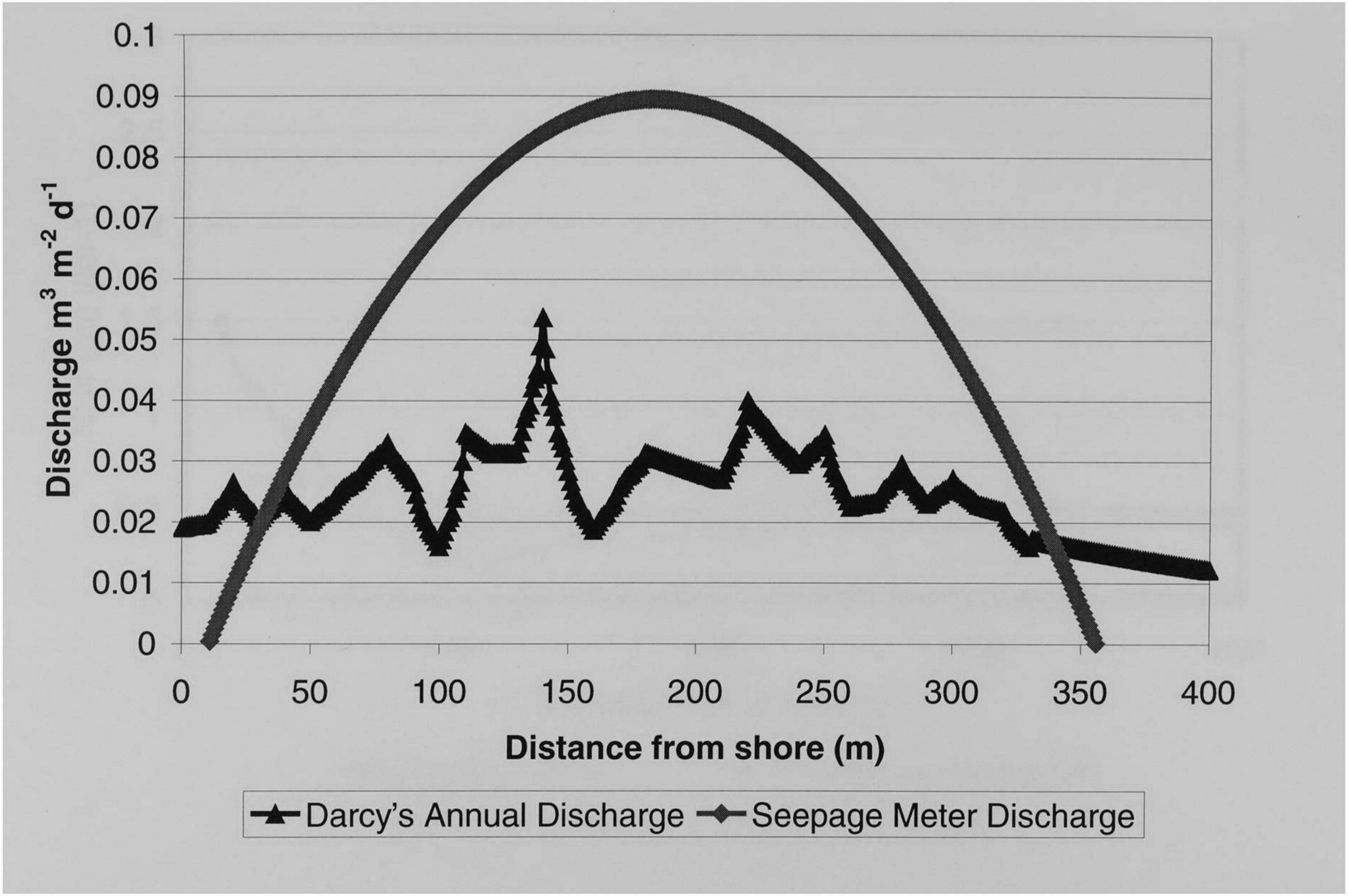


Figure 10. Groundwater and Surface water mean ammonium concentration.

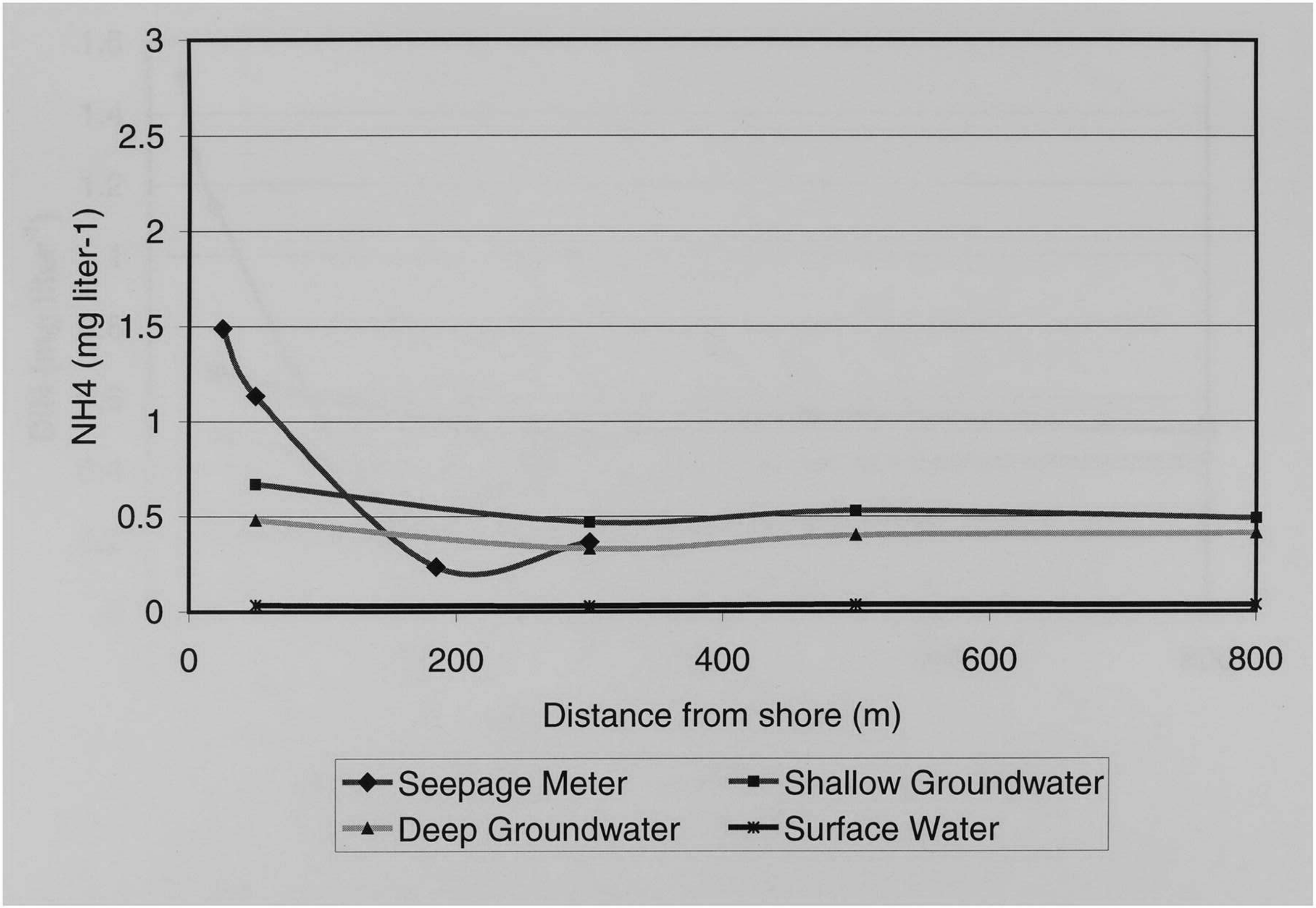


Figure 11. Groundwater and Surface water mean dissolved nitrogen concentration.

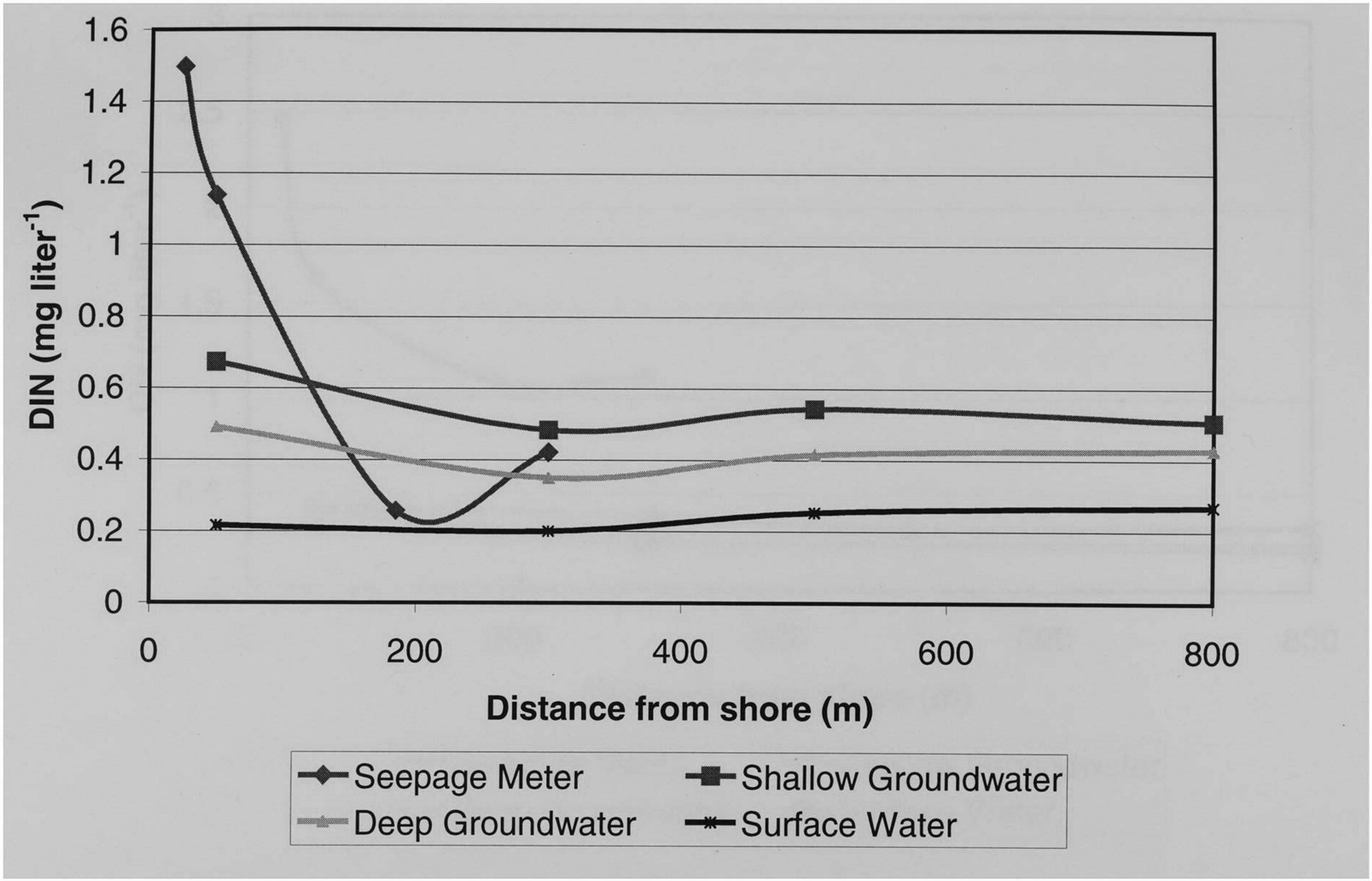


Figure 12. Groundwater and Surface water mean organic nitrogen concentration.

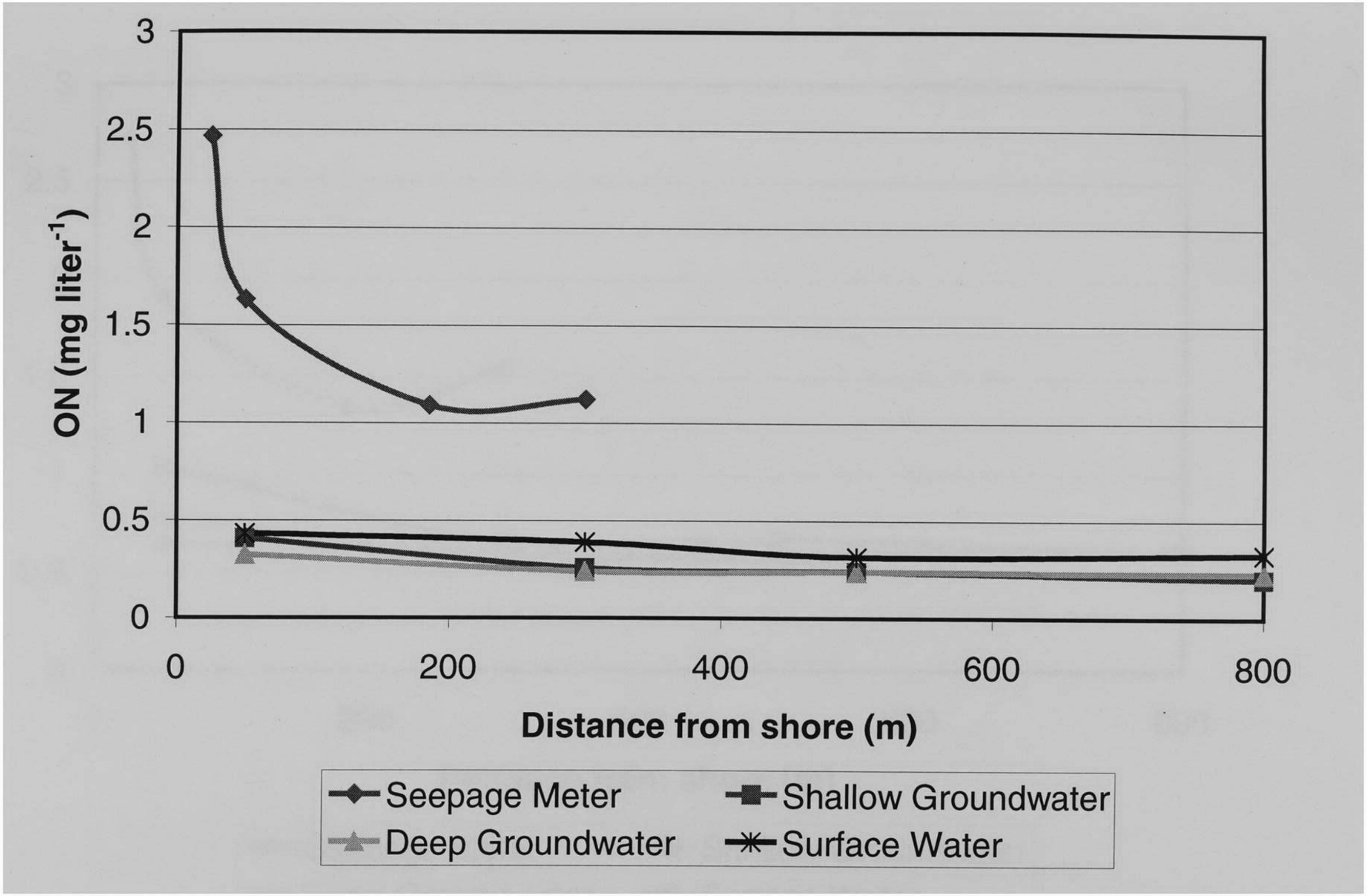


Figure 13. Groundwater and Surface water mean total nitrogen concentration.

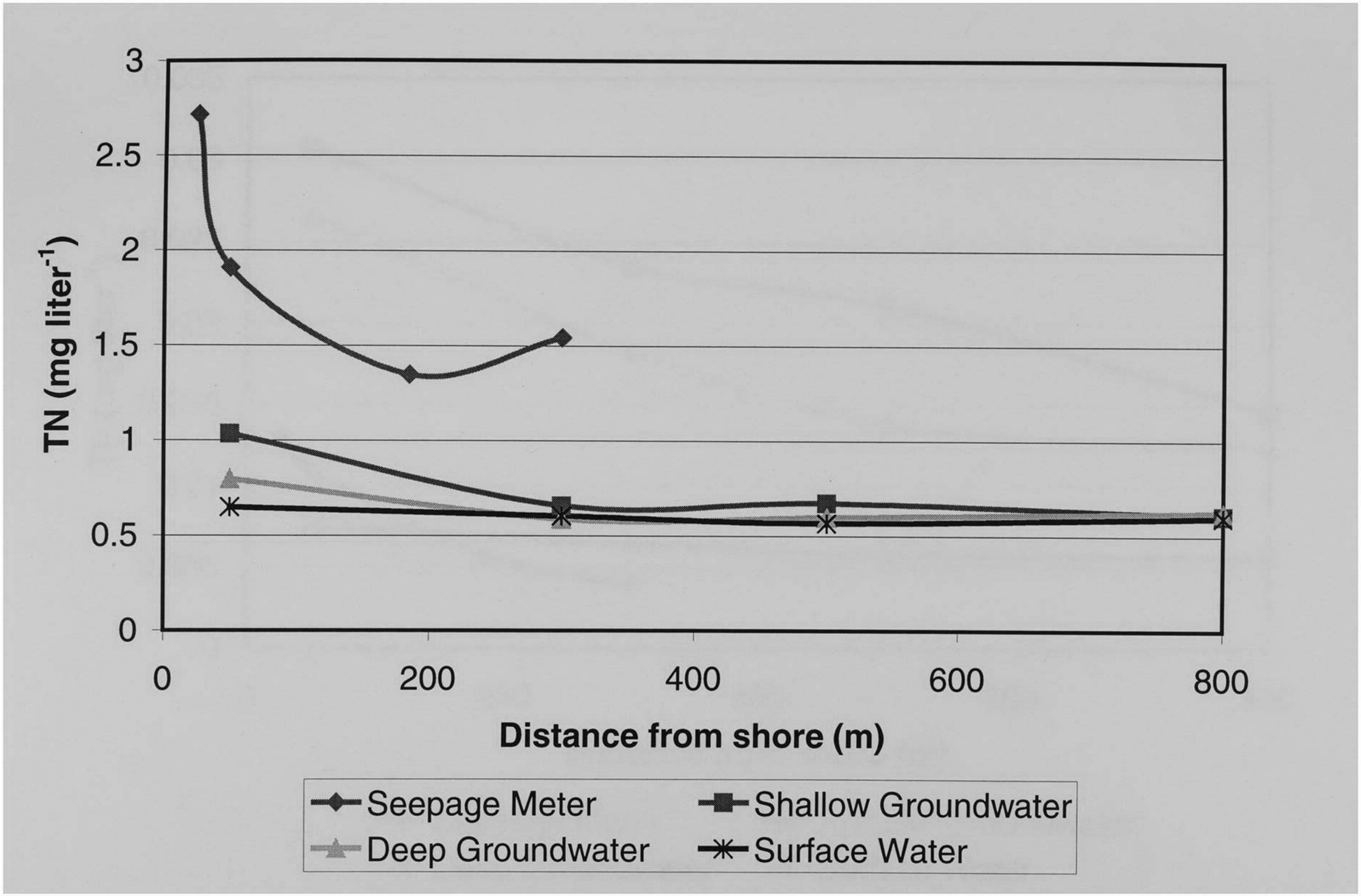


Figure 14. Groundwater and Surface water mean total phosphorus concentration.

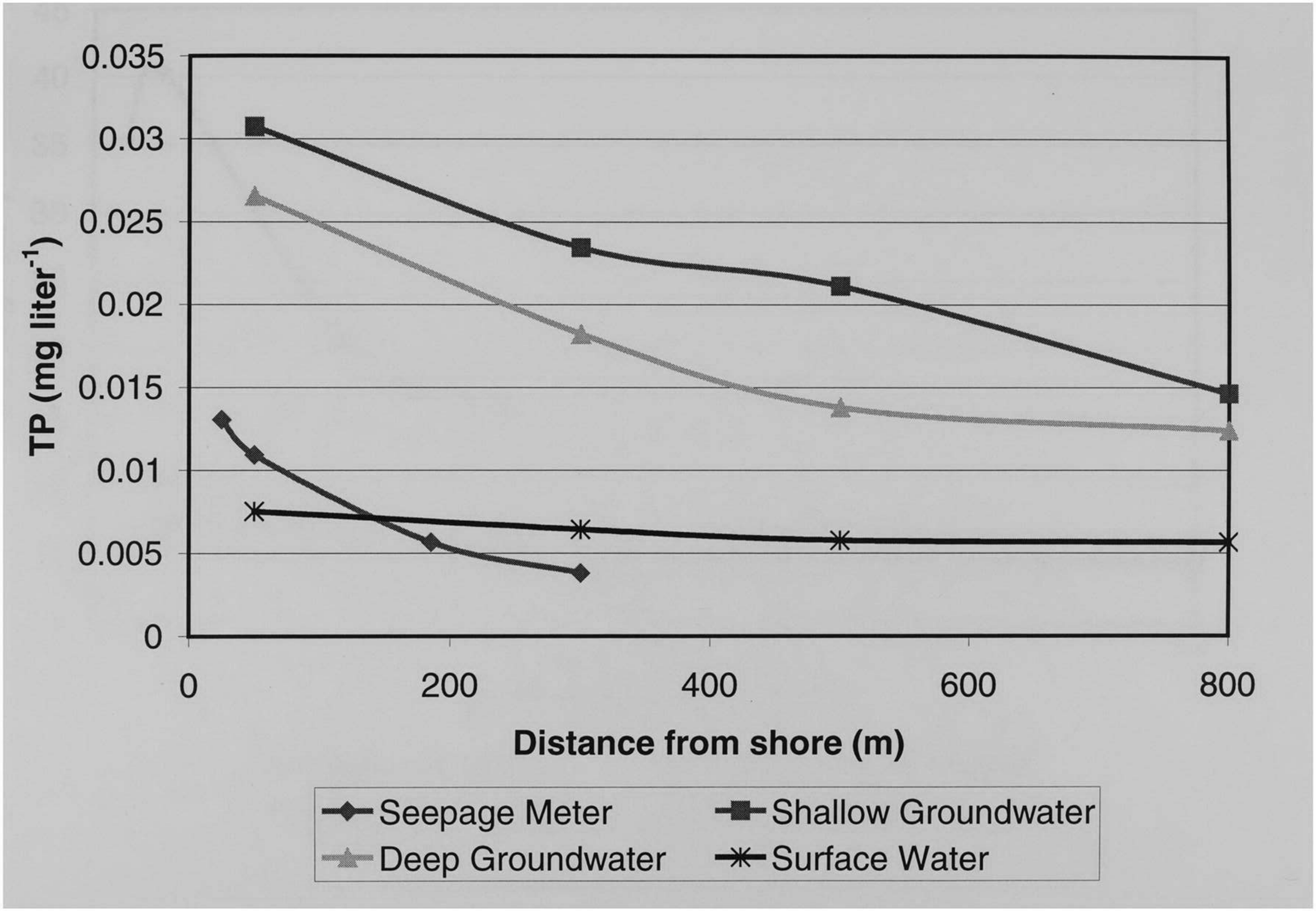


Figure 15. Groundwater and Surface water mean total organic carbon concentration.

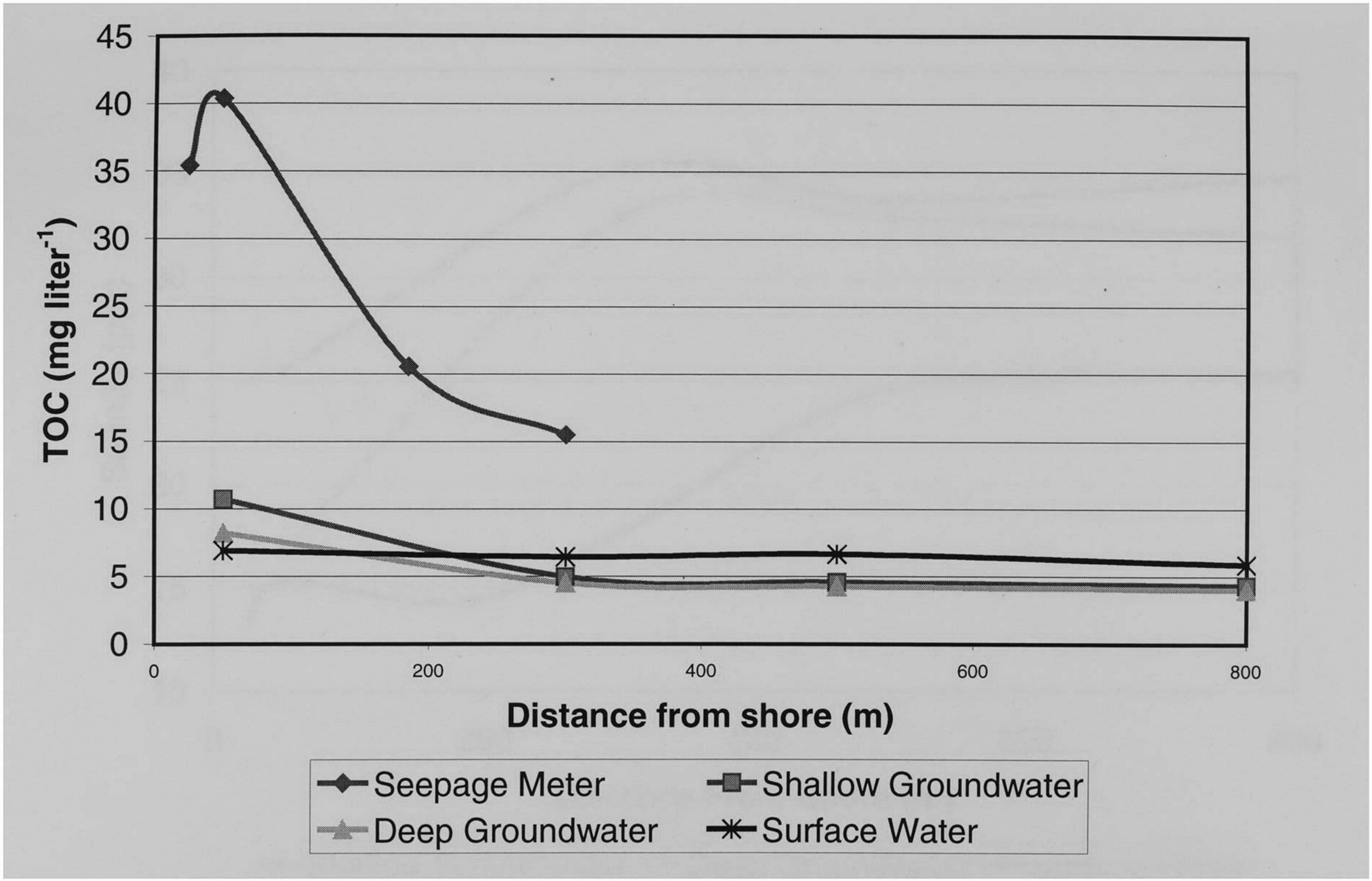


Figure 16. Groundwater and Surface water mean total salinity concentration.

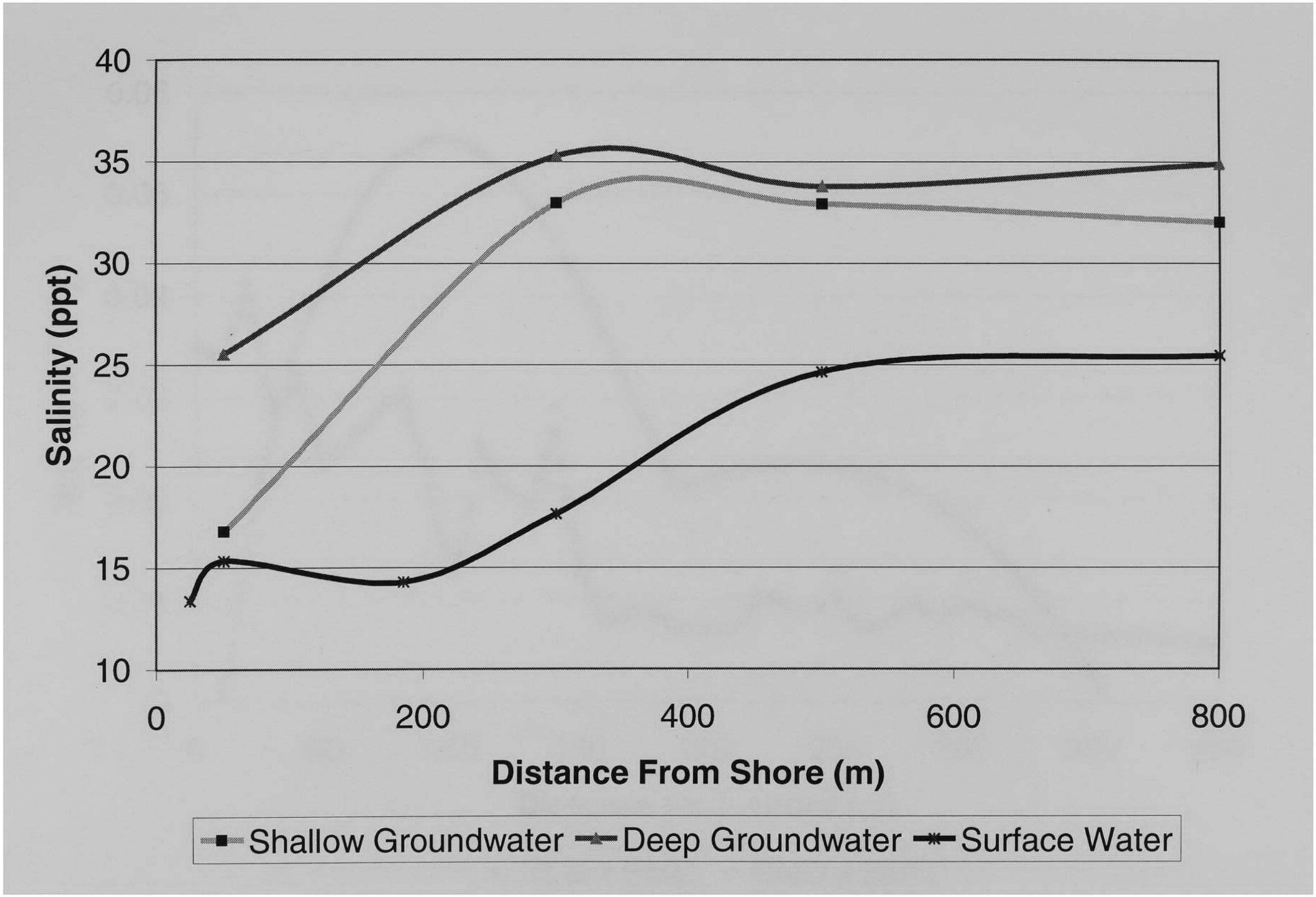


Figure 17. NH_4^+ Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

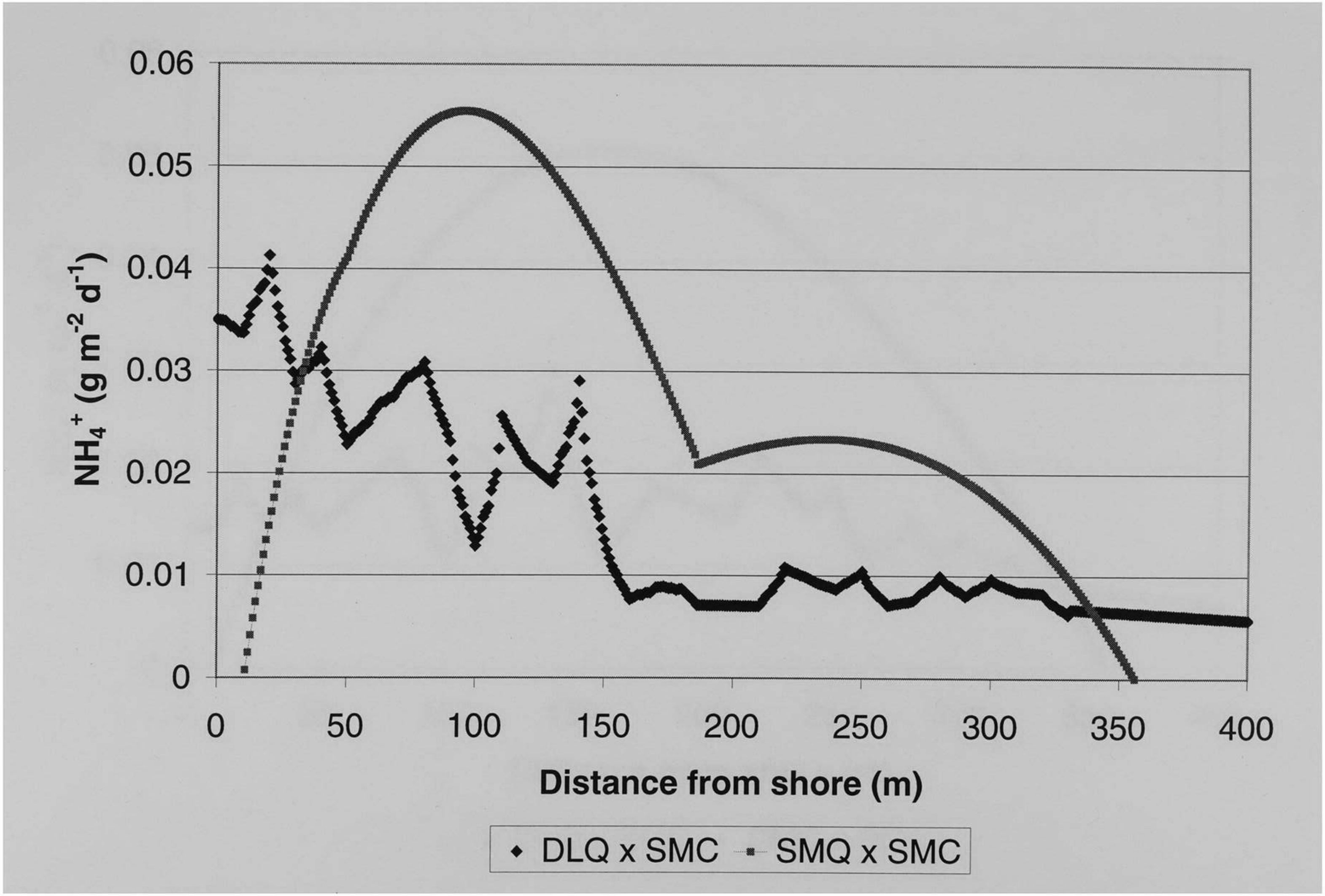


Figure 18. NH_4^+ Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

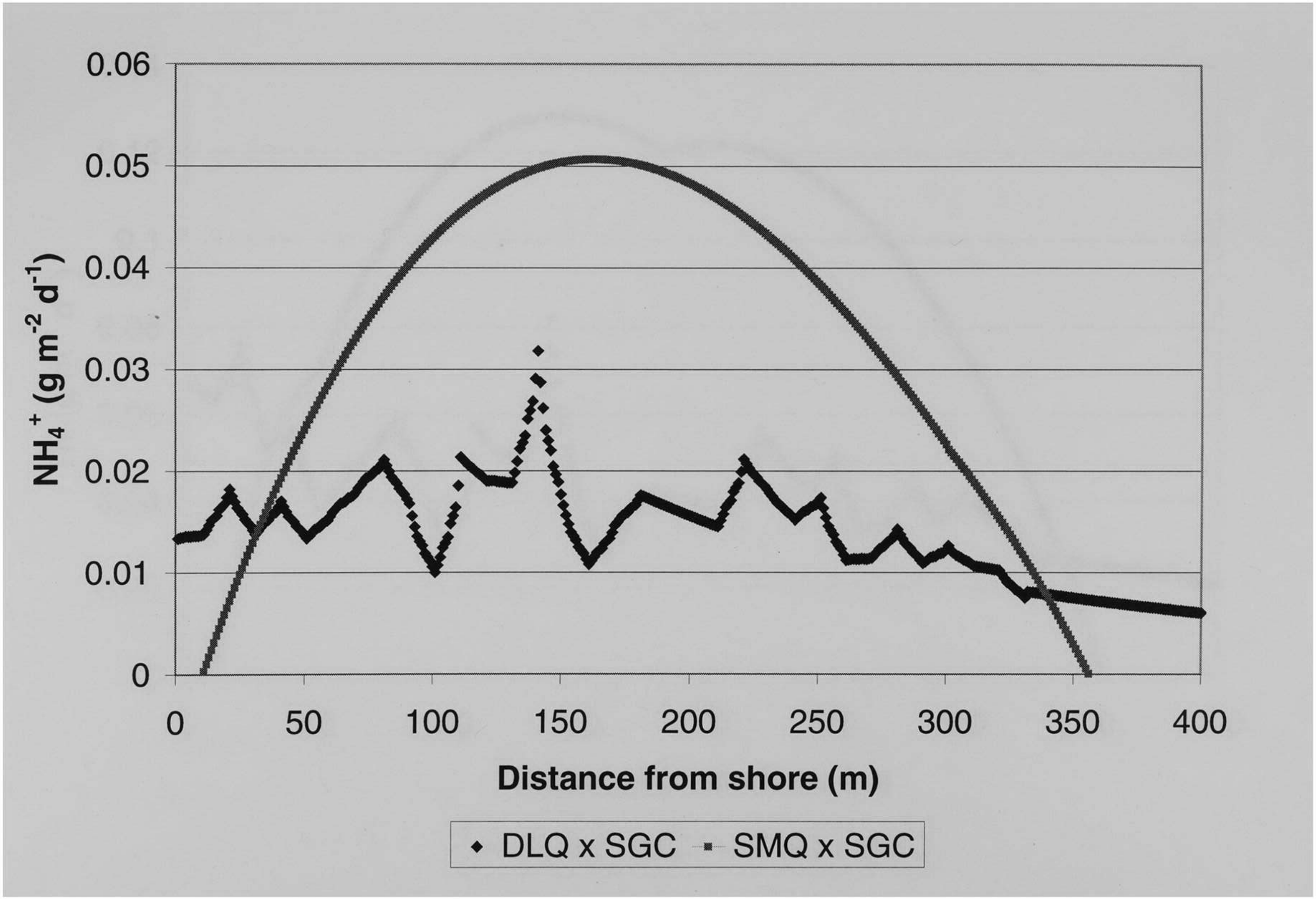


Figure 19. TN Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

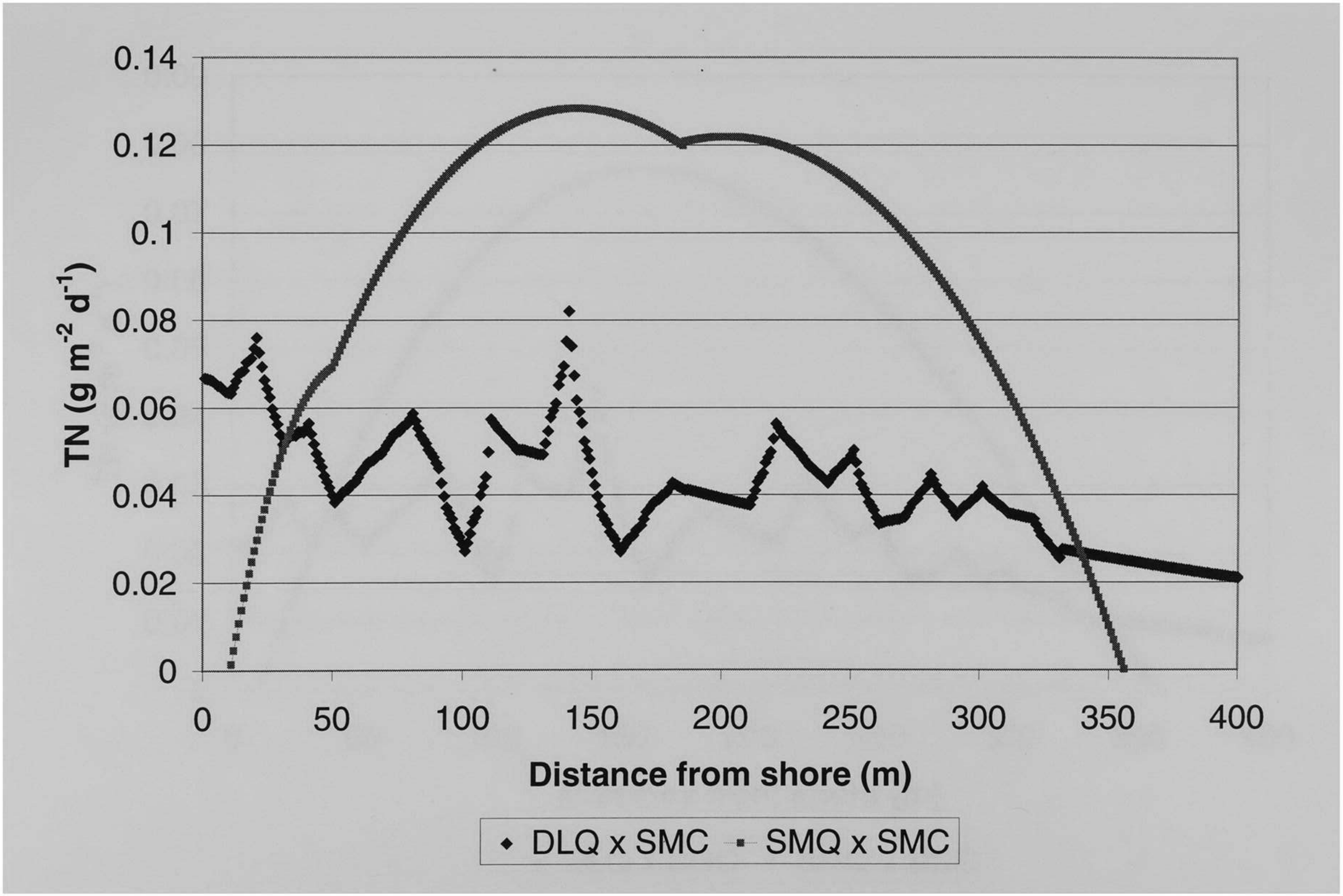


Figure 20. TN Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

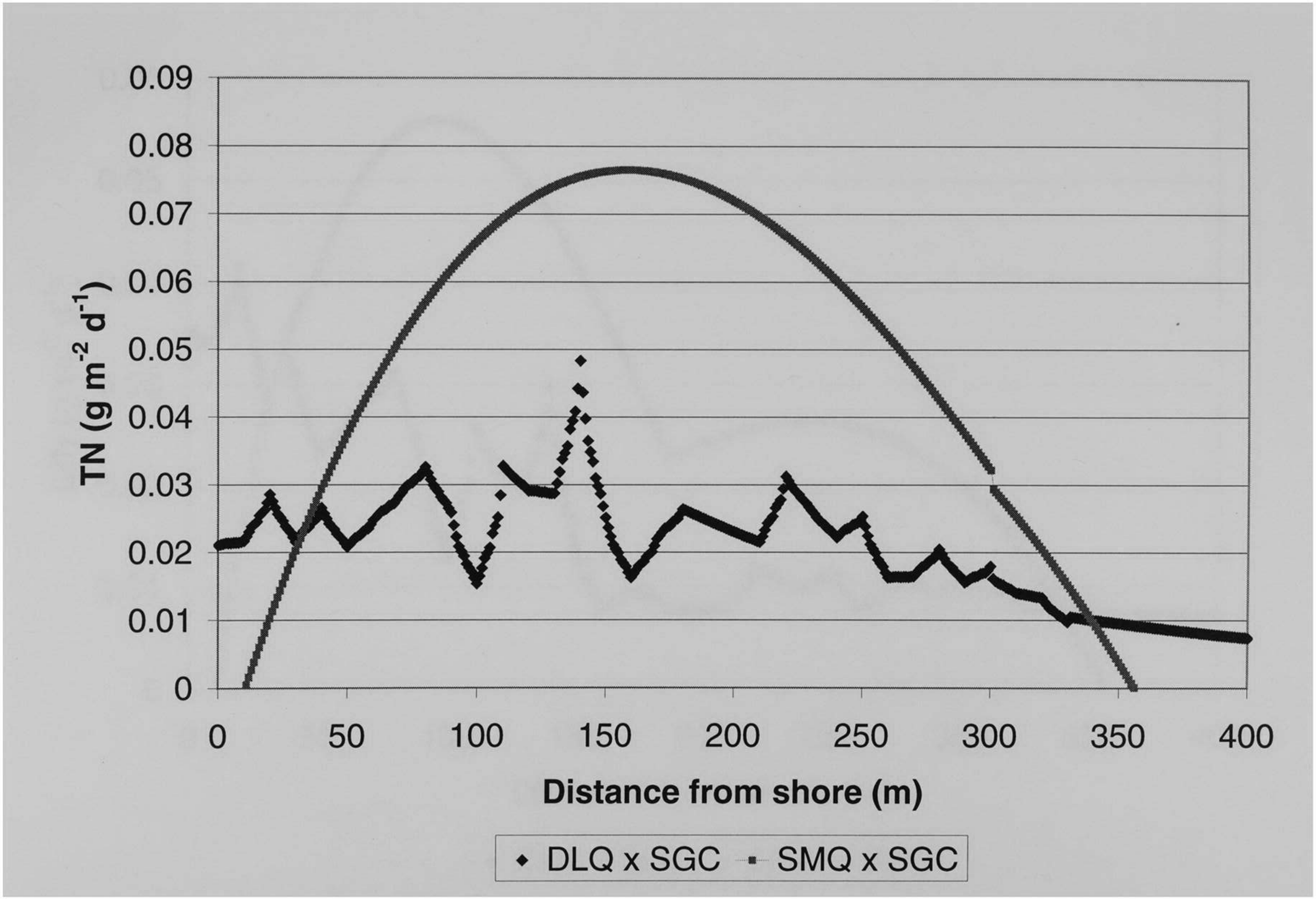


Figure 21. DIN Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

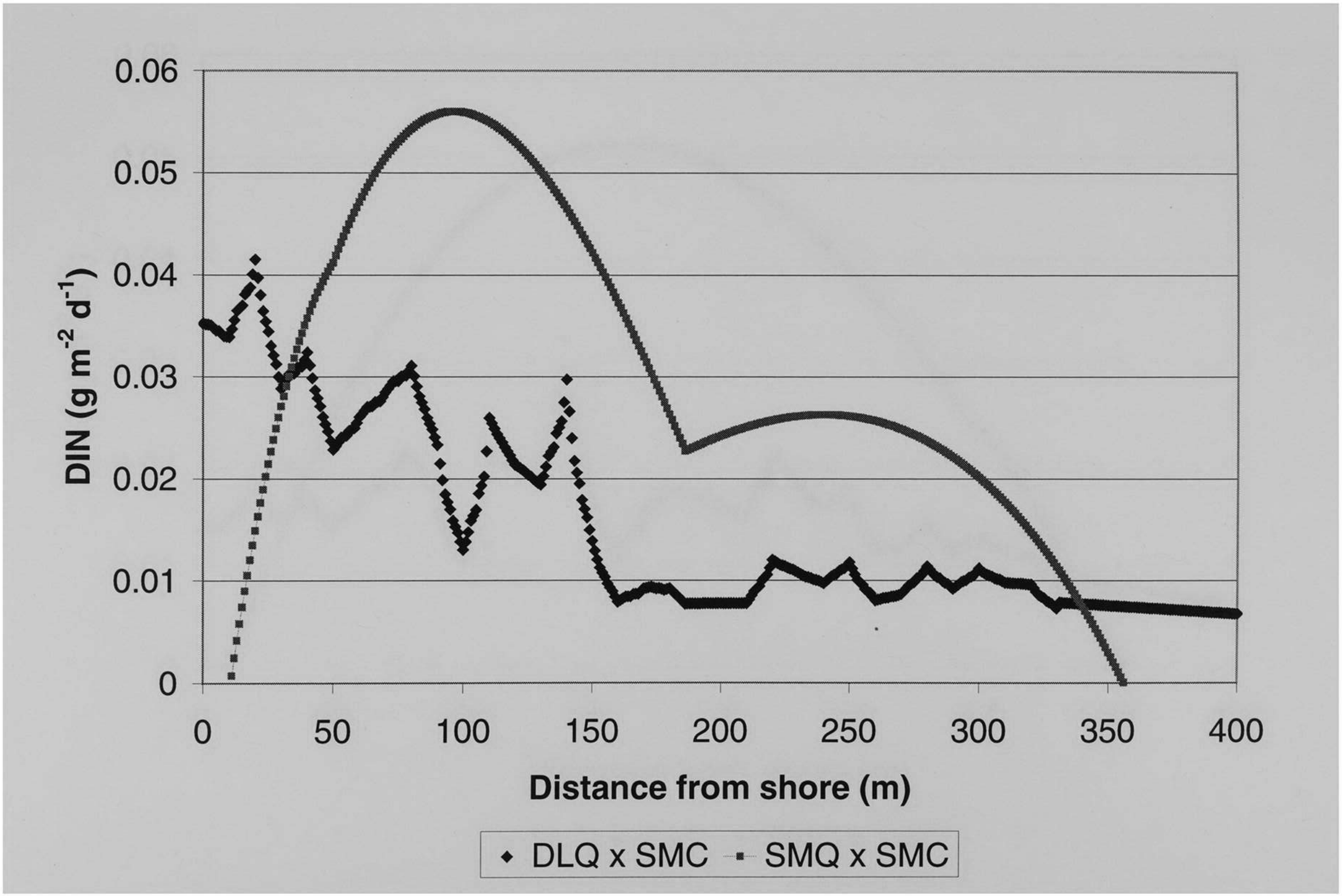


Figure 22. DIN Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

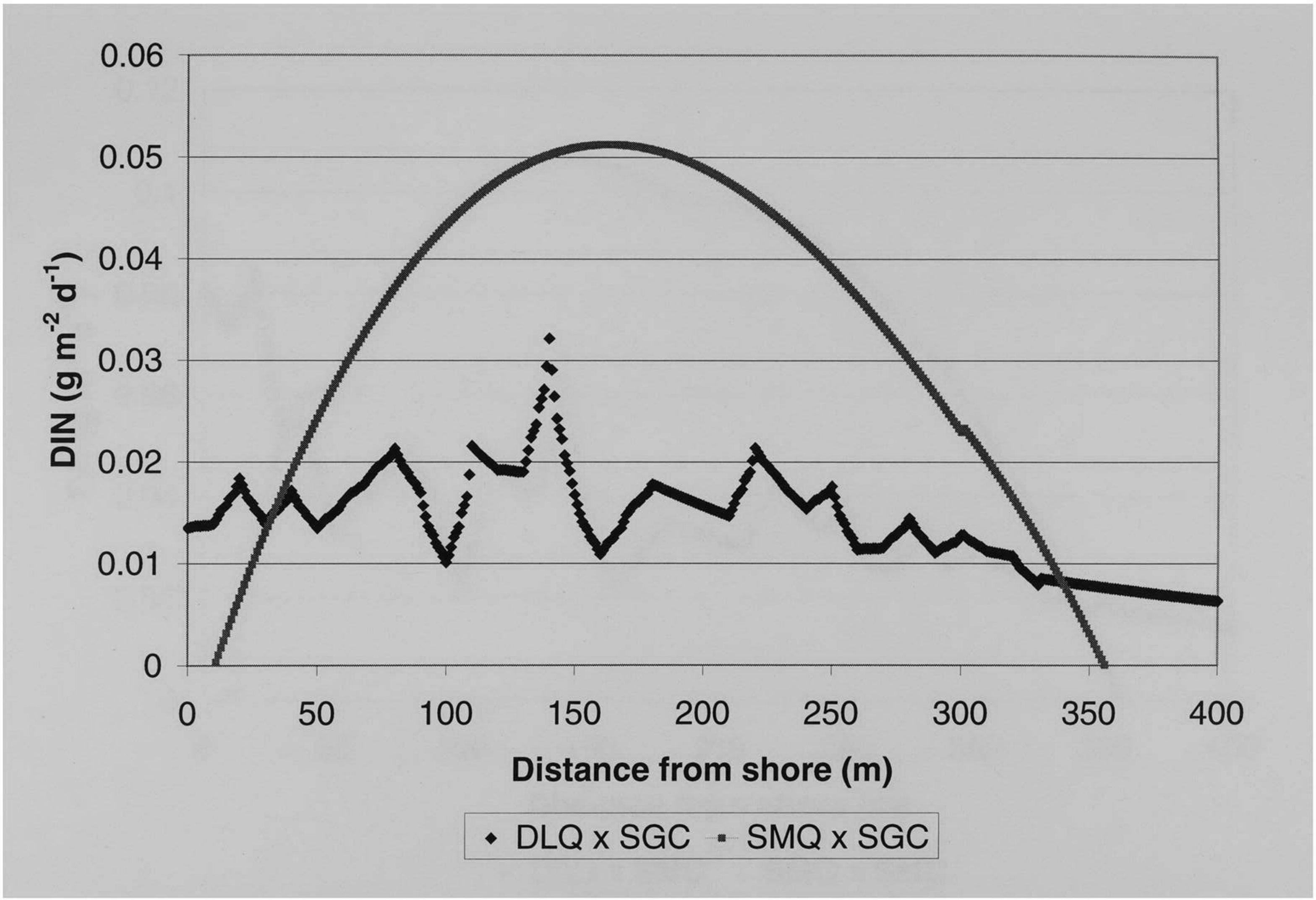


Figure 23. ON Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

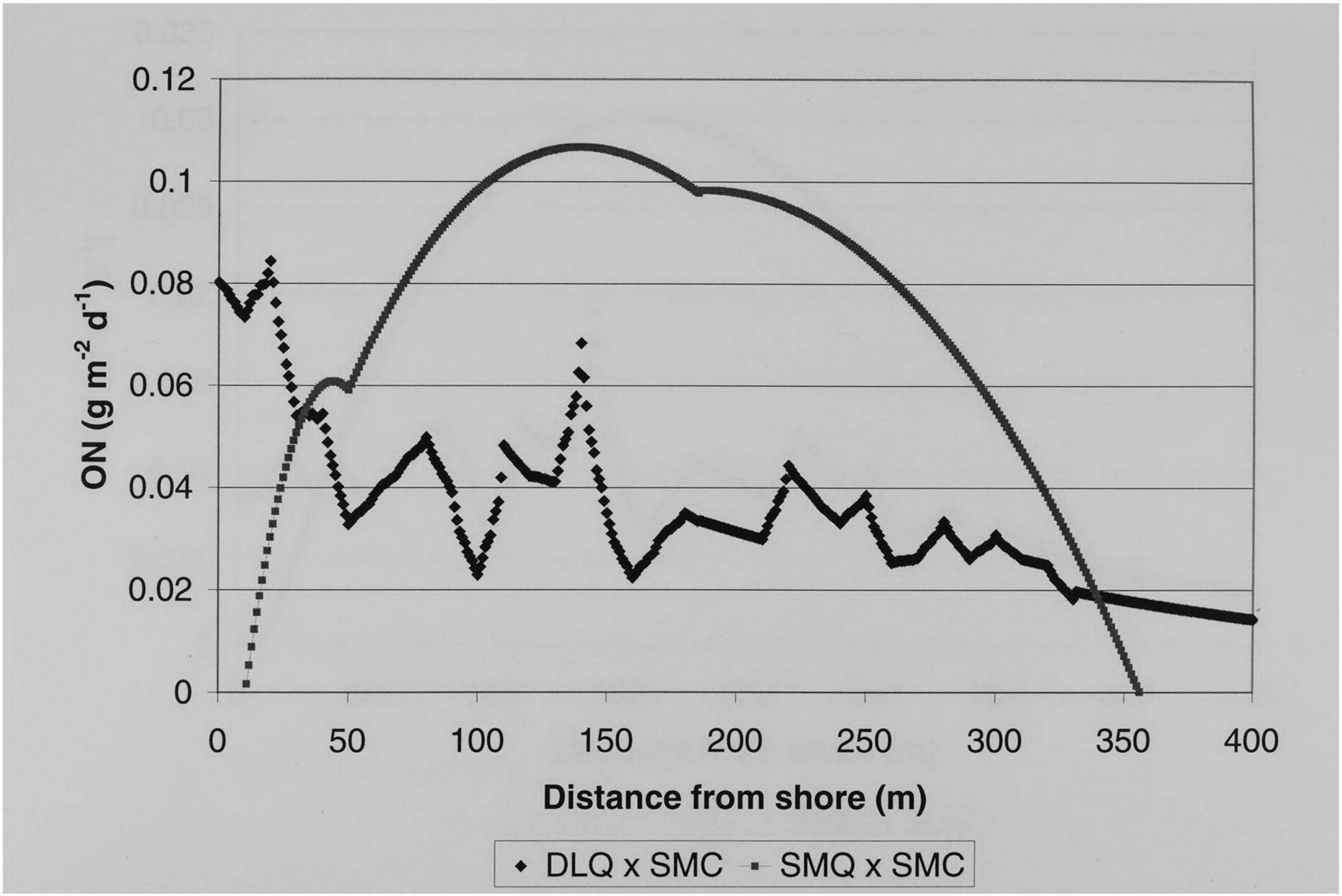


Figure 24. ON Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

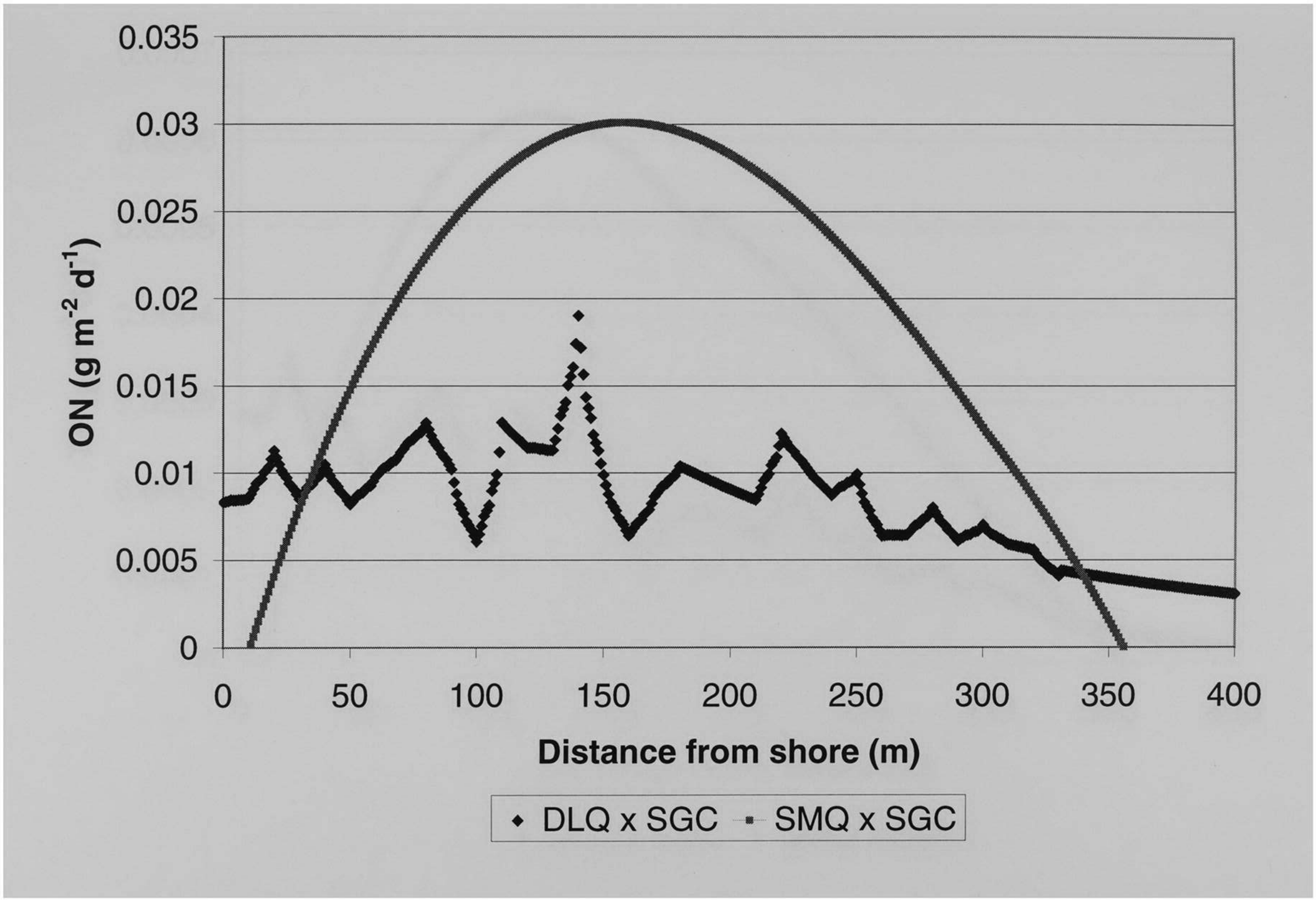


Figure 25. TP Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

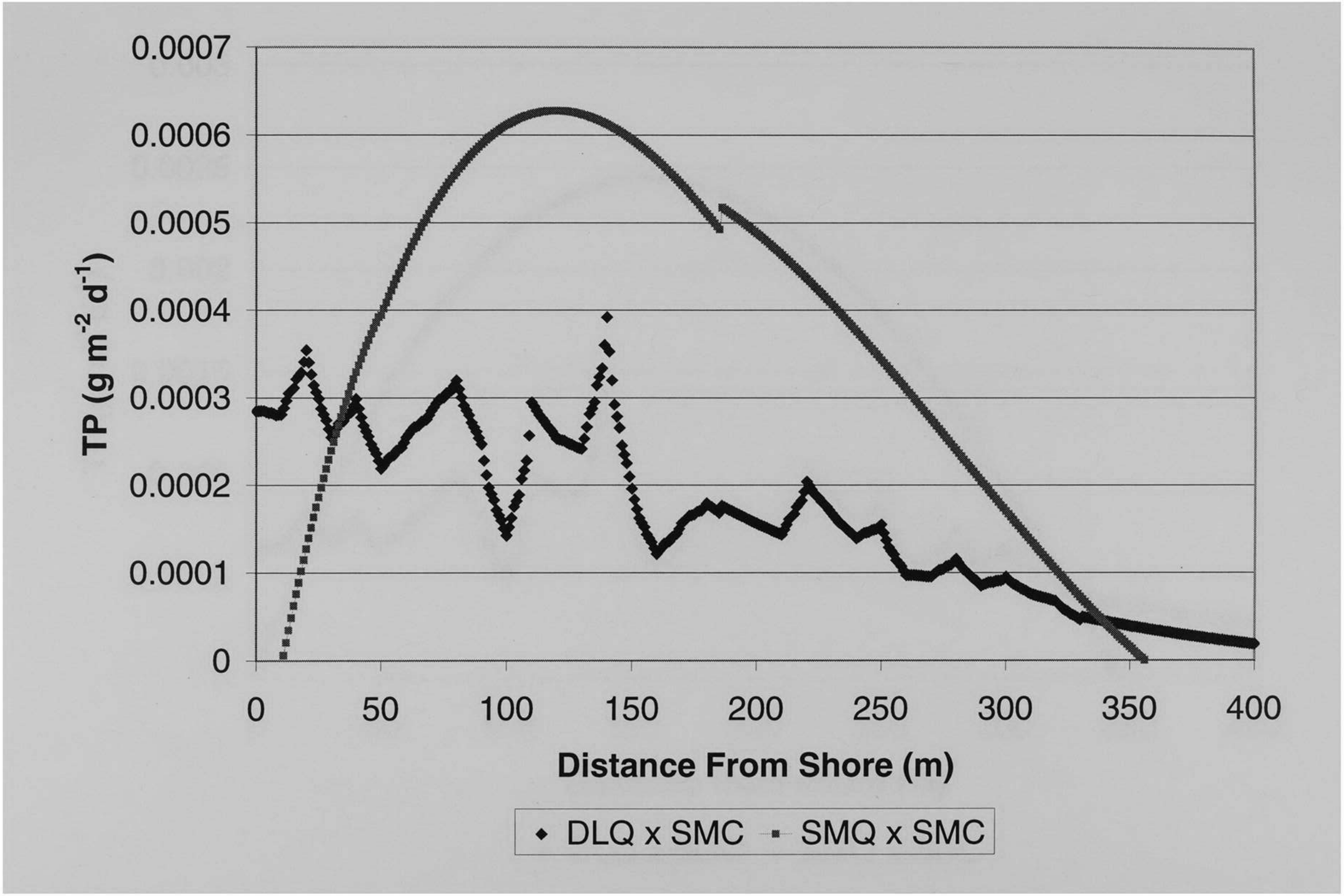


Figure 26. TP Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

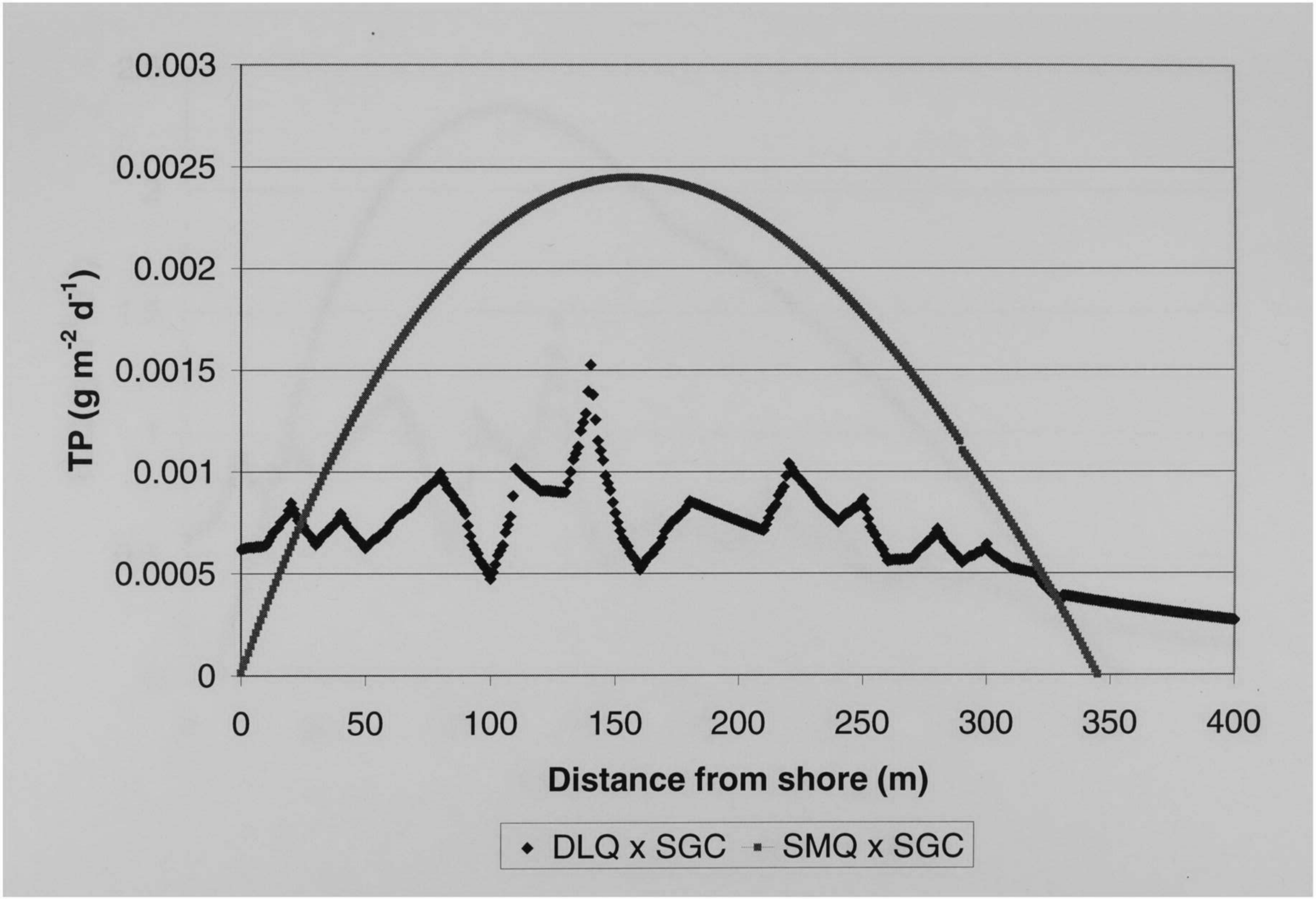


Figure 27. TOC Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Seepage Meter Nutrient Concentration (SMC)

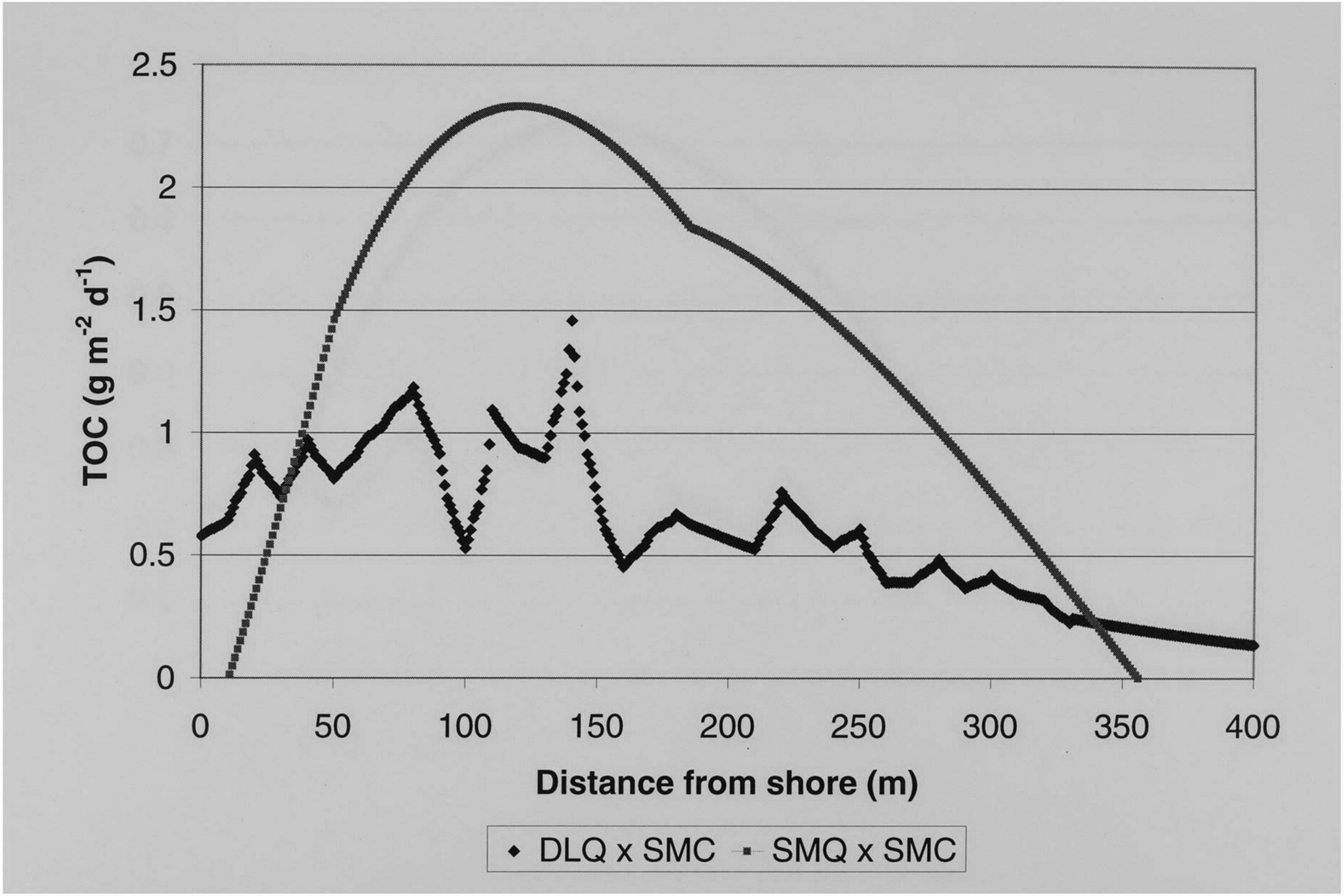


Figure 28. TOC Loading; Seepage Meter Discharge (SMQ) and Darcy's Law Discharge (DLQ) versus Shallow Groundwater Nutrient Concentration (SGC)

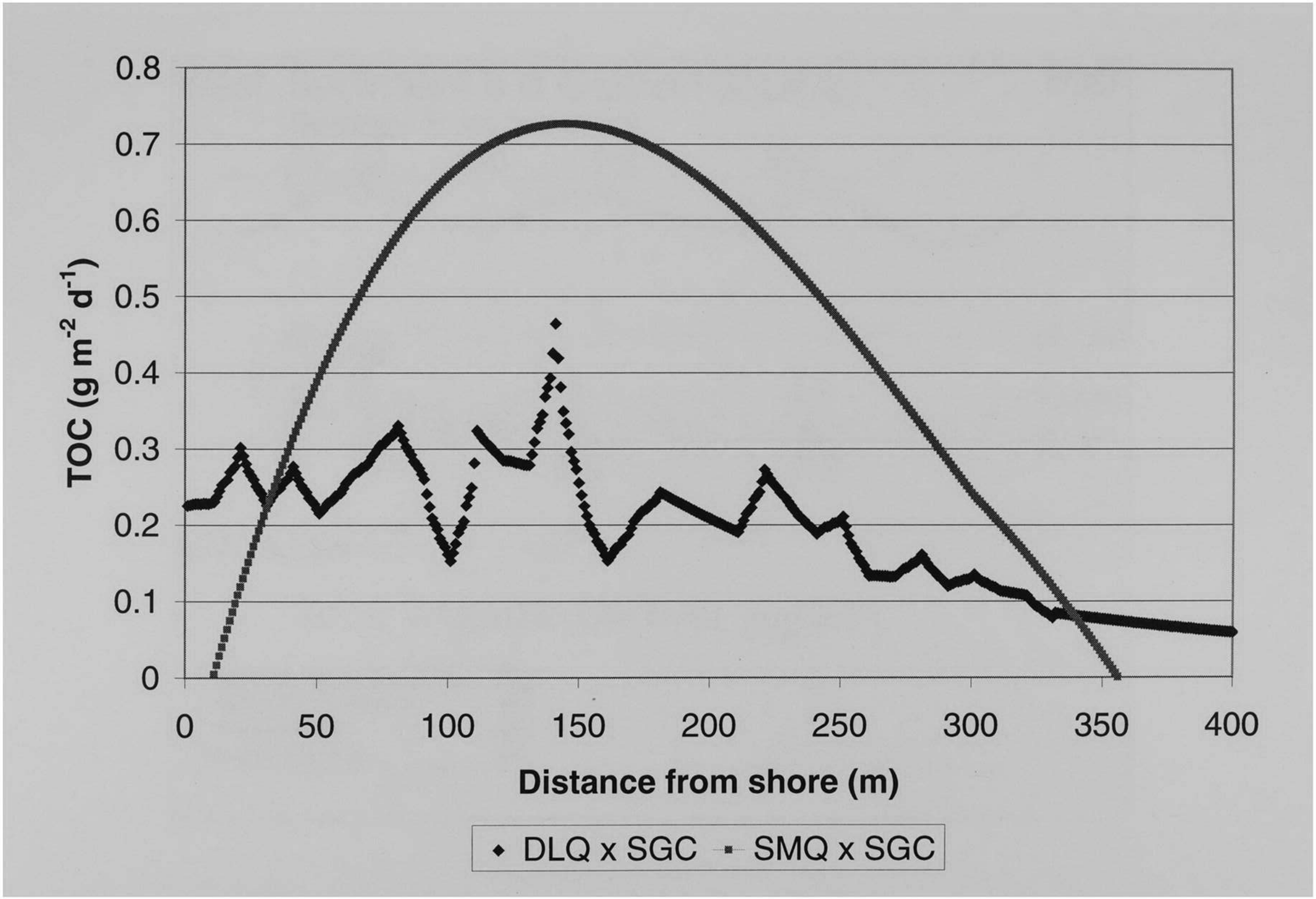


Figure 28. TOC concentration and export from sediment

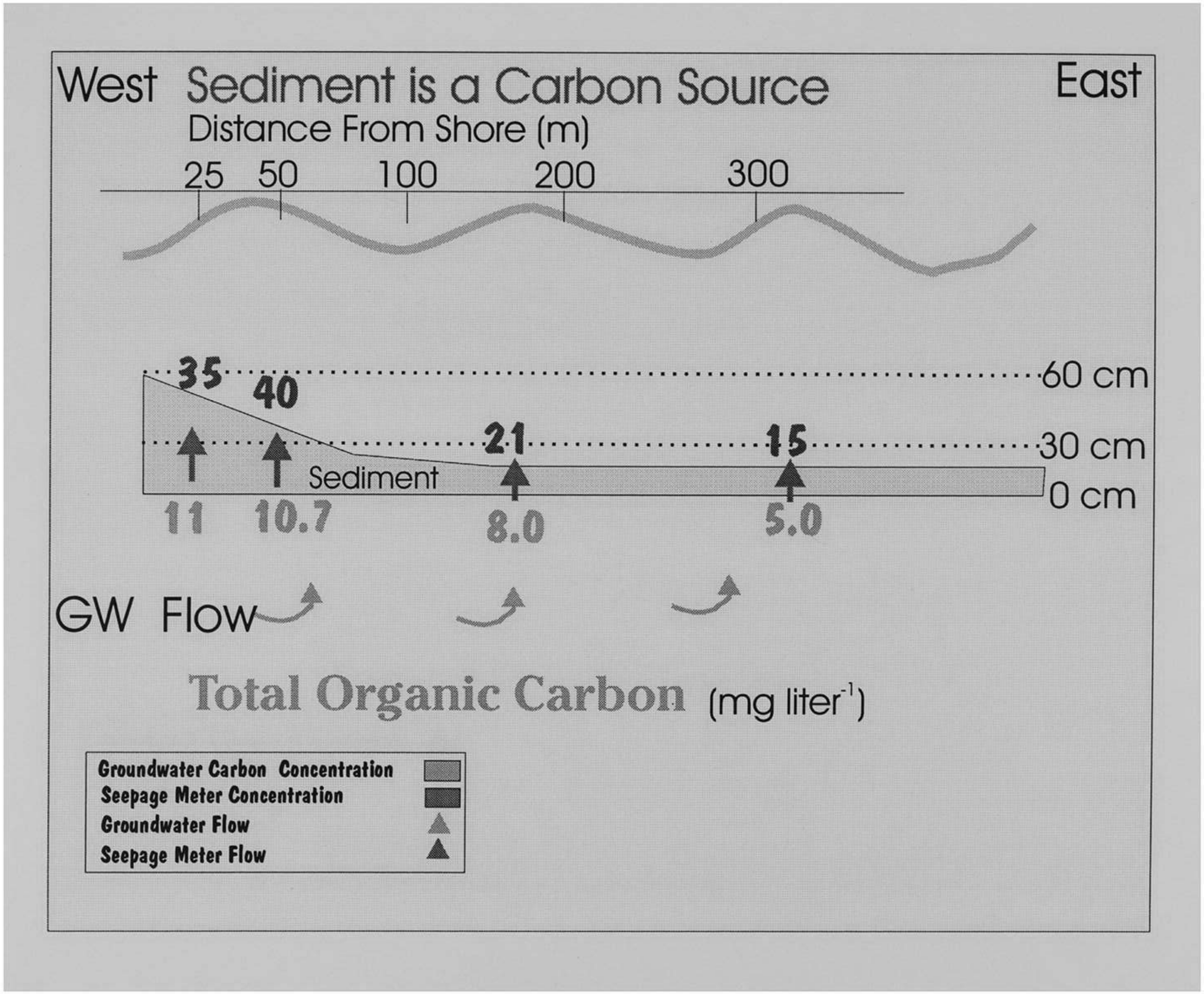


Figure 29. TN concentration and export from sediment

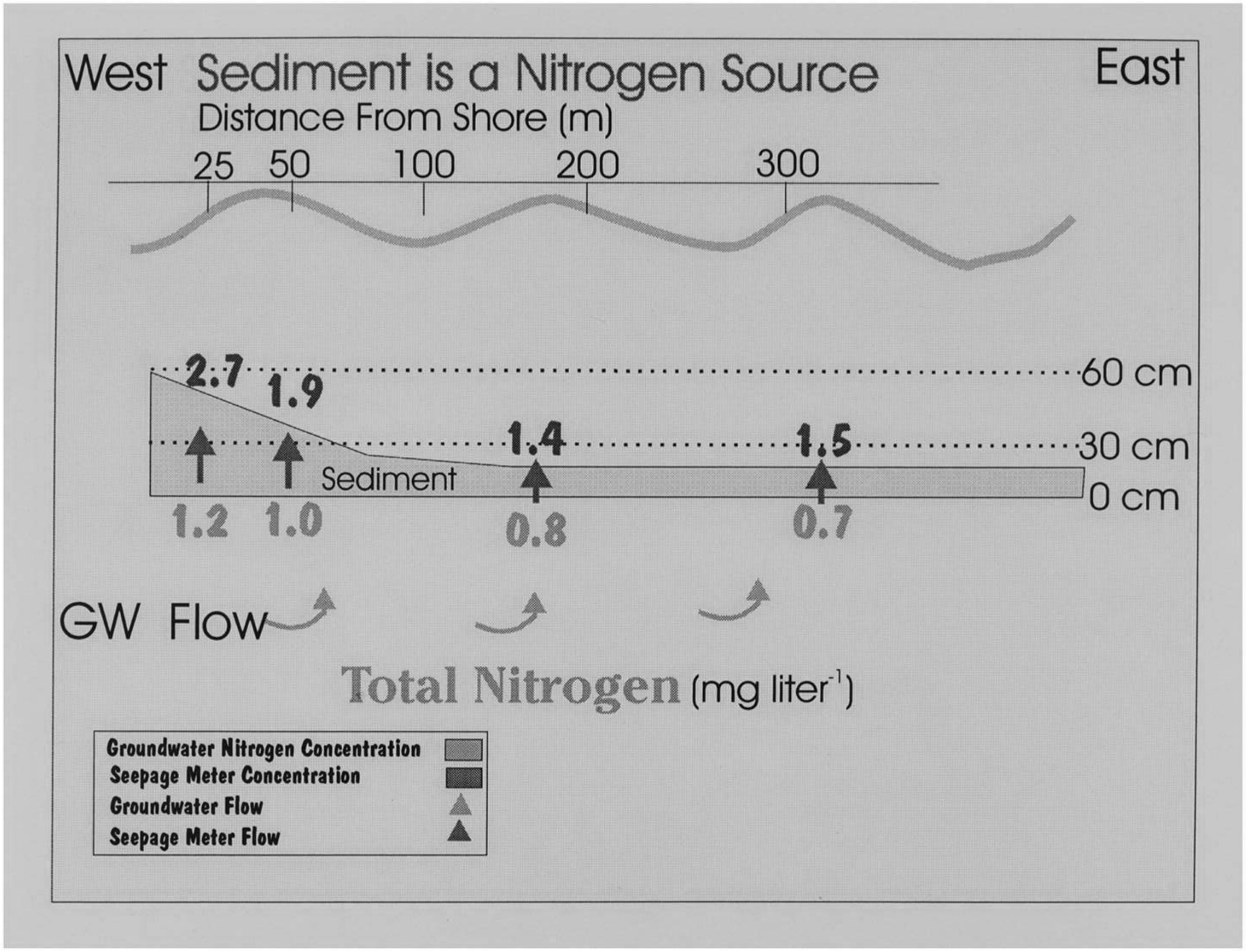


Figure 31. TP concentration and import to sediment

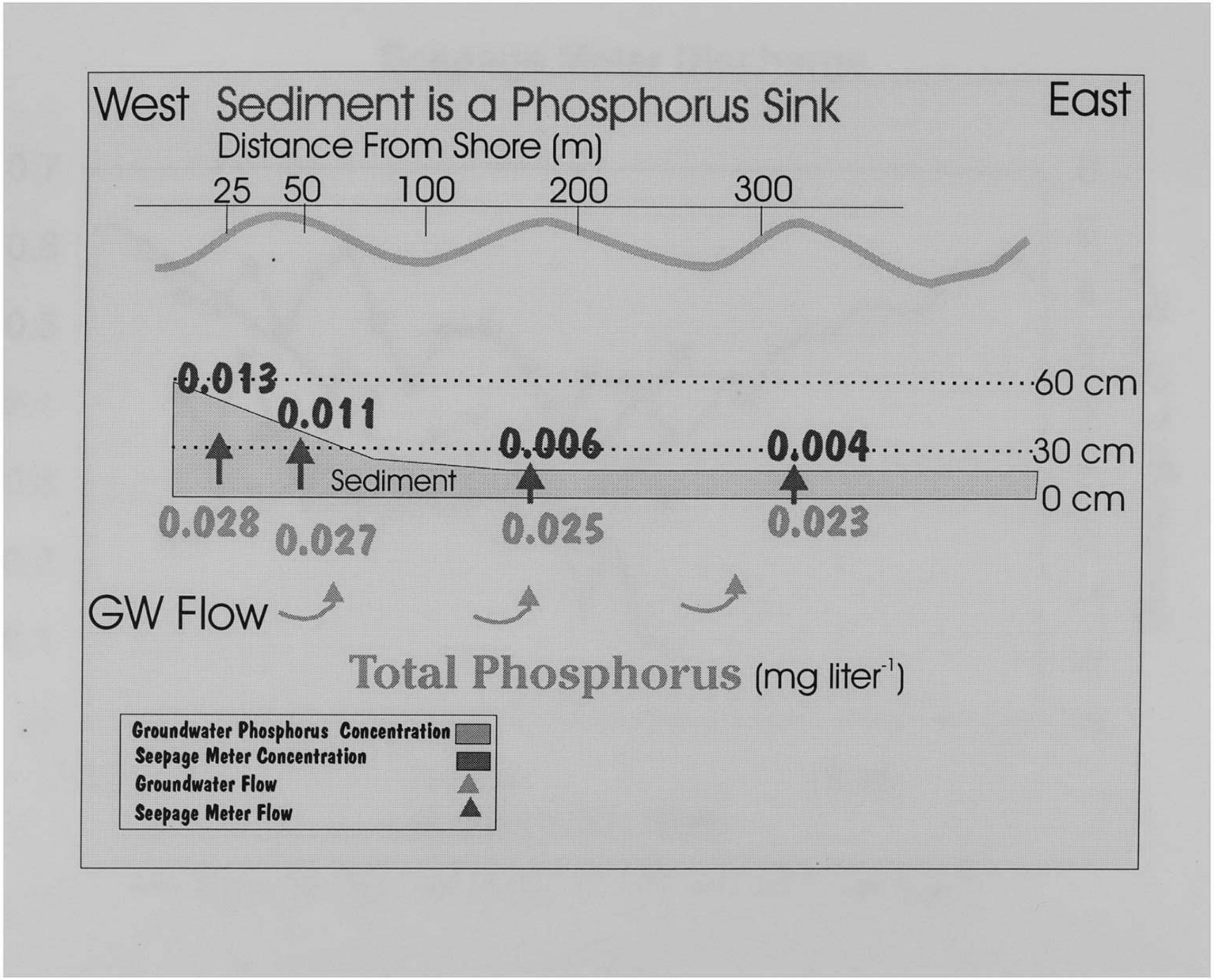


Figure 32. Tidal variation and seepage meter discharge

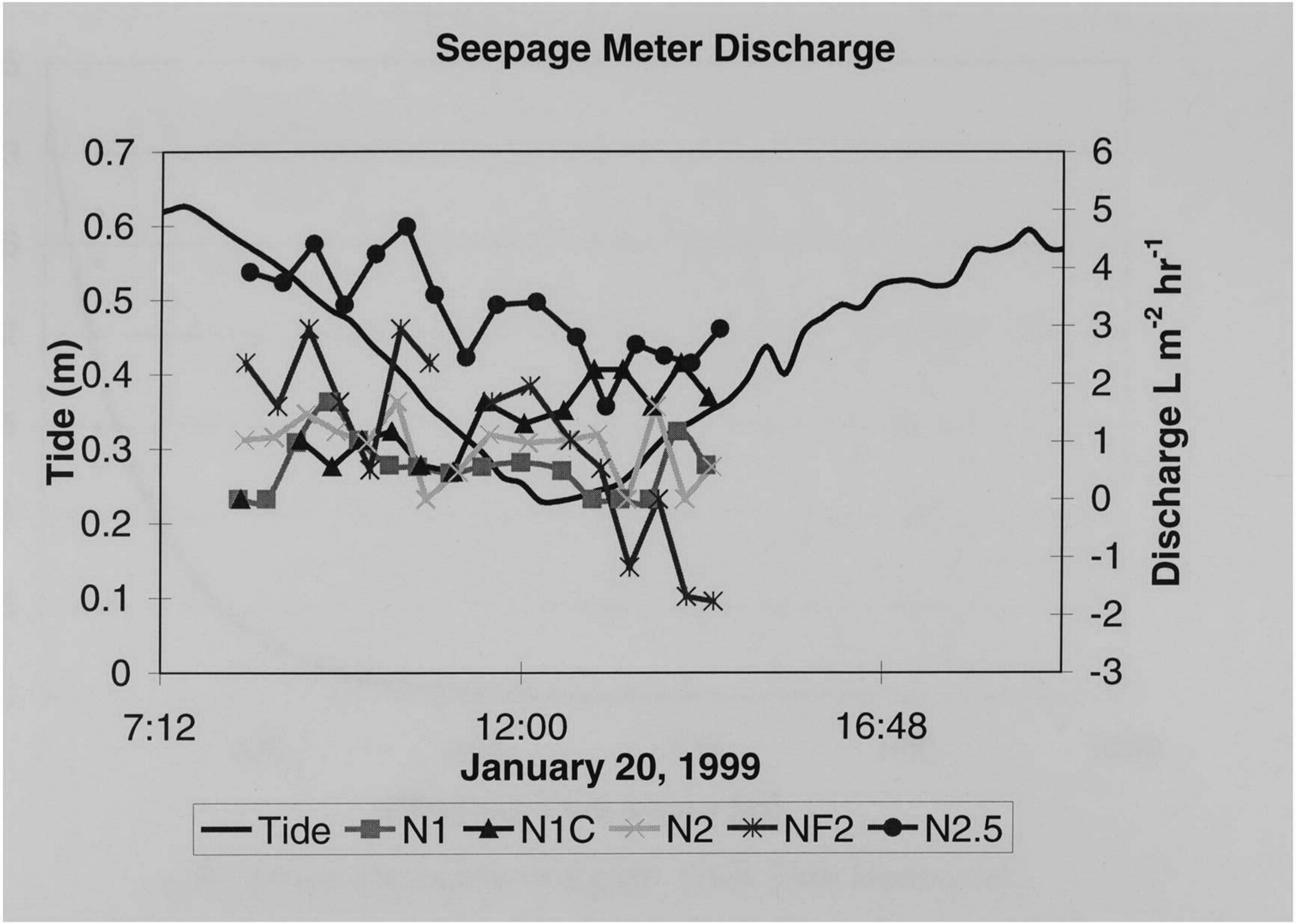
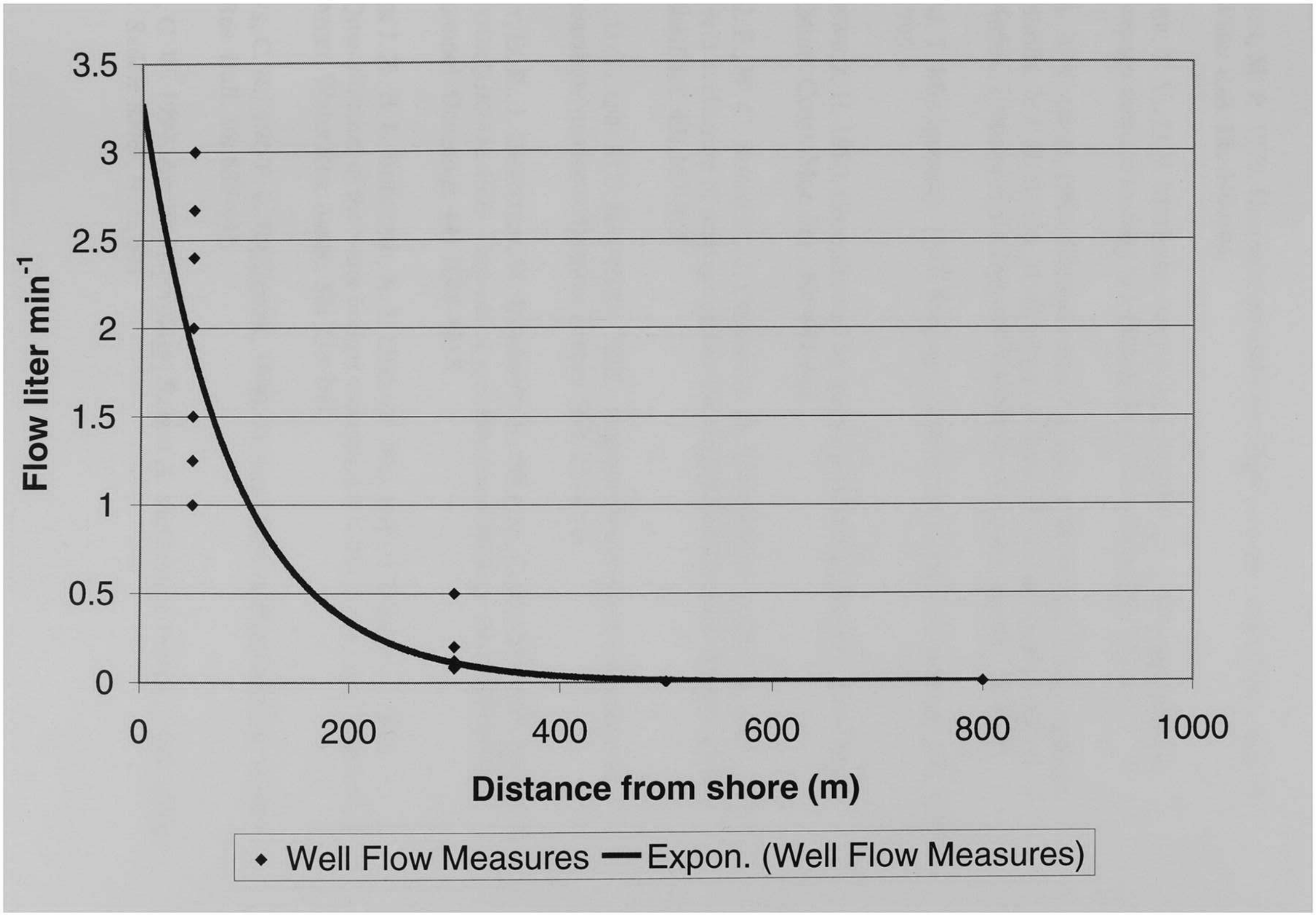


Figure 33. Well flow measurements



AGASSIZ, A. AND L. S. GRISWOLD. 1896. The Florida elevated reef with notes on the geology of southern Florida. Bull. Mus. Comp. Zool., Harvard Univ., **7:** 29-62.

ANDERSON, M. P. 1976. Unsteady groundwater flow beneath strip oceanic islands. Water Res. **12:** 640-644.

BELANGER, T. V., D. F. MIKUTEL, AND P. A. CHURCHILL. 1985. Groundwater seepage nutrient loading in a Florida lake. Water Res. **19**: 773-781.

———, R. B.WALKER. 1990. Ground water seepage in the Indian River Lagoon, Florida. *In* J. H. Krisha, V. Quinones-Aponte, F. Gomez-Gomez and G. Morris, Tropical Hydrology and Caribbean Water Resources: 367-375.

———, M. T. Montgomery. 1992. Seepage meter errors. Limnol. Oceanogr. **37:** 1787-1795.

BOKUNIEWICZ, H. 1980. Groundwater Seepage into Great South Bay, New York. Estuar. Coast. Mar. Sci., **10:** 437-444.

CABLE, J. E., W. C. BURNETT, J. CHANTON, D. R. CORBETT, AND P. CABLE. 1997. Field evaluation of seepage meters for coastal marine work. Estuar. Coast. Shelf Sci. **45:** 367-375.

CAPONE, D.G., AND M.F. BAUTISTA. 1985. A groundwater source of nitrate in nearshore marine sediments. Nature **313:** 214-216.

CORBETT, D. R., J. CHANTON, W. BURNETT, K. DILLON, C. RUTKOWSKI, AND J. W. FOURQUREAN. 1999. Patterns of groundwater discharge into Florida Bay. Limnol. Oceanogr. **44:** 1045-1055.

DREXLER J. Z., B. L. BEDFORD, A. T. DEGAETANO, AND D. I. SIEGAL. 1999. Quantification of the water budget and nutrient loading in a small peatland. J. Amer. Water Res. Assoc. **35:** 753-769.

FELLOWS, C. R., AND P. L. BREZONIK, 1980. Seepage flow in Florida lakes. Water Res. Bull. **16:** 635-641.

FETTER, C. W. 1994. Applied Hydrology; Robert A. McConnin, Prentice Hall, Upper Saddle River, N. J., 691.

FISH, J. E. AND STEWART, M. 1990. Hydrogeology of the Surficial Aquifer System, Dade County, Florida. U. S. Geological Survey, Water-Resources Investigations Report 90-4108, 50.

FOURQUREAN, J. W., J. C. ZIEMAN, AND G. V. N. POWELL. 1992. Phosphorus limitation of primary production in Florida Bay: Evidence from C:N:P ratios of the dominant seagrass *Thalassia testudinum*. Limnol. Oceanogr. **37:** 162-171.

GIBLIN, A.E. AND A.G. GAINES. 1990. Nitrogen inputs to a marine embayment: The importance of groundwater. Biogeochemistry 10: 309-328.

HARR, M.E. 1962. Groundwater and seepage. McGraw-Hill, New York.

HARLEM, P. W. 1979. Aerial Photographic interpretation of the historical changes in northern Biscayne Bay, Florida: 1925 to 1976. Sea Grant Technical Bulletin N. #40, December, 1979.

HERRERA-SILVEIRA, J. A. 1994. Nutrients from underground water discharge in a coastal lagoon (Celestun, Yucatan, Mexico). Verh. Internat. Verein. Limnol. **25:** 1398-1401.

HUBERT, M. K. 1940. The Theory of Groundwater motion. J. Geol. **48**: 785-944.

IMAN, R. L. AND W. J. CONOVER. 1983. A modern approach to statistics. John Wiley and Sons: 497.

JOHANNES, R. E. 1980. The ecological significance of the submarine discharge of groundwater. Mar. Ecol. Prog. Ser. 3: 365-373.

KOHOUT, F.A., 1960. Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida. Journal of Geophysical Research, vol. 65 (7) 2133-2141.

———, 1964. The flow of Fresh water and Saltwater in the Biscayne Bya Aquifer of the Miami Area, Florida. Seawater in Coastal Aquifers. U.S. Geological Survey Water Supply Pap. 1616-C: 12-32.

———, 1967. Relation of Seaward and Landward Flow of Ground Water to the Salinity of Biscayne Bay. Thesis, University of Miami. Pp. 98.

———, and KOLIPINSKI, M. C., 1967. Biological zonation related to ground water discharge along the shore of Biscayne Bay, Miami, Florida. Estuaries.

LANGEVIN, C. D., M. T. STEWART, AND C. M. BEAUDOIN. 1998. University of sea water canals on fresh water resources; an example from Big Pine Key, Florida. Ground Water **36:** 503-513.

LAPOINTE, B., J. O'CONNELL, AND G. S. GARRETT. 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters and nearshore surface waters of the Florida Keys. Biogeochemistry **10:** 289-307.

LEE, T.N. AND J.B. MCQUINN.1973. The use of ocean outfall for marine waste disposal in southeast Florida's coastal waters. Univ. Miami Sea Grant, Coast. Zone Manage. Ser., Bull. **2:** 19.

LEE, D. R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. **22:** 140-147.

LOEB, S. L. AND C. R. GOLDMAN 1979. Water and nutrient transport via groundwater from Ward Valley into Lake Tahoe. Limnol. Oceanogr. **24:** 1146-1154.

MACINTYRE, I.G. 1975. A diver operated hydraulic drill for coring submerged substrates. Atol. Res. Bull. **185:** 21-25.

MATSON, E. A. 1993. Nutrient flux through soils and aquifers to the coastal zone of Guam (Mariana Islands), Limnol. Oceanogr. **38:** 361-371.

MAUL, G. A. AND D. M. MARTIN. 1993. Sea level rise at Key West, Florida. 1846-1992: America's longest instrument record. Geophys. Res. Lett. **20:** 1955-1958.

MCNULTY, J.K. 1961. Ecological effects of sewage pollution in Biscayne Bay, Florida: Sediments and the distribution of benthic and fouling organisms. Bull. Mar. Sci. Gulf Carib. **11:** 394-447.

———. 1970. Effects of abatement of domestic sewage pollution on the benthos, volumes of zooplankton and the fouling organisms of Biscayne Bay, Florida. Studies in Tropical Oceanography, Univ. Miami **9:**1-107.

MEEDER, J. F., M. S. ROSS, G. TELESNICKI, P. L. RUIZ, J. P. SAH. 1996. Vegetation analysis in the C-111 Taylor slough basin. Final Report to South Florida Water Management District, Contract # C-4244.

MICHEL, J.F. 1976. The impact of works of man on the physical regime of Biscayne Bay. *In*. Biscayne Bay: present, past and future. A. Thoraug [ed.]. Univ. Miami Sea Grant Spec. Report **5:**265-270.

MOORE, H.B., I. HELA, E.S. REYNOLDS, J.K. MCNULTY, S. MILLER AND C.A. CARPENTER, JR. 1955. Report on the preliminary studies of pollution in Biscayne Bay. Report to Fed. Security Agency. Public Health Service, Nat. Instit. Health, Washington D.C.

NUTTLE, W. K., AND J. W. HARVEY. 1995. Fluxes of water and solute in a Coastal Wetland Sediment. 1. The contribution of Regional Groundwater discharge. Journal of Hydrology, **164** 89-107.

PANDIT, A., AND C. C. EL-KHAZEN. 1988. Modeling of water exchange between Indian River Lagoon and surficial aquifer in Port St. Lucie, Florida. Department of Civil Engineering, Florida Institute of Technology Melbourne, FL, Pp. 145.

PARKER, G. G., G. E. FERGUSON, S. K. LOVE, AND OTHERS. 1955. Water Resources of southeastern Florida. U. S. Geological Survey water-supply paper 1255. Pp. 965.

———.1974. Hydrogeology of the Pre-Drainage System of the Everglades in Southern Florida , *In* P. J. Gleason, Environments of South Florida, Present and Past: 18-27.

PERKINS, R. D., 1977. Pleistocene depositional framework in south Florida, *In* P. Enos, and R. D. Perkins, Quaternary sedimentation in south Florida. Geol. Soc. Am. Bull. **147:** 131-198.

REAY, W. G., D. L. GALLAGHER, AND G. M. SIMMONS, JR. 1992. Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. Water Res. Bull. **28:** 1121-1134.

ROSS, M. S., J. F. MEEDER, P. L. RUIZ, A.RENSHAW, G. T. TELESNICKI, J. ALVORD, M. JACOBSON, M. BYRNE, Z. D. ATLAS, D. REED, B. FRY, M. T. LEWIN, AND C. WEEKLEY. The L-31E surface water rediversion pilot project: Phase I Final Report. South Florida Water Management District Contract # C-4245.

SERAFY, J. E., J. S. AULT, AND M. E. CLARKE. 1996. Red drum stock enhancement program Biscayne Bay fishery-independent assessment, Final Report, Contract # MR018.

SHAW, R. D., AND E. .E PREPAS. 1990. Groundwater-lake interaction: I. Accuracy of seepage meter estimates of lake seepage. J. Hydrol. **119:** 105-120.

SHINN, E. A., R. S. REESE, AND C. D. REICH. 1994. Fate and pathways of injection-well effluent in the Florida Keys. U.S. Geological Survey Open-File Report 94-276.

SONTAG, W. H. 1987. Chemical characteristics of water in the surficial aquifer system, Dade County, Florida. U. S. Geological Survey, Water-Resources Investigations Report 87- 4080, Tallahassee, Florida.

SOUTH FLORIDA WATER MANAGEMENT DISTRICT. 1993. L-31 E redistribution pilot project technical feasibility, by Project Management Division, Construction Management Department, June.

———, 1995. Biscayne Bay, Surface water improvement and management, Technical supporting document, by Planning Department. November.

STAVER, K. W., AND R. W. BRINSFIELD. 1996. Seepage of groundwater nitrate from a riparian agroecosystem into the Wye River Estuary. Estuaries **19:** 359-370.

TEAS, H.J., H. R. WANLESS AND R. CHARDON. 1976. Effects of man on the shore vegetation of Biscayne Bay. In A. Thorhaug, Biscayne Bay: Past, Present and Future. Univ. Miami Sea Grant Spec. Rep. **5:** 133-156.

TURNER, R.J. 1990. The effects of a mid-foreshore groundwater effluent zone on tidal-cycle sediment distribution in Puget Sound, Washington. J. Coast. Res. **6:** 597-610.

U.S. ARMY CORPS OF ENGINEERS. 1900. Examination of Biscayne Bay, Florida. House Doc. No. 662, 56th Congress, 1st Session, 28p.

———, 1999. The Central and Southern Florida (C&SF) Project Comprehensive Review Study ("Restudy").

VALIELA, I., J.M. TEAL, S. VOLKMANN, D. SHAFER AND E.J. CARPENTER. 1978. Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and imputs by precipitation and groundwater. Limnol Oceanogr. **23:**798-812.

———, ———, ———, C.M. COGSWELL, AND R.A. HARRINGTON. 1980. On the measurement of tidal exchanges and groundwater flow in salt marshes. Limnol Oceanogr. **25:**187-192.

VAN DE KREEKE, J. AND J. D. WANG. 1984. Hydrography of north Biscayne Bay. Part I: Results of field measurements. Metro-Dade County, Fla. Environ. Resour. Manag. And Fla. Sea Grant. Pp. 85.

WANLESS, H.R.1976. Man's impact on sedimentary environments and processes. *In* A. Throhaug, Biscayne Bay: Present, Past and Future. Univ. Miami Sea Grant Spec Pub. **5:** 287-299.

WINTER, T. C. 1995. Recent advances in understanding the interaction of groundwater and surface water. Reviews of Geophysics Sup. **July:** 985-994.