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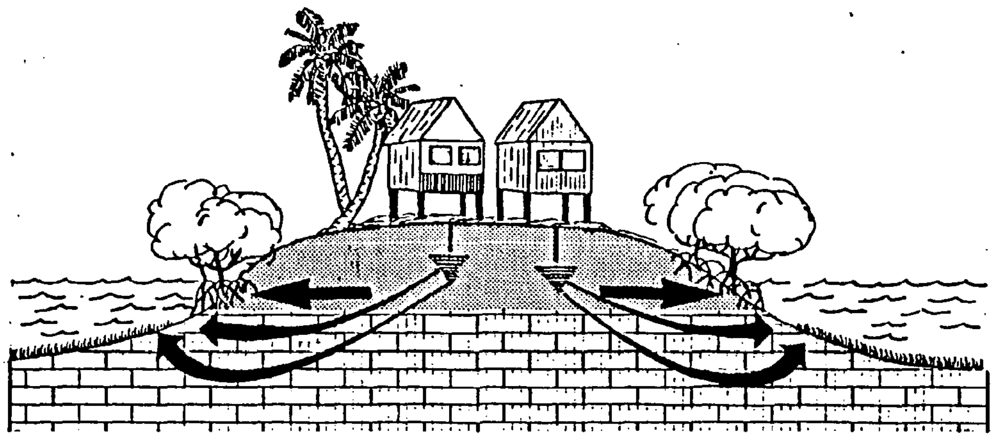
THE EFFECTS OF ON-SITE SEWAGE DISPOSAL SYSTEMS ON NUTRIENT RELATIONS OF GROUNDWATERS AND NEARSHORE WATERS OF THE FLORIDA KEYS



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PROJECT SUMMARY

The effects of on-site sewage disposal systems (OSDS; septic tanks and aerobic treatment units) on nutrient concentrations of upland groundwaters and adjacent inshore waters of the Florida Keys, Monroe County, was studied between December, 1986 and September, 1987. Monitor wells designed to sample groundwater at 8-10 ft below grade were installed at four residential stations in the Upper Keys (Key Largo Limestone substrate) and four residential stations in the Lower Keys (Miami Oolite substrate) to determine the effects of septic tanks on groundwater quality. A deeper monitor well cluster, consisting of three wells of different depths (15´, 30´, 60´ below grade), was installed adjacent to the injection well of an aerobic treatment unit on Big Pine Key. Control monitor wells (15´ and 30´ below grade) were located in the pristine environs of the Key Deer National Wildlife Refuge (KDNWR) and remote from potential sources of contamination. All the monitor wells, as well as the most adjacent inshore surface water (i.e. canal) at each site, were sampled monthly for determination of ammonium, nitrate, soluble reactive phosphate (SRP), salinity, and temperature. In addition, nutrient concentrations and chlorophyll in seawater were determined along an offshore transect adjacent to Big Pine Key to determine seasonal variability in chlorophyll and possible correlations with dissolved seawater nutrients.

Results of this study indicate that OSDS result in extremely elevated nutrient concentrations of groundwaters. The highest nutrient concentrations were associated with groundwaters adjacent to OSDS and the effluent of the aerobic treatment units, where concentrations as high as 2.5 mM for ammonium, 2.3 mM for nitrate, and 120 μM for SRP occurred. Annual mean concentrations of ammonium and nitrate in residential groundwaters were approximately 350-fold higher than in the control groundwaters, whereas concentrations of SRP were approximately 60-fold higher. The reduced level of SRP enrichment of

groundwaters in the Keys appears to be due to mineral formation associated with carbonate geologies (i.e. fluoroapatite) and scavenging by oxides of iron and aluminum.

Maximum concentrations of groundwater nutrients occurred during winter (minimum during summer), whereas maximum concentrations in surface waters occurred during summer (and minimum in winter); this inverse seasonal pattern suggests that maximum discharge of groundwater nutrients into surface waters occurs during summer. Approximately three-fold higher concentrations of chlorophyll also occurred in inshore surface waters during summer, possibly in response to seasonal nutrient enrichment from groundwater seepage. Increased discharges of nutrient-enriched groundwaters during summer may result from increased groundwater recharge during summer (elevated rainfall, reduced evaporation) that would result in elevated hydraulic head and groundwater flow rates. Furthermore, increased mixing of groundwaters with OSDS during the seasonally high sea level that occur during late spring-early summer would enhance discharge of OSDS derived nutrients to surface waters in summer. Groundwater flow rates, directly determined with a GeoFlo groundwater flowmeter at several locations on Big Pine Key during summer 1987, indicated an average lateral flow rate of 2.8 ft/day. However, higher lateral flow rates were observed during ebbing tides (up to 5 ft/day) and rain events (up to 12 ft/day). Direction of groundwater flow was dependant upon the natural grade and flow patterns and explains previous failures to trace rhodamine dye from septic effluents into adjacent man-made surface waters.

Based on an average distance to the down gradient receiving waters of 350′ for one canal residence on Big Pine Key, an average of 6 months would be required for discharge of nutrients into the nearest surface waters. Considering the expanded tourist and part-time resident population of the Keys during winter (approximately 68% greater population compared to summer), the bulk of the resulting nutrient load would seep into surface waters during the following summer. Such a "delayed discharge" would be facilitated by increased sea level, groundwater recharge, hydraulic head, and groundwater flow during late spring and summer. Nutrient enrichment resulting from contaminated groundwater seepage will enhance eutrophication processes in nearshore waters of the Keys.

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INTRODUCTION

The marine environment of the Florida Keys is one of the most important assets to the economy of Monroe County. The clear, oligotrophic waters of the Keys support extensive growth of corals and seagrasses that are linked directly or indirectly, to tourism, commercial and sport fisheries, and the distinctive "Keys" way of life. To determine potential impacts on the marine environment by increasing use of on-site sewage disposal systems (OSDS), we conducted a one year study to quantify effects of OSDS on nutrient concentrations of upland groundwaters and adjacent inshore waters. Twenty groundwater monitor wells were installed and, together with adjacent inshore waters, sampled for determination of nutrient concentrations (ammonium, nitrate, soluble reactive phosphate), salinity, and temperature. Rate and direction of groundwater flow was determined at several sites on Big Pine Key to determine subsurface flow patterns and quantify potential dispersion rates of septic leachate associated with OSDS in both Miami Oolite and Key Largo Limestone substrate. Concentrations of nutrients and chlorophyll-a were also measured at hydrographic stations in nearshore waters along a transect extending from canal waters on Big Pine Key to offshore waters at Looe Key National Marine Sanctuary (LKNMS).

BACKGROUND

The Florida Keys are truly unique in North America in having the most biologically diverse and productive shallow water (<10m) tropical marine ecosystem. The archipelago island chain of the Keys separates the marine environments of Florida Bay and the Gulf of Mexico from that of the Florida Straits and Atlantic Ocean, with numerous tidal passes between the Keys providing water exchange between these water bodies. The most unique feature of the Keys marine environment is the extensive coral reef formations that extend for 220 miles between Soldier Key and Dry Tortugas that include patch and bank reef systems ranging from 25m to 13 km offshore and collectively referred to as the Florida Reef Tract (Vaughn, 1914; Jaap, 1984). Coral reef ecosytems are one of the most biologically diverse and productive ecosystems on earth (Goreau, 1979) and make tourism and recreation a major factor in the regional economy. Several species of tropical seagrasses also form extensive meadows in the shallow Keys marine environment and are important as sources of food and habitat for marine organisms, stabilization of sediments, and recycling and storage of nutrients (Zieman, 1982).

The importance of maintaining water quality with increasing upland development was a major element that spurred legislation to protect the unique Keys marine environment. In 1974, the Florida Keys were designated as an "Area of Critical State Concern" under Chapter 380 of the Florida Statutes. Section 380.0552, "The Principles for Guiding Development in the Florida Keys Area of Critical State Concern" was adopted by the Administrative Commission ten years later to "insure a water management system that will reverse the deterioration of water quality and provide optimum utilization of our limited aquatic resources, facilitate orderly and well planned development, and protect the health, welfare, safety, and quality of life of the residents of this state." Subsequently, in 1985, the waters of the Florida Keys were designted as "Outstanding Florida Waters" under Chapter 403 of the Florida Statutes.

In accordance with the guidelines of "The Principles for Guiding Development", the use of OSDS for wastewater management in the Florida Keys remains controversial. The bulk of liquid domestic waste disposal in Monroe County is met by septic tanks (approximately 22,000 total septic tanks and cess pits are currently in use) and aerobic "package" treatment units, such as the

"Multi-Flo" unit, coupled with injection wells (approximately 400). Considering that only 20% of the 53,000 platted, subdivided lots in the Florida Keys are developed at present, cumulative impacts of increasing use of OSDS could have dramatic effects on inshore water quality. The potential for impacts on nearshore water quality of the Keys is exacerbated by the large number of finger canal developments that dramatically increase the interface between groundwaters and nearshore waters. While studies of septic tank systems in Dade County, FL have determined that septic leachate enters surface waters in canals and causes water quality degradation (Barada, 1972), there still exists no general consensus regarding potential effects of OSDS on water quality in the Florida Keys.

The controversial issue of environmental impacts of canalization and septic tank use on water quality in the Keys results, in part, from the disparate conclusions of previous studies. For example, Chesher (1973) studied 13 canal stations in Summerland Key Cove subdivision on Summerland Key and reported satisfactory water quality and that "there were no adverse environmental conditions attributable to septic tanks". However, a subsequent E.P.A. study (Hicks et al., 1975) concluded that canal systems in the Keys have poor flushing characteristics that result in frequent violations of both State and Federal water quality criteria. Furthermore, although dye studies failed to demonstrate septic leachate directly entering canal waters in Doctor's Arm subdivision on Big Pine Key, elevated dissolved nutrients and total organic carbon in developed canals compared to undeveloped canals appeared to be responsible for lower oxygen levels and ecological imbalances in the developed canals (Hicks et al., 1975).

An assessment of OSDS on nearshore water quality of the Keys will necessarily have to address groundwater quality. Groundwaters are known to be important nutrient sources to lakes (Keeney et al., 1971; Brock et al., 1982; Loeb and Goldman, 1979) but only recently have they been demonstrated as significant nutrient sources to nearshore marine waters. For example, groundwaters are an important nutrient source in salt marsh systems on Cape Cod, Massachusetts (Valiela et al., 1978), in nearshore waters of Long Island Sound, New York (Capone and Bautista, 1985), and in back-reef habitats on coral reefs along the north shore of Jamaica (D'Elia et al., 1981). While a historical importance of groundwater nutrient inputs on nutrient budgets of coastal waters is recognized (e.g. Manheim, 1967) increasing development and agriculture in upland, coastal areas are dramatically increasing the role of groundwaters in nutrient budgets of nearshore marine waters (Capone and Bautista, 1985; Pye and Patrick, 1983). The potential for nutrient enrichment of nearshore waters by groundwaters enriched with septic leachate is exacerbated in the Florida Keys because of the high porosity and permeability of its coral-derived substrate and the ubiquitous close proximity of OSDS to oligotrophic marine ecosystems; there also exists the possibility that elevated tides and cross island heads accelerate flow of enriched groundwaters toward oligotrophic marine habitats. Studies of groundwater flow along Florida's east coast have clearly demonstrated brackish groundwater fluxes into nearshore marine waters on the order of 45 m^3/day from a strip one meter wide (Kohout, 1960), suggesting that enriched groundwaters could become a significant source of nutrients to nearshore marine environments in South Florida.

Special concern regarding increased nutrient availability on the ecology of nearshore waters of the Florida Keys is based on the known high degree of nutrient limitation that is the key to maintaining outstanding water quality in these oligotrophic waters. Nutrient-limitation bioassays with several species of dominant macroalgae in Pine Channel and Florida Bay demonstrated severe limitation of productivity by phosphorus and nitrogen (Lapointe, 1987; Lapointe, 1988), supporting the the contention that limited nutrient availability regulates, to a large extent, marine plant growth in these waters. Consequently, increased nitrogen and phosphorus flux to nearshore waters of the Keys marine environment could lead to cumulative water quality degradation through enhanced eutrophication. Water quality experts consider eutrophication to be the single most important water quality issue (Clark et al., 1977) and scientists have clearly demonstrated excessive nutrient loading to enhance eutrophication (Ryther and Dunstan, 1971; Lee and Jones, 1981). Cumulative effects of eutrophication include reduced water transparency (and submarine light) due to excessive phytoplankton biomass, reduced dissolved oxygen concentrations, odors (hydrogen sulfide), fish kills, ecological imbalances, and an overall reduction of biological diversity. Because inorganic forms of dissolved nitrogen (nitrate and ammonium) and phosphorus (soluble reactive phosphate, SRP) are the most important nutrients associated with domestic wastewater that support marine plant growth (Parsons et al., 1977) and enhance eutrophication, a knowledge of the contribution of OSDS to concentrations of these nutrients in groundwaters and surface waters of the Florida Keys is necessary.

SCOPE OF THE PRESENT STUDY

The objectives of the present study were to:

1) determine if use of OSDS affects nutrient concentrations of upland groundwaters and/or adjacent inshore waters.

2) determine groundwater flow rates in typical geologies of the Keys to quantify interaction of groundwaters with inshore marine waters.

3) Determine the relationship between dissolved inorganic nutrients and phytoplankton chlorophyll in nearshore waters to predict potential effects of increased nutrient availability.

MATERIALS AND METHODS

Study Area

This study took place in Monroe County, FL, and included a variety of residential canal locations that extended from Key Largo in the Upper Keys to Big Pine Key in the Lower Keys. The surface geology of the Upper Keys is composed primarily of coral reef rock known as Key Largo Limestone whereas that of the Lower Keys is formed of small spherical grains of calcium carbonate cemented together and known as Miami Oolite (Hoffmeister, 1974; Multer, 1971). Key Largo Limestone is porous and highly permeable because of numerous solution features and voids that allow rapid vertical and horizontal groundwater flow; consequently, this formation retains little fresh water and therefore, no freshwater lenses occur in the Upper Keys (Parker et al., 1955; Hoffmeister and Multer, 1968). Although Miami Oolite in the Lower Keys is also porous, its fewer horizontal voids compared to Key Largo Limestone results in decreased permeability; therefore, retention of fresh water is enhanced and results in several fresh water Ghyben-Herzberg lenses, most notably those of Big Pine Key (Hanson, 1980).

Monitor Wells: Design and Installation

To determine potential effects of septic tank leachate on groundwater nutrient concentrations, nutrient concentrations were determined in groundwaters of 16 monitor wells on eight upland residential lots with septic tank/drainfield systems currently in use and compared to values for pristine groundwaters of the Key Deer National Wildlife Refuge (KDNWR) that were used as the "control" wells (see list of stations in Table 1 and location of the stations in Figs 1-4). We believe that the KDNWR provided the best setting in the Keys for our control wells because of its remote location from human activities that could potentially contaminate its groundwaters; furthermore, both Miami Oolite (0-22′) and Key Largo Limestone (> 24′) could be sampled at this one location (Hanson, 1980). Four residential stations were selected in the Upper Keys and four in the Lower Keys to address the different surface geologies of these areas and its possible effects on nutrient relations of groundwaters and nearshore waters.

Two monitor wells were installed on each of the eight residential lots. One well was installed in the vicinity of the septic tank drainfield and the other well was installed on the waterfront side of the lot, approximately halfway towards the surface water closest to the septic drainfield. A portable hand-held 1" auger was used to bore a 10′ deep borehole; initial development utilized a portable well point sampler designed for groundwater plume tracking (Kerfoot, 1984). Following development, the boreholes were cased with 1/2 inch PVC pipe that had a 2′ long section of continuous slotted well screen (0.010 of an inch slot width) adjusted to a horizon 8-10 ft below grade at each location. Saturated groundwaters were commonly reached at 3-4 ft below grade at most locations, but we believed that by sampling somewhat deeper groundwaters a more representative and consistent sample of groundwaters would be realized.

To determine potential effects of injection well wastewater on groundwater nutrient concentrations both at depth and in near-surface groundwaters, a site in the lower Keys (Halcyon Trailer Park; See Table 1) with a "Multi-flow" aerobic treatment unit coupled to a 60′ injection well was monitored. At this site, a cluster of three monitor wells, each sampling a different and discrete depth, was installed according to guidelines outlined in Driscoll (1986). From grade, three boreholes (60′, 30′, and 15′) were augered along a transect towards the closest adjacent surface waters from the injection well. These monitor wells were cased with 2" PVC pipe (to also allow groundwater flow determinations, see below) and each casing had a 5′ section of .010 inch continuous slotted well screen at the bottom; annular space in these wells was packed with with coarse carbonate substrate.

These monitor wells meet or exceed published guidelines for monitor well installation for monitoring of dissolved inorganic nutrients as outlined by Driscoll (1986) and for groundwater flow determinations as suggested by Kerfoot (1986); well logs that contain details of the wells (e.g. grade and exact locations of wells) are available from the Monroe County Planning Department.

Sampling of Groundwaters

The monitor wells were sampled monthly following installation, which began in December 1986 and ended in September 1987. Initial groundwater samples were collected with a portable well point sampler (Kerfoot, 1984); after casing of the wells, either a submersible pump fitted with Tygon plastic tubing (for 2" I.D. monitor wells) or a peristaltic pump fitted with teflon tubing was used for sample extraction. Sampling protocal consisted of initially removing approximately 3-5 casing volumes prior to sample collection (Driscoll, 1986). All wellpoint sampler parts, pump tubing and fittings were rinsed with tap water between well samplings to prevent cross contamination of different groundwater samples.

Collection and preservation of the groundwater samples followed the methodologies suggested in Standard Methods (Greenberg, 1985). Specifically, protocal consisted of sample collection into acid-washed 1 liter Nalgene polyethylene containers, immediate determination of temperature (using a mercury thermometer) and salinity (using a Bausch and Lomb hand-held refractometer) and subsequent preservation with a biocide (10mg/l HgCl). The samples were held on ice in the dark until return to the laboratory where they were immediately filtered through a 0.45 μm Gelman glass fiber filter and either analyzed immediately for nutrient analysis or frozen for subsequent analysis (within 2 weeks).

Determination of Groundwater Flow Rate and Direction

To understand interactions of groundwaters with inshore surface waters, a knowledge of the direction and rate of horizontal subsurface flow is needed. Direct determinations of the rate and direction of groundwater flow were made at several locations on Big Pine Key using a Model 30 GeoFlo groundwater flowmeter (K-V Associates, Inc; Falmouth, MA). This flowmeter is a portable, self-contained system that allows direct measurement of the rate and direction of lateral flow of groundwater through permeable saturated geologies. The Model 30 GeoFlo flowmeter uses a submersible sensor consisting of a circular array of thermistors arranged around a central heat source. A five vector response is displayed on an LCD readout which, in combination with a calibration curve and vector worksheet, can allow determination of groundwater flow rate in the range of .03-500 ft/day (± 15%) and direction of groundwater flow (± 10%).

The accuracy and precision of the GeoFlo flowmeter is greatly affected by monitor well design and calibration of the flowmeter; therefore, procedures suggested by the manufacturer were closely followed (See Kerfoot, 1986). The GeoFlo flowmeter was deployed in 2" I.D. PVC monitor wells that had sections of slotted well screen inserted at desired depths below grade. This involved use transect are listed in Table 2 and locations are illustrated in Fig 6. Surface water samples collected from canals adjacent to the residential stations were handled in identical fashion to that described above for groundwater samples; however, the transect samples, which were also analyzed for chlorophyll-a, were not spiked with a biocide because of interference with the chlorophyll analysis.

Nutrient and Chlorophyll Analysis: Methodologies and Quality Assurance

Surface and groundwater samples were analyzed for dissolved inorganic nitrogen in the form of nitrate, nitrite and ammonium using a Technicon Autoanalyzer II system. Preliminary analyses indicated that nitrite was negligible compared to nitrate in groundwater and surface water samples at all stations; comparable results have also been reported for similar carbonate groundwaters and inshore waters of Bermuda (Simmons et al., 1984) and Jamaica (D'Elia et al., 1981). Therefore, we determined and report herein total nitrate and nitrite (referred to as nitrate, NO_3) using the copper-cadmium reduction method according to standard Technicon Industrial methodology (Technicon, 1973). The ammonium determinations were made using a modified phenol-hypochlorite method described by Slawyk and MacIssac (1972). Nutrient concentrations are reported in units of uM (= ug-at/l) to conform with the marine chemistry literature. The detection limit during these analyses was 0.10 μM for nitrate and 0.20 μM for ammonium.

Because phosphate appears to be the primary limiting nutrient in the nearshore Keys marine environment (Lapointe, 1987; Lapointe, 1988) and is present at very low concentrations (e.g. frequently < 30-50 nM), concentrations of soluble reactive phosphate (SRP) were determined using the highly sensitive manual method described by Strickland and Parsons (1977). This method is a modification of the Murphey and Riley (1962) molybdenum blue method and utilized a Bausch and Lomb Spectronic 88 spectrophotometer fitted with a 10 cm. cell for maximum sensitivity.

Quality assurance of our nutrient determinations is based on known internal standards that were analyzed regularly with all unknown samples. A continuous record of analyses of standards and recoveries was maintained and assures that our determinations were accurate and within acceptable upper and lower limits (EPA, 1972). Interlaboratory comparisons of unknown samples (available from EPA) indicated that mean recoveries for our nutrient determinations are excellent and range from 95-103% of stated EPA values.

Chlorophyll-a concentrations of seawater were determined using a Turner Designs Model 10 fluorometer that was calibrated using known concentrations of chlorophyll. A 800 ml seawater sample was filtered through a 0.45 μ Gelman glass fiber filter and analyzed for chlorophyll-a using a modified dimethyl sulfoxide (DMSO)-acetone method (Burnison, 1979). Immediately following filtration, the filters were placed in 10 mls DMSO in a cool, dark place to extract for one hour; following this, 15 mls of acetone was added. After two hours of further extraction, the samples were analyzed for fluorescence. Subsequent acidification with 10% HCL was also performed to correct for phaeophytin.

Statistical Analyses

Several hypotheses were tested in this study. First, to consider potential effects of OSDS on nutrient concentrations (ammonium, nitrate, and SRP) of groundwaters in the Florida Keys, groundwater nutrient concentrations of the eight residential monitor stations were compared to nutrient concentrations of of a high quality, continuous slotted well screen (Timco, sch 40, .010 inch slit width, 59 slots per foot), centralization of the well, and careful annular packing with washed, coarse carbonate substrate. Groundwater flow monitor wells were installed at several locations on Big Pine Key and included three wells at Halcyon Trailer Park (HTP, see above description of monitor well installation) as well as two wells (15′ and 30′) in the Key Deer National Wildlife Refuge (KDNWR) and one well (15′) in Port Pine Heights subdivision (PPH, See Table 1).

Calibration of the GeoFlo flowmeter involved use of a flow chamber packed with carbonate substrate similar to that surrounding the monitor wells (Miami Oolite) and a metering pump to provide controlled and variable flow rates. A typical calibration curve for the GeoFlo flowmeter in Miami Oolite substrate is illustrated in Fig 5; regression of the readout of the GeoFlo versus known rates of lateral flow allows rapid, on-site determination of groundwater flow rates. The five vector response is used with a worksheet to test for uniform cosine flow and then plotted on polar graph paper to determine direction of flow. Field logs for all groundwater flow determinations are available from Monroe County Planning Department.

Sampling of Surface Waters

During the monthly sampling at the eight residential monitor stations and the "Multi-Flo" station on Big Pine Key, samples of adjacent surface waters were also collected for determination of nutrient concentrations. Samples were collected either by hand using a 3 liter Nalgene container or using a 3.7 liter Niskin bottle sampler. Surface water samples were also collected at monthly intervals along an onshore-offshore transect extending from an inshore canal system (PPH) on Big Pine Key to Looe Key National Marine Sanctuary (LKNMS), located 5 miles south of Big Pine Key; the hydrographic stations along this the "control" station at the KDNWR. Specifically, the following null and alternative hypotheses were tested:

H_o: nutrient concentrations of groundwaters adjacent to OSDS are equal to those of groundwaters of the KDNWR.

H_A: nutrient concentrations of groundwaters adjacent to OSDS systems are greater than those ofgroundwaters of the KDNWR.

Second, to consider potential seasonal seepage of nutrients from groundwaters into the nearshore marine environment due to climatological forcing, nutrient concentrations (ammonium, nitrate, SRP) of groundwaters and nearshore marine waters (canal waters adjacent to sites) at the eight residential OSDS sites during winter (December-April) were compared to those of summer (May-September). Specifically, the following null and alternative hypotheses were tested:

H_o: nutrient concentrations of groundwaters during winter are equal to those of summer.

H_A: nutrient concentrations of groundwaters during summer are lower than those of winter.

H_o: nutrient concentrations of nearshore marine waters during summer are equal to those of winter

H_A: nutrient concentrations of nearshore marine waters during summer are higher than those of winter.

These *a priori* hypotheses were tested using the Kruskall-Wallis test, a conservative nonparametric test statistic. The experimental design involved comparisons of data within individual stations to reduce station-to-station variability and increase the power of these statistical tests. Because of the sensitivity of our nutrient analyses and the randomized block experimental design, we used a conservative alpha level of $P=0.05$ to represent the probability of making a Type I error; thus, significance reported in the results below indicates the probability of making an incorrect inference is <0.05 or less than 1 chance in 20.

RESULTS

Groundwater Nutrient Concentrations

Mean values and ranges for concentrations of ammonium, nitrate, and SRP as well as salinity and temperature of groundwaters sampled at monthly intervals between December 1986 and September 1987 from groundwater monitor wells at the eight septic sites and KDNWR are presented for winter and summer in Table 3. The highest groundwater nutrient concentrations generally occurred during winter at the septic locations; lower concentrations occurred at the midpoint locations and the lowest concentrations typically occurred in groundwaters of the KDNWR. Over the entire study, ammonium and nitrate concentrations ranged from 0.77 μM to 2.75 mM and 0.03 μM to 2.89 mM, respectively; SRP concentrations ranged from 0.06 μM to 107.4 μM (Table 3). Salinity of the groundwater samples ranged from 0% (fresh) to 45% ppt (hypersaline) and temperature ranged from a low of 21.0 ^{o}C in January to a high of 32.0 ^{o}C in August (Table 3).

Nutrient concentrations in groundwaters did not vary significantly between the Upper and Lower Keys, but an overall seasonal trend was evident.

Concentrations of ammonium, nitrate, and SRP in groundwaters from a majority of the monitor wells decreased significantly from winter to summer, 1987 (See Table 3). Overall, nutrient concentrations decreased from winter to summer in 8 out of 13 monitor wells for nitrate (Table 4), 7 out of 13 wells for ammonium (Table 5), and 8 out of 13 wells for SRP (Table 6). The average groundwater nutrient concentration (average of both septic and midpoint locations) during winter was 541 μM for ammonium, 494 μM for nitrate, and 10.3 μM for SRP; the average concentration during summer was 345 μM for ammonium, 125 μM for nitrate, and 4.0 μM for SRP (Table 3).

Nutrient concentrations of groundwaters at the KDNWR "control" station did not vary significantly from winter to summer and were consistently lower than nutrient concentrations characteristic of the residential stations. During winter, nutrient concentrations averaged 1.91 μM for ammonium, 0.76 μM for nitrate, and 0.11 μM for SRP; during summer, nutrient concentrations averaged 1.40 μM for ammonium, 0.20 μM for nitrate, and 0.14 μM for SRP (Tables 4-6).

A comparison of groundwater nutrient concentrations from the residential stations and the KDNWR station indicates significantly elevated nutrient concentrations on developed, residential lots with septic tank/drainfield systems. For example, concentrations of ammonium, nitrate, and SRP during winter were all significantly higher in residential groundwaters compared to groundwaters in the KDNWR in all 24 cases analysed; during summer, 17 out of 24 cases indicated significantly elevated nutrient concentrations in residential groundwaters compared to groundwaters of the KDNWR (Table 7). The various nutrients were enriched in residential groundwaters, relative to groundwaters of the KDNWR, some 625 to 650-fold for nitrate, 246 to 283-fold for ammonium, and 29 to 94-fold for SRP.

However, flow rates were greater in the deeper (30′) Key Largo Limestone formation, which averaged 3.7 ft/day and ranged from 3.38 to 4.10 ft/day; flow rates in the more shallow Miami Oolite (15′) averaged 0.38 ft/day and ranged from 0.0 to 0.75 ft/day.

Groundwater flow rates at the Halcyon Trailer Park monitor wells (15′, 30′, and 60′) averaged 2.2 ft/day and ranged from 2.17 to 3.38 ft/day; no differences in flow rate at different depths were apparent. However, at this station, direction of groundwater flow was different between the different depths; flow at 15′ was 197° or southwestward whereas flow at 60′ was 305° or northwestward (Table 10).

Surface Water Nutrient Concentrations and Chlorophyll

Mean values and ranges for concentrations of ammonium, nitrate, and SRP as well as salinity and temperature of surface waters sampled at monthly intervals between December 1986 and September 1987 from nearshore canal waters adjacent to the groundwater monitor wells at the eight residential sites and KDNWR are presented for winter and summer in Table 3. A significant seasonal trend opposite that of groundwaters was observed for the nearshore waters; consistently, the lowest nutrient concentrations occurred during winter and the highest occurred during summer (Table 4-6). For example, concentrations of nitrate ranged from 0.27 µM to 4.05 µM during winter and from 0.28 µM to 49.0 µM during summer; ammonium ranged from 0.15 µM to 2.39 µM during winter and from 0.33 µM to 6.92 µM during summer; SRP ranged from 0.03 µM to 0.35 µM during winter and from 0.12 µM to 1.60 µM during summer (Table 3).

In all 12 surface water samplings along the hydrographic transect, nutrient concentrations and chlorophyll consistently decreased towards offshore waters.

Nutrient concentrations of groundwaters adjacent to the "Multi-Flo" injection well were also significantly elevated compared to those of the KDNWR. During summer, concentrations of ammonium and SRP averaged 19.1 μM and 0.67 μM, respectively, about 5-fold higher than concentrations of 3.35 μM and 0.12 μM for ammonium and SRP, respectively, in KDNWR (Table 8). Concentrations of ammonium and SRP were approximately the same at different depths at the "Multi-Flo" site (15′ to 60′) whereas ammonium concentrations appeared to increase with depth at the KDNWR. Salinity increased with depth at both sites and waters at 60′ at the "Multi-Flo" site were always hypersaline (Table 8).

Groundwater Flow

Direct measurement of groundwater flow indicates that rainfall and tides affect the instantaneous lateral velocity of subsurface groundwater movements. At Port Pine Heights (PPH) on Big Pine Key, groundwater flow rate ranged between 0 and 5.0 ft/day during an ebbing tide on July 24 1987 with the lowest rates occuring during peak high tide and highest rates occuring during the ebbing tide (Fig 7); over the full 12 hrs of the ebbing tide, the flow rate averaged 2.3 ft/day (Table 10). On October 2 1987, groundwater flow rate at the same site during a flooding tide ranged between 2.8 and 12.1 ft/day with anomoulously high flow rates occurring between 2130 and 2300 hrs when a major rain event occurred (>1.0 inches of rain fell in 6 hrs; Fig 8); the average flow rate during this flooding tide was 5.5 ft/day (Table 9). During both groundwater flow studies, the direction of groundwater flow ranged between 163^{o} and 222^{o} and averaged 184^{o} or southward (Table 9).

Groundwater flow rates in the KDNWR monitor wells (15′ and 30′ wells) ranged from 0 to 4.10 ft/day and averaged 2.1 ft/day; the direction of flow at both depths was consistently between 71^{o} and 104^{o}, or eastward (Table 10).

Over all these samplings, concentrations of nitrate ranged from 0.08 µM (LKNMS) to 3.02 µM (PPH canal), ammonium ranged from 0.02 (LKNMS) to 0.94 µM (PPH canal), SRP ranged from 0.03 µM (LKNMS) to 0.29 µM (PPH canal) and chlorophyll ranged from 0.04 µg/l (LKNMS) to 0.78 µg/l (PPH canal; Table 11). Out of the twelve samplings, chlorophyll was significantly and positively correlated ($r > 0.70$) with SRP six times, with ammonium twice, and with nitrate three times (Table 12).

Chlorophyll concentrations were significantly greater during summer compared to winter in the nearshore waters during these studies. The mean chlorophyll concentration in PPH canal waters during summer was 0.62 µg/l (± 0.19, N =10), about three-fold higher than the winter mean value of 0.22 µg/l (± 0.08, N = 16).

DISCUSSION

OSDS as a Nutrient Source to Groundwaters and Nearshore Waters

Elevated nutrient concentrations in residential groundwaters compared to pristine groundwaters indicates that OSDS represent a significant source of nutrients to groundwaters in the Florida Keys. It is unlikely that the high concentrations of ammonium (2.5 mM), nitrate (2.5 mM) and SRP (100 μM) observed in residential groundwaters would result from a natural source such as the decomposition of leguminous matter, nitrogen fixation, or rainwater (D'Elia et al., 1981). That nutrient concentrations were generally higher at the septic locations compared to midpoint locations during the study clearly point to an anthropogenic source for these elevated nutrient concentrations. Furthermore, the highest nutrient concentrations observed in groundwaters during this study are typical of secondarily-treated wastewater, characterized by concentrations of 2 mM of inorganic nitrogen (either in the form of ammonium or nitrate, depending on the degree of oxidation of effluent) and 200 μM inorganic phosphate (Dunstan and Menzel, 1971). These high nutrient concentrations were also typical of effluents sampled from several aerobic treatment units ("Multi-Flo") during this study.

Our conclusion that elevated nutrient concentrations of groundwaters in residential areas of the Florida Keys are anthropogenic in origin are consistent with similar conclusions for groundwaters in Bermuda. Bermuda's groundwaters have highly elevated concentrations of nitrate due to high population densities and widespread use of cesspits for domestic wastewater disposal (Simmons et al., 1984). However, while the dominant nitrogenous form in Bermuda's groundwaters is nitrate, groundwaters of the Keys have higher mean concentrations of ammonium compared to nitrate; the mean concentration of nitrate in Bermuda's groundwaters is 749 μM (ammonium is negligible) compared to the Keys where the annual mean concentration of total inorganic nitrogen is 753 μM and consists of 310 uM nitrate and 443 μM of ammonium.

Accordingly, use of OSDS is resulting in cumulative increases in nutrient concentrations of groundwaters in the Keys. The mean SRP concentration of residential groundwaters (both midpoint and septic locations) was 10.3 μM during winter and 4.0 μM during summer, considerably higher than background SRP concentrations of 0.11 μM to 0.14 μM in the KDNWR during winter and summer, respectively. Thus, SRP concentrations of enriched groundwaters on residential sites of the Keys were on the order of 29- to 94-fold higher than background concentrations with an annual average of 60-fold higher SRP concentrations. For nitrogen, even higher enrichment occurred. The average total nitrogen concentration (ΣIN = ammonium and nitrate) on residential stations during winter was 1036 μM, compared to a lower value of 471 μM during summer. Relative to background concentrations in the KDNWR, this represents a 370 to 346-fold increase during winter and summer, respectively, with an annual average of 358-fold increase above background concentrations.

Elevated N:P molar ratios observed in enriched residential groundwaters during this study suggests that SRP is, to some extent, scavenged during subsurface flow through carbonate geologies. The N:P ratio of groundwaters (both the septic and midpoint locations) ranged from 94:1 to 147:1, much higher than the 10:1 molar ratio typical of domestic wastewater (Ryther and Dunstan, 1971). In carbonate geologies, SRP is well known to react and co-precipitate with calcium carbonate to form calcium carbonate-phosphate surface complexes and/or the mineral apatite; additionally, SRP can be scavenged by adsorption onto oxides of iron (II), iron (III), and aluminum (III) (Berner, 1981). In both oxic and anoxic sulfidic sediments, apatite formation is considered the dominant mineral sink of phosphate. The two primary minerals are fluroapatite

($Ca_5(PO_4)_3F$) and hydroxyapatite ($Ca_5(PO_4)_3OH$), with the fluoride-rich form being the predominant form in marine sediments (Berner, 1981). Consequently, concentrations of SRP are often low in natural carbonate-rich waters because of equilibrium with carbonate fluoroapatite (Gulbrandsen and Robertson, 1973). However, while removal of SRP by calcium carbonate in upland groundwaters appears to be efficient when based on N:P molar ratios, SRP is not completely removed from enriched groundwaters as described above by comparison of residential groundwaters to those of the KDNWR.

A knowledge of the relative importance of N vs. P limitation of plant growth in the Keys nearshore waters is needed to understand which of these nutrients associated with wastewater nutrient loading controls the eutrophication process. The most widely used approach to identify the relative importance of N vs. P limitation is through determination of N:P ratios of seawater and comparison of these ratios with those of marine plant populations. This approach is based on extensive analyses of marine plankton and dissolved inorganic nutrients, both of which indicate an average N:P ratio of 16:1 by atoms in oceanic waters (Redfield, 1958). Deviation of either marine plant composition or seawater nutrients from this ratio is then used as an indirect method to infer which nutrient element limits productivity; N:P ratios $< 10:1$ indicate N-limitation wheras ratios $> 30:1$ indicate P-limitation. While enriched groundwaters are clearly P-limited in that N:P ratios are typically > 94, surface waters in canals during this study had a mean N:P ratio of 14, dramatically lower than those of groundwaters. This pattern clearly suggests a trend towards N-limitation in marine waters, a finding consistent with general P-limitation in fresh waters and N-limitation in marine waters (Smith, 1984).

Despite the trend towards N-limitation between groundwaters and surface waters of the Keys, a variety of experimental and correlative data clearly indicate that nearshore waters of the Keys are limited primarily by P and secondarily by N. Frequent correlation of SRP and chlorophyll in the present study suggests that SRP is the primary nutrient limiting phytoplankton production, a conclusion also reported for phytoplankton on the northwest Florida continental shelf (Myers and Iverson, 1981). Experimental bioassays with marine macroalgae in nearshore waters of the Keys (Lapointe, 1987) and Florida Bay (Lapointe, 1988) also indicate primary limitation by P and secondary limitation by N; intense P-limitation was especially evident from highly-elevated carbon:phosphorus ratios (a mean of 1,555:1) in macroalgal tissue that are typically lower (550:1) in marine macrophytes (Atkinson and Smith, 1983). A similar predominance of P-limitation occurs in carbonate-rich waters of Shark Bay, Australia, (Smith and Atkinson, 1984) and contrasts precepts of N- rather than P-limitation of marine productivity in coastal marine waters (Ryther and Dunstan, 1971). Considering the relatively low cost of P-stripping compared to N-stripping in advanced wastewater treatment systems (Clark et al., 1977) and the predominance of P-limitation in oligotrophic Keys waters, P-stripping will offer particularly cost effective treatment compared to N-stripping to minimize eutrophication associated with wastewater nutrient loading.

We believe the dominance of ammonium rather than nitrate to the nitrogenous composition of groundwaters suggests generally low oxygen availability in groundwaters of the Keys. Ammonium represents the most reduced species of inorganic nitrogen and results from decomposition of organic matter in oxygen-depleted waters; in the presence of oxygen, ammonium is rapidly oxidized to nitrite and subsequently to nitrate by nitrifying bacteria. The apparent lack of adequate oxygen needed to support oxidation of nitrogen (e.g. ammonium) in OSDS wastewater in shallow groundwaters may be related to the generally limited vadose zone underlying drainfields in the Keys; an average of 12" of vadose zone (above mean high water) separates drainfields from the piezometric surface in the Keys. Groundwaters below the piezometric surface typically have low oxygen concentrations and impacts of organic waste loads causes suboxic or anoxic groundwaters (Iliffe et al. 1984). Consequently, biogeochemical zones (e.g. sulfide reduction zone that produces hydrogen sulfide) usually restricted to deeper anoxic zones in groundwaters will shift upward towards the piezometric surface, in a similar manner to organic-rich marine sediments (Champ et al., 1978; Baedecker and Back, 1979), thereby increasing the flux of hydrogen sulfide to the atmosphere. In contrast to ammonium-rich groundwaters enriched by septic tanks, the nitrogenous composition of effluents of the aerobic treatment units was dominated by nitrate, indicating a better-oxidized effluent. Possibly, a fraction of the nitrate derived from OSDS may be denitrified by bacteria in anoxic groundwaters and sediments (Capone and Bautista, 1985) and to some extent, this process could mitigate the effects of groundwater N-enrichment of surface waters.

The significant decrease of groundwater nutrient concentrations and parallel increase in nutrient concentrations of nearshore surface waters during summer suggests that nutrients derived from enriched groundwater discharge into adjacent surface waters in a seasonally-variable manner with maximum rates during summer. This finding contrasts the view that groundwater nutrient concentrations are relatively constant (Freeze and Cherry, 1979) and supports observations of increased ammonium and nitrate in nearshore waters of the Keys during summer months compared to winter (Lapointe, 1987; Lapointe, 1988). Based on elevated ammonium and total organic carbon concentrations in developed canals compared to undeveloped canals Hicks et al. (1975) also concluded that septic leachate enters surface waters and may be partially responsible for observed ecological imbalances in adjacent waters. Considering the significant seasonality of hydrological characteristics in the Keys, we below consider a variety of hydrological mechanisms that might regulate groundwater seepage to inshore receiving waters.

Mechanisms of Groundwater Seepage to Inshore Waters

In general, nutrients associated with fresh groundwaters enter adjacent surface waters primarily through horizontal groundwater flow, although inclined and vertical flow can also occur (Visher and Mink, 1964; Cooper, 1959; Kohout, 1960). The general direction of flow is offshore because of decreasing hydraulic gradients between the piezometric surface on land and sea level at adjacent inshore surface waters where seepage through canal walls or bottom sediments occurs. The instantaneous rate of groundwater flow is a function of porosity and permeability of the substrate and hydraulic head. Direct determination of groundwater flow rates in the Lower Keys (PPH) during summer 1987 indicated average instantaneous groundwater flow rates in Miami Oolite substrate of 2.8 ft/day (omitting higher flow rates during rain events), a value consistent with the known high porosity of this geology (bulk porosity of 40-60%; Evans, 1983). Distinctly lower flow rates were associated with Miami Oolite in the KDNWR on Big Pine Key where flow rates ranged from 0 to 0.75 ft/day, a finding consistent with the ability of this geology to support a Ghyben-Herzberg fresh water lens (Hanson, 1980).

Our observed decrease of dissolved nutrients in groundwater and simultaneous increase in adjacent surface waters during summer suggests that a seasonal hydrological mechanism enhances flow of nutrient-rich groundwaters into surface waters. Such a dramatic discharge would require enhanced lateral groundwater flow during summer compared to winter, and would be best explained by increased hydraulic head (and therefore, hydraulic conductivity) of groundwater during summer compared to winter. Recharge to groundwaters of the Keys is seasonally maximum during the "wet" summer and early fall in the Keys when the bulk of annual rainfall occurs and high humidity results in low evaporation/evapotranspiration rates. The typical seasonal rainfall pattern did not occur during this study and there was no significant seasonal correlation between rainfall and groundwater nutrient concentrations ($r = -0.25$ for ammonium and nitrate; $r = -0.23$ for SRP); however, evapotranspiration potential (estimated from dew point data) was inversely and significantly correlated ($r^2 = 0.78$; Fig 9) with mean monthly groundwater nutrient concentrations. This finding could explain the observed seasonal pattern of groundwater and surface water nutrients; increased recharge, hydraulic head, and offshore flow of nutrient enriched Keys groundwaters would occur during summer when the minimum seasonal evapotranspiration from groundwaters occurs. This possibility of enhanced dispersion of nutrients during summer is directly supported by monthly average sea level and groundwater table height data reported by Hanson (1980) for Big Pine Key and illustrated in Fig 10; the increased hydraulic head during summer and early fall would support increased offshore lateral flow compared to reduced hydraulic head and flow during winter and early spring.

However, seasonal patterns in tide height also correlated significantly and inversely ($r = -0.71$ for nitrate and ammonium, $r = -0.75$ for SRP) with our observed patterns for dissolved nutrients (Fig 9), suggesting that increased mixing with shallow drainfield nutrient plumes could also be involved with the seasonal discharge of nutrients. Sea level is generally acknowledged as the dominant component of fluctuations of groundwater surfaces on carbonate oceanic islands (Hanson, 1980; Rowe, 1984), although rainfall becomes the more important factor during periods of heavy rain (Hanson,1980). Annual variations of 0.8' in sea level occur in the Keys in response to astronomical, isostatic, and mass transfer effects (Marmer, 1954; Pattullo, 1963) and results in maximum sea levels and groundwater tables during summer -- also the period of maximum groundwater recharge. Consequently, the seasonal maximum in groundwater flow during summer and fall would coincide with enhanced mixing of groundwaters with nutrient rich drainfield plumes. Accordingly, increased inclined flow (Visher and Mink, 1964) and subsurface dispersion (Cooper, 1959; Kohout, 1960) of enriched groundwaters towards nearshore surface waters would result. Such a seasonal mechanism for enhanced mixing of groundwaters and surface waters is further supported by the elevated salinities commonly observed in groundwaters of the Keys during summer as compared to winter (Table 3).

While groundwater seepage may vary seasonally as a function of recharge and hydraulic head and regulate seasonal patterns in discharge of nutrients to inshore waters, the most dramatic increases in groundwater flow occurs on shorter time scales (i.e. hours-days) during rain events. Lateral groundwater velocities up to 12 ft/day occurred during rain events, causing rapid increases in groundwater discharge to inshore waters that were some 5- to 7- fold higher than background flow rates. The rapid flow response and lack of long lag periods of increased flow is consistent with the high porosity and permeability of carbonate geologies of the Keys. This finding also explains the phytoplankton blooms that often follow major rain events in inshore waters of the Keys, clearly an ecological response to pulsed nutrient input to these highly nutrient-limited waters.

The direction of lateral, shallow groundwater flow appears to be related primarily to the direction of the hydraulic gradient as affected by natural elevation grades and not necessarily by anthropogenic changes. For example, groundwater flow at the PPH residential station on Big Pine Key was consistently

(14 determinations over 3 months) southerly, the direction of decreases in natural grade, even though the adjacent surface water body (canal) was 50′ to the west of the flow monitor well. Previous studies using Rhodamine dye injections into septic tanks on Big Pine Key failed to detect septic leachate entering adjacent canal waters (Hicks et al., 1975), quite possibly because the surface waters sampled for dye intrusion were not downstream of the groundwater flow from the septic tank drainfield. Future dye studies in the Keys need to obtain preliminary information regarding natural subsurface flow patterns to support the assumptions generally made in such tracer dye studies.

Patterns and Effects of Nutrient Flux to Nearshore Waters of the Keys

By assuming an average groundwater flow rate and distance to probable receiving waters (not necessarily the closest surface water), the travel time of nutrients associated with groundwaters towards surface waters can be estimated. For example, assuming an average flow rate of 2.0 ft/day for nutrients associated with groundwaters and an average distance of 350′ to nearshore waters typical of the OSDS in our study, a travel time of approximately 0.5 yrs would be required for discharge of new septic-derived nutrients into surface waters. This suggests that seasonally increased nutrient input to groundwaters during the winter tourist season would require about 6 months before discharge to nearshore waters, resulting in "delayed discharge". This seasonal oscillation of nutrient enrichment is supported by recent *in situ* nutrient limitation bioassays with the red macroalga *Gracilaria* in waters adjacent to Big Pine Key that indicated N-limitation during winter but not summer because of elevated concentrations of ammonium and nitrate in Pine Channel during summer months (Lapointe, 1987; Lapointe, 1988). Considering that irradiance and temperature are also maximum during summer, conditions favorable for phytoplankton blooms past ten years in response to nutrient enrichment by groundwater seepage resulting from widespread use of unlined cesspits (Lapointe and O´Connell, 1988); this has resulted in reduced species diversity and loss of habitat for the commercially-valuable Calico clam (von Bodungen et al., 1982). In addition, cave systems that border Harrington Sound - some of Bermuda´s major tourist attractions - have become anoxic due to groundwaters contaminated with organic matter and is resulting in extinction of entire species of cavernicolous fauna (Iliffe et al., 1984). In general, aquatic ecosystems that have high species diversity contain more complex patterns of energy flow between trophic levels and represent more stable ecosystems compared to simpler, less diverse communities (Odum, 1971). Thus, reduction of benthic community diversity by nutrient enrichment may reduce the stability of the Keys marine ecosystem. In addition, reduced diversity will reduce the number and alter the quality of prey items available to consumers (i.e. detritavores and herbivores) and consequently food chain production.

Excessive enrichment could also enhance phytoplankton blooms that could inhibit growth of deep seagrasses by reduction of submarine light intensity. Caperon et. al. (1971) have documented increases in phytoplankton standing crop and physiological response to increasing nutrient concentrations during a decade of eutrophication caused by a municipal sewage outfall in Kaneohe Bay, Hawaii. Similarly, the significant correlation of phytoplankton chlorophyll and dissolved nutrients, particularly SRP, during our study suggests that cumulative nutrient enrichment of inshore waters of the Keys will also result in a trend toward increased phytoplankton biomass and "greening" of the nearshore waters. Because the lower depth limit of seagrasses is set by light availability (Dennison, 1987), increased phytoplankton biomass, which reduces submarine light quality and quantity, will result in loss of the deeper seagrass beds. As deeper seagrass beds deteriorate, their nutrient mass, including the elevated nutrients associated with their pore waters, will also become available to phytoplankton and will exacerbate the eutrophication process. Thus, the loss of seagrasses in many developing coastlines of the world, such as Chesapeake Bay (Orth and Moore, 1983), can become autocatalytic because of the major role of seagrasses to nutrient cycling and storage in coastal ecosystems (Zieman, 1982). Phytoplankton blooms resulting from sewage enrichment of Hillsborough Bay, Tampa, caused widespread loss of seagrasses and replacement by the red alga _Gracilaria_ (Taylor et al., 1973), a macrophyte that is more tolerant of low light, high nutrient environments (Lapointe and Duke, 1984).

Increased concentrations of nutrients and phytoplankton chlorophyll are also well known to degrade coral reef ecosystems (Johannes, 1975). Not only do reef corals become stressed by decreased light quality and quantity resulting from increased phytoplankton biomass, but increased nutrient concentrations themselves enhance the growth of fleshy, frondose macroalgae that can outcompete slower growing reef corals and coralline algae (Lapointe et al., 1987). In addition, elevated nutrient concentrations directly inhibit coral growth. For example, in enrichment studies on the Great Barrier Reef, calcification rates of dominant reef corals were suppressed by > 50% (Kinsey and Davies, 1979); the mechanism involved appears to be that SRP is a poison of crystal formation in that it blocks calcification (Simkiss, 1964).

Increased nutrient concentrations of Keys waters could also lead to conditions favoring the growth of the toxic red tide dinoflagellate species. Blooms of red tide species are increasing world-wide in waters adjacent to developing coastlines, suggesting that run-off derived from mans activities favor initiation of these devastating blooms. Red tides composed of the species _Gymnodinium_ _breve_ on the east coast of Florida in 1972 originated from seed that was carried from the west coast of Florida through the Keys to the east coast (Murphy et al., 1975); this suggests that potential seeding of the Keys waters with red tide organisms already exists but that previous environmental conditions have not favored blooms in Keys waters. Anoxic conditions of bottom waters is one environmental factor known to favor growth of red tide organisms (Hirayama and Iizuka, 1975) as is the stimulating effects of nutrient enrichment from wastewater (Doig and Martin, 1974).

While the effects of nutrient enrichment will be realized most severely in canal systems that have poor flushing characteristics, our hydrographic studies suggest that subtle but significant effects can also be realized in waters as far offshore as the Florida Reef Tract. In virtually all our transect studies, nutrient concentrations and chlorophyll increased measurably towards land from LKNMS, suggesting that effects of nutrient enrichment and/or elevated chlorophyll concentrations can impact the reef tract. This is directly supported by nutrient-limitation bioassays at LKNMS that found non-nutrient limited growth of several macroalgae during summer months when nutrient concentrations were elevated seasonally; while some of these nutrients might be associated with shelf-break upwelling, tidal flow of enriched high-chlorophyll surface water towards LKNMS from the lower Keys (i.e Florida Bay) is also thought to be a significant nutrient source (Littler et al., 1986; Lapointe and Smith, 1987). The recent proliferation of black-band disease (caused by enhanced growth of the blue-green alga Phormidium) on reef corals as well as the massive coral bleaching at LKNMS during the previous summers may well be the barometers of deteriorating nearshore water quality due, in part, to eutrophication.

Although many consider that continental shelf and bay waters of the Keys flush adequately so dramatic effects of eutrophication will not be realized on a large system-wide scale (e.g. see Jaap, 1984), the shallow shelf waters of the will also result. A similar delayed discharge of nutrients occurs on Cape Cod, MA, where nutrients introduced to groundwaters during the summer tourist season are discharged to surface waters during winter (Dr. William Kerfoot, personal communication).

The effects of increased nutrient seepage to nearshore waters of the Keys will be cumulative enhancement of natural eutrophication processes. Because the productivity and nutrient dynamics of inshore waters of the Keys are controlled to a large extent by benthic macrophytes that are themselves nutrient limited (Lapointe, 1987; Lapointe, 1988), increases in biomass of some inshore marine macrophytes, both seagrasses and macroalgae, will undoubtedly occur. The significant increase in groundwater nutrient concentrations found in the present study suggests that previous nutrient enrichment has already enhanced seagrass and macroalgal growth rates in the shallow inshore environment where high light intensities induce nutrient limitation (Lapointe and Duke, 1984). This enrichment could be responsible, in large part, for the extensive seagrass and macroalgal biomass that is sloughed by natural processes (wind, dessication during low tides) and accumulates in canals and along windward shorelines; as this extensive biomass decomposes, dissolved oxygen is reduced and hydrogen sulfide increased in adjacent waters.

Several examples serve to illustrate the initially subtle but often devastating ecological imbalances that cultural eutrophication can have on the diversity and stability of benthic communities in marine ecosystems. Reef corals in Kaneohe Bay, Hawaii, slowly became overgrown with the green "bubble alga" *Dictyospheria* that bloomed in response to nutrient enrichment from a secondary sewage outfall; diversion of the sewage outfall to an offshore location has since partially restored water quality (Smith, 1981). In inshore waters of Bermuda, the green alga *Cladophora prolifera* has increased dramatically over the

Keys are in fact "low energy" systems (Tanner, 1960) and are not mixed and diluted to the same extent that "high energy" systems typical of waters offshore the Florida Reef Tract are. Consequently, cumulative impacts of "new" nutrients entering nearshore waters through groundwater seepage, which can represent 20 to 50% of "new" nutrient input in coastal marine ecosystems (Capone and Bautista, 1985; Johannes, 1980), could accumulate and recycle within the system (Nixon, 1981). The resulting annual phytoplankton blooms during summer could become successively more severe. Considering that primary production in the Keys is to a large extent dominated by diverse benthic communities (i.e. seagrasses and macroalgae), increased nutrient seepage into the water column will favor a shift of the ecosystem towards a more unstable phytoplankton based system; such a shift could have devastating effects on biological diversity and food chain production in this ecosystem.

CONCLUSIONS

Continued development and use of OSDS will pose an ever-increasing threat to water quality in the Florida Keys. The contamination of groundwaters with high concentrations of nutrients and seepage of groundwaters into surface waters will enhance eutrophication in this highly nutrient-limited system. In addition to nutrients, groundwaters in the Keys could also be contaminated by a spectrum of synthetic organic and metal pollutants. High density zoning, porous and permeable geologies, and close proximity to oligotrophic waters exacerbate the impacts of OSDS on water quality of nearshore waters. While future central sewage collection could help to mitigate the depletion of oxygen in groundwaters otherwise impacted by organic wastes from OSDS, the effluents from central sewage systems will also add nutrients to the nearshore environment unless specific measures for nutrient control in nearshore waters, such as tertiery waste treatment (nutrient stripping) or placement of outfalls in offshore locations, is practiced. Because the stability of the unique and sensitive marine communities (coral reefs, seagrass beds) in the Keys are dependant upon oligotrophic water quality conditions, continued enrichment could have devastating cumulative effects. Current class III water quality criteria do not prevent the often subtle nutrient enrichment that occurrs from OSDS, and improved criteria (and enforcement) to protect groundwaters and surface waters are clearly needed if effective environmental protection of sensitive marine communities and resources are to be achieved.

RECOMMENDATIONS

1) Although this study provides significant and important baseline information, there are many obvious limitations that suggest further study:

   a) while the study included 9 months of sampling, by design, seasonal studies should include two full natural cycles to address year to year variation; thus, extension of this sampling for another full natural cycle would be appropriate.

   b) site-specific sampling should be initiated using a wellpoint sampler and plume-tracking methods to characterize the three-dimensional shape of septic plumes associated with OSDS.

   c) seasonal studies should be performed to characterize seasonal changes in plume characteristics as well as how variable groundwater flow, as affected by tides and groundwater recharge, affects movement and nutrient concentrations of these plumes.

2) The nearshore and offshore waters of the Florida Keys support a biologically diverse marine ecosystem comprised of coral reefs (bank reefs, patch reefs) and seagrass communities that are known to be sensitive to eutrophication; furthermore, these marine resources are major elements of the Monroe County's economy (tourism and commercial fishing) and are responsible for designation of the Keys as an area of "critica state concern". Accordingly, a State of Florida legislative initiative should be adopted to specifically assess existing water quality and its relationship to potential loss of fundamental marine resources such as seagrass beds and reef corals. This study could also include assessment of marine algae (macroalgae and phytoplankton) that could be used as "indicator" species of eutrophication.

3) Currently, numerous products (e.g. detergents) are available to the consumer in Monroe County that contain elevated levels of phosphorus. Because of primary enhancement of eutrophication by phosphorus in the Keys nearshore waters, improved state and local control of such products would significantly and immediatly reduce the impact of wastewater loading on eutrophication of the Keys waters.

4) Cumulative impacts of nutrients associated with OSDS as well as ancillary but related sources, should be objectively and quantitatively assessed on an areal basis as a step in the planning and permitting of development of upland recharge areas of any inshore or nearshore waters that are to be given the highest degree of environmental protection. The following standards, adapted from the Planning Board of the Town of Falmouth, MA, are given as an example:

a) Loading per person: 5 lbs nitrogen/person/year and 0.25 lbs phosphorus/person/year for OSDS within 300 ft of shoreline. Average number of persons per dwelling unit = 3.0

b) Loading from lawn fertilizers: 3 lbs nitrogen/1000 ft^2/year

c) Loading from road runoff: 0.19 lbs nitrogen/curb mile/day; 0.15 lbs phosphorus /curb mile/day

d) Critical marine eutrophic levels: 16 lbs N/40,000ft^2/yr

While the above per capita loading rates represent a long-term national average, the critical eutrophic levels cited above are specific to Cape Cod waters (i.e. nitrogen-limited marine waters compared to phosphorus-limited waters in the Keys). We recommend that studies be performed to provide a quantitative data base assessing phosphorus loading on a variety of Keys inshore environments; this would provide accurate critical eutrophic levels specific to inshore marine waters of the Keys, waters that are clearly more sensitive to nutrients than those of Cape Cod, MA.

5) A study should be initiated to consider cost/benefit relationships of various types of waste treatment options for the unique Keys environment that will effectively minimize eutrophication of Keys nearshore waters. Such a study should consider:

a) increased use of centralized waste collection and tertiery treatment (nutrient stripping) for high density areas that clearly are in excess of critical eutrophic levels as cited above. However, without nutrient stripping of this wastewater, there will be little benefit because direct input of a nutrient-rich secondarily-treated effluent to surface waters will result in severe eutrophication (e.g. Kaneohe Bay, Hawaii, Smith, 1981).

b) improved OSDS such as the alternate sewers described by Godfrey, (1986).

c) central collection of wastewater (domestic and stormwater) coupled to ocean outfalls (Officer and Ryther, 1977) such as that used to divert sewage effluent from Kaneohe Bay, Hawaii, that could effectively mitigate and improve nearshore water quality

6) Currently, little baseline data is available to document the degree and extent of eutrophication in nearshore waters of the Florida Keys. Therefore, a monitoring study should be initiated to specifically address subtle increases in nutrients and chlorophyll in nearshore waters. Such a study should use highly sensitive methodology to assess the broad temporal (seasonal) and spatial (high density versus low density areas of the Keys) variability of water quality in the generally oligotrophic waters of the Keys. The effects of stormwater runoff and groundwater seepage as nutrient sources should be specifically assessed by time series sampling.

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TABLE 1. Key to abbreviations for groundwater monitoring stations.

ABBREVIATION	STATION
KDNWR	Key Deer National Wildlife Refuge
PPH	Port Pine Heights, Big Pine Key, FL
EP	Eden Pines, Big Pine Key, FL
DA	Doctor's Arm, Big Pine Key, FL
WP	Whispering Pines, Big Pine Key, FL
DL	Dodge Lake, Marathon, FL
YT	Yellow Tail, Marathon, FL
TH	Treasure Harbor, Plantation Key, FL
OS	Ocean Shores, Key Largo, FL

TABLE 2. Hydrographic monitoring stations and locations in nearshore waters of Big Pine Key, FL.

STATION	LOCATION	LAT/LON
1	Port Pine Heights finger canal	$24^{\circ}42.88'$N $81^{\circ}23.87'$W
2	Port Pine Heights main canal	$24^{\circ}42.86'$N $81^{\circ}23.88'$W
3	South Pine Channel	$24^{\circ}41.58'$N $81^{\circ}24.50'$W
4	Munson Island	$24^{\circ}38.30'$N $81^{\circ}23.64'$W
5	Hawks Channel	$24^{\circ}34.13'$N $81^{\circ}23.62'$W
6	Looe Key National Marine Sanctuary Back Reef	$24^{\circ}32.90'$N $81^{\circ}23.46'$W
7	Looe Key National Marine Sanctuary Fore Reef	$24^{\circ}31.96'$N $81^{\circ}24.22'$W

TABLE 3. Mean values and ranges for nutrient concentrations (μM), temperature (°C) and salinity (o/oo) at canal, midpoint and septic locations in winter vs. summer. Groundwater represents the average of the the midpoint and septic values. Values represent means ± standard deviation.

LOCATION	N		NO3	NH4	SRP	N:P	TEMPERATURE	SALINITY
WINTER								
CANAL	32	MEAN	1.61 ± 0.55	0.88 ± 0.29	0.15 ± 0.05	16.6	25.5 ± 3.1	37.1 ± 2.1
		RANGE	0.27-----4.05	0.15-----2.39	0.03----0.35		19.0--30.1	33.0--42.0
MIDPOINT	28	MEAN	118.25 ± 179.89	256.94 ± 325.88	2.54 ± 2.83	147.7	25.2 ± 1.9	4.7 ± 3.4
		RANGE	0.03---545.45	3.61--2750.34	0.12---13.79		21.0--30.0	0.5--12.0
SEPTIC	32	MEAN	817.36 ±1052.80	784.89 ± 808.27	17.00 ± 26.85	94.3	26.0 ± 1.9	3.3 ± 3.9
		RANGE	6.69--2896.70	32.41--2417.79	0.14--107.39		21.0--29.3	0.0--19.0
GROUNDWATER		MEAN	467.81 ± 494.34	520.92 ± 373.32	9.77 ± 10.22	101.2	25.6 ± 0.6	4.0 ± 1.0
		RANGE	0.03--2896.70	3.61--2417.79	0.12--107.39		21.0--30.0	0.0--19.0
SUMMER								
LOCATION	N		NO3	NH4	SRP	N:P	TEMPERATURE	SALINITY
CANAL	30	MEAN	3.22 ± 8.38	1.69 ± 1.48	0.43 ± 0.38	11.4	30.7 ± 1.3	40.9 ± 2.1
		RANGE	0.28----49.02	0.33-----6.92	0.12----1.60		28.5--33.9	37.0--45.0
MIDPOINT	26	MEAN	30.76 ± 89.91	188.45 ± 306.32	1.63 ± 2.78	134.5	27.9 ± 1.9	15.2 ±12.4
		RANGE	0.04---409.02	0.77--1046.95	0.09---14.14		25.5--32.0	1.0--45.0
SEPTIC	30	MEAN	220.12 ± 482.13	502.97 ± 784.07	6.37 ± 16.28	113.5	28.1 ± 1.7	11.6 ±11.9
		RANGE	0.10--1969.71	3.60--2579.00	0.06---85.34		25.5--31.5	1.0--44.5
GROUNDWATER		MEAN	125.44 ± 133.89	345.71 ± 222.40	4.00 ± 3.35	117.8	28.0 ± 0.1	13.4 ± 2.5
		RANGE	0.04--1969.71	0.77--2579.00	0.06---85.34		25.5--32.0	1.0--45.0

TABLE 4. Statistical analysis (Kruskal-Wallis test) of summer vs. winter nitrate concentrations (μM) at residential sites and a control site at Key Deer National Wildlife Refuge. Values represent means ± standard deviation.

STATION	LOCATION	$\overline{X}$ SUMMER	N	$\overline{X}$ WINTER	N	P
PPH	CANAL	2.00 ± 1.41	10	1.71 ± 1.35	10	N.S.
	MIDPOINT	164.73 ± 212.56	6	258.46 ± 187.79	10	N.S.
	SEPTIC	1.17 ± 1.09	8	18.77 ± 10.04	10	<.001
EP	CANAL	1.32 ± 0.36	8	1.02 ± 0.32	10	N.S.
	MIDPOINT	0.57 ± 0.36	8	4.55 ± 2.62	10	<.001
	SEPTIC	196.49 ± 385.52	8	66.77 ± 71.77	10	N.S.
DA	CANAL	14.65 ± 23.20	8	1.31 ± 0.73	10	N.S.
	MIDPOINT	0.85 ± 0.83	6	277.25 ± 303.57	10	.001
	SEPTIC	393.91 ± 783.84	8	1989.61 ± 909.59	10	.004
DL	CANAL	2.21 ± 1.99	8	0.47 ± 0.55	10	.047
	MIDPOINT	2.03 ± 3.13	8	9.02 ± 11.92	10	N.S.
	SEPTIC	2.54 ± 2.42	8	350.28 ± 527.79	10	<.001
WP	CANAL	0.98 ± 0.49	8	2.18 ± 1.63	8	N.S.
	MIDPOINT	2.93 ± 2.10	8	8.58 ± 4.89	8	.019
	SEPTIC	340.60 ± 244.70	8	197.07 ± 249.98	8	N.S.
YT	CANAL	4.32 ± 4.27	8	2.43 ± 1.04	8	N.S.
	SEPTIC	496.33 ± 982.26	8	2742.03 ± 150.83	8	.001
TH	CANAL	1.05 ± 0.63	8	1.65 ± 1.00	8	N.S.
	MIDPOINT	53.92 ± 105.97	8	6.93 ± 10.88	8	N.S.
	SEPTIC	194.35 ± 385.22	8	506.59 ± 842.36	8	.034
KDR	CONTROL	0.20 ± 0.23	8	0.76 ± 1.20	12	N.S.

N.S. = P>0.05

TABLE 5. Statistical analysis (Kruskal-Wallis test) of summer vs. winter ammonium concentrations (μM) at residential sites and a control site at Key Deer National Wildlife Refuge. Values represent means ± 1 standard deviation.

STATION	LOCATION	$\bar{X}$ SUMMER	N	$\bar{X}$ WINTER	N	P
PPH	CANAL	1.88 ± 1.33	10	0.62 ± 0.21	10	.003
	MIDPOINT	11.18 ± 9.95	6	16.38 ± 12.41	10	N.S.
	SEPTIC	37.73 ± 3.46	8	83.89 ± 59.62	10	.001
EP	CANAL	1.74 ± 0.45	8	0.84 ± 0.13	10	<.001
	MIDPOINT	16.49 ± 11.13	8	23.63 ± 9.99	10	N.S.
	SEPTIC	2311.19 ± 252.22	8	2146.90 ± 473.46	10	N.S.
DA	CANAL	2.69 ± 2.95	8	0.81 ± 0.51	10	.035
	MIDPOINT	200.71 ± 132.34	6	62.86 ± 43.89	10	.016
	SEPTIC	743.08 ±1175.76	8	1415.57 ± 778.03	10	N.S.
DL	CANAL	0.83 ± 0.83	8	0.50 ± 0.23	10	N.S.
	MIDPOINT	19.21 ± 13.22	8	27.71 ± 10.29	10	N.S.
	SEPTIC	28.99 ± 7.09	8	201.57 ± 224.91	9	.007
WP	CANAL	2.24 ± 1.72	8	1.03 ± 1.03	8	N.S.
	MIDPOINT	188.10 ± 59.39	8	137.80 ± 51.25	8	.018
	SEPTIC	507.51 ± 191.99	8	259.79 ± 176.84	8	N.S.
YT	CANAL	1.35 ± 1.32	8	0.96 ± 0.75	8	N.S.
	SEPTIC	156.0 ± 274.36	8	254.50 ± 169.63	8	N.S.
TH	CANAL	1.55 ± 0.75	8	1.40 ± 0.67	8	N.S.
	MIDPOINT	939.86 ± 109.74	8	146.12 ± 9.00	8	N.S.
	SEPTIC	603.54 ± 198.55	8	1588.40 ± 400.84	8	.001
KDR		1.40 ± 0.48	8	1.91 ± 1.39	12	N.S.

N.S. = P>0.05

TABLE 6. Statistical analysis (Kruskal-Wallis test) of summer vs. winter soluble reactive phosphate (μM) concentrations at residential sites and a control site at the Key Deer National Wildlife Refuge. Values represent means ± 1 standard deviation.

STATION	LOCATION	$\overline{X}$ SUMMER	N	$\overline{X}$ WINTER	N	P
PPH	CANAL	0.32 ± 0.21	8	0.08 ± 0.02	10	<.001
	MIDPOINT	0.43 ± 0.17	8	0.97 ± 0.78	10	N.S.
	SEPTIC	0.15 ± 0.07	8	0.92 ± 0.81	10	<.001
EP	CANAL	0.30 ± 0.18	8	0.13 ± 0.03	10	.008
	MIDPOINT	0.23 ± 0.17	8	0.86 ± 0.97	10	.016
	SEPTIC	18.16 ± 7.62	8	65.82 ± 38.07	10	.029
DA	CANAL	0.94 ± 0.66	8	0.19 ± 0.09	10	.008
	MIDPOINT	2.14 ± 0.65	8	4.92 ± 3.05	10	.031
	SEPTIC	2.26 ± 0.86	8	5.46 ± 2.32	10	.001
DL	CANAL	0.25 ± 0.15	8	0.15 ± 0.06	10	N.S.
	MIDPOINT	6.05 ± 5.40	8	7.15 ± 4.08	10	.029
	SEPTIC	0.84 ± 0.72	8	0.77 ± 0.37	10	.001
WP	CANAL	0.68 ± 0.64	8	0.12 ± 0.02	8	.002
	MIDPOINT	0.70 ± 0.18	8	0.50 ± 0.18	8	N.S.
	SEPTIC	0.23 ± 0.14	8	0.51 ± 0.21	8	.006
YT	CANAL	0.35 ± 0.17	8	0.15 ± 0.07	8	.011
	SEPTIC	24.73 ± 40.54	8	44.53 ± 32.94	8	N.S.
TH	CANAL	0.37 ± 0.11	8	0.22 ± 0.06	8	.015
	MIDPOINT	0.44 ± 0.18	8	0.76 ± 0.43	8	N.S.
	SEPTIC	0.67 ± 0.88	8	1.08 ± 1.02	8	N.S.
KDR	CONTROL	0.14 ±0.11	8	0.11 ± 0.02	12	N.S.

N.S.= P>0.05

TABLE 7. Statistical analysis (Kruskal-Wallis test) to determine differences in nutrient concentrations at residential stations and the control station at Key Deer National Wildlife Refuge. Values represent the probability that no difference exists between residential sites and the control station; N.S.= not significant (P >.05).

LOWER KEYS

	WINTER				SUMMER		
LOCATION	NO3	NH4	SRP	LOCATION	NO3	NH4	SRP
PPHM	<.001	.001	<.001	PPHM	.002	.117	.002
PPHS	<.001	<.001	<.001	PPHS	.012	.001	N.S.
EPM	<.001	<.001	<.001	EPM	N.S.	.056	N.S.
EPS	<.001	<.001	<.001	EPS	N.S.	.001	.001
DAM	<.001	<.001	<.001	DAM	.037	.002	.001
DAS	<.001	<.001	<.001	DAS	.001	.001	.001
WPM	.001	<.001	<.001	WPM	.001	.001	.001
WPS	<.001	<.001	<.001	WPS	.001	.001	N.S.

UPPER KEYS

	WINTER				SUMMER		
LOCATION	NO3	NH4	SRP	LOCATION	NO3	NH4	SRP
DLM	.045	<.001	<.001	DLM	N.S.	.001	.001
DLS	<.001	<.001	.008	DLS	.012	.001	N.S.
THM	.008	<.001	<.001	THM	.055	.001	.004
THS	<.001	<.001	<.001	THS	.003	.001	N.S.
YTS	<.001	<.001	<.001	YTS	.003	.001	.001
OSM	---	---	---	OSM	.002	.006	.002
OSS	---	---	---	OSS	.019	.002	.002

TABLE 8. Mean values for nutrients (μM) and salinity (parts per thousand) for Halcyon Trailer Park and Key Deer National Wildlife Refuge. Values represent ± 1 standard deviation.

LOCATION	NO_3	NH_4	SRP	SALINITY
KDNWR-30´	0.07 ± 0.02	5.67 ± 7.00	0.12 ± 0.08	2.0 ± 0.0
KDNWR-60´	0.33 ± 0.21	1.03 ± 0.46	0.13 ± 0.12	0.3 ± 0.6
HTP-MF	2691.29 ± 518.15	203.29 ± 342.33	117.06 ± 6.46	2.9 ± 2.7
HTP-60´	0.13 ± 0.04	17.96 ± 4.37	0.74 ± 0.38	41.8 ± 2.9
HTP-30´	0.29 ± 0.24	19.05 ± 7.34	0.93 ± 0.50	39.5 ± 1.1
HTP-15´	2.63 ± 4.11	20.29 ± 8.49	0.34 ± 0.18	22.2 ± 7.1
HTP-Open Water	0.44 ± 0.19	0.91 ± 0.94	0.35 ± 0.17	42.6 ± 3.0

TABLE 9. Rate and direction of groundwater flow during a flooding and ebbing tide at Port Pine Heights, Big Pine Key, FL. * Denotes occurrence of a heavy rain event.

LOCATION	DATE	TIME	TIDE	RATE(ft/d)	DIRECTION
PPH	7-24-87	1215	Flooding	2.58	199°
		1345	High	0.00	-----
		1515	Ebbing	2.21	193°
		1800	Ebbing	5.00	188°
		1930	Ebbing	2.64	163°
		2130	Ebbing	1.52	176°
		2300	Low	2.08	181°
PPH -- Average			Ebbing	2.29	183°
PPH	10-02-87	1830	Low	2.83	190°
		2130	Flooding	12.10*	222°
		2300	Flooding	9.68*	160°
	10-03-87	0320	Flooding	4.19*	172°
		1130	High	3.32	187°
		1500	Ebbing	3.73	174°
		2230	Low	2.83	190°
PPH -- Average			Flooding	6.40	185°

* Heavy rain event

TABLE 10. Rate and direction of groundwater flow at Halcyon Trailer Park (HTP) and the Key Deer National Wildlife Refuge (KDNWR) at different depths and tides.

LOCATION	DATE	TIME	TIDE	RATE(ft/d)	DIRECTION
HTP 15′	8-09-87	1500	High	2.17	305°
HTP 15′	10-20-87	1830	Low	3.32	277°
HTP 60′	8-09-87	1330	High	2.17	197°
HTP 30′	10-20-87	1730	Low	1.21	188°
KDNWR 15′	8-08-87	1345	High	0.00	----
KDNWR 15′	10-15-87	1710	Low	0.75	71°
KDNWR 30′	8-08-87	1515	High	3.38	104°
KDNWR 30′	10-15-87	1750	Low	4.10	87°

TABLE 11. Mean values and ranges of nutrient concentrations (μM) and chlorophyll-a (μg/l) along an onshore-offshore transect from inshore canal waters on Big Pine Key (PPH) to offshore waters at Looe Key National Marine Sanctuary (LK). Values represent means ± 1 standard deviation.

STATION		NO3	NH4	SRP	EN:P	Chl-a
1---PPH-BEL	MEAN	1.60 ± 0.92	0.57 ± 0.23	0.09 ± 0.07	24.1	0.34 ± 0.22
	RANGE	0.39---3.02	0.22---0.94	0.03---0.29		0.09---0.78
2---PPH-MAIN	MEAN	1.67 ± 0.57	0.49 ± 0.18	0.07 ± 0.05	30.8	0.19 ± 0.09
	RANGE	0.38---2.36	0.18---0.79	0.03---0.22		0.07---0.42
3---PINE CHANNEL	MEAN	0.84 ± 0.32	0.32 ± 0.12	0.05 ± 0.02	23.2	0.14 ± 0.06
	RANGE	0.26---1.29	0.12---0.48	0.03---0.10		0.06---0.21
4---LITTLE MUNSON IS.	MEAN	0.78 ± 0.42	0.27 ± 0.11	0.05 ± 0.02	21.0	0.22 ± 0.11
	RANGE	0.27---1.75	0.09---0.49	0.03---0.08		0.08---0.50
5---HAWKS CHANNEL	MEAN	0.40 ± 0.34	0.16 ± 0.07	0.05 ± 0.03	11.2	0.24 ± 0.13
	RANGE	0.13---1.05	0.05---0.31	0.03---0.11		0.09---0.50
6---LK-BACK REEF	MEAN	0.40 ± 0.32	0.21 ± 0.16	0.05 ± 0.02	12.2	0.18 ± 0.09
	RANGE	0.14---0.94	0.02---0.06	0.03---0.10		0.10---0.43
7S--LK-FORE REEF SURFACE	MEAN	0.38 ± 0.33	0.23 ± 0.14	0.04 ± 0.02	15.3	0.13 ± 0.07
	RANGE	0.08---0.96	0.02---0.53	0.03---0.08		0.05---0.32
7B--LK-FORE REEF BOTTOM	MEAN	0.52 ± 0.38	0.22 ± 0.09	0.06 ± 0.04	12.3	0.19 ± 0.10
	RANGE	0.14---1.35	0.02---0.33	0.03---0.16		0.07---0.37

TABLE 12. Correlation matrices of nutrient concentrations and chlorophyll-a data along and onshore-offshore transect from inshore canal waters on Big Pine Key to offshore waters of Looe Key National Marine Sanctuary (LK). Data were collected at samplings from 10/17/86 to 6/19/87. Values represent correlation coefficients; *r >0.70 is considered significant.

10/17/86	LK #1	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.82 *	.67	.52
	AMMONIA		.66	.82 *
	PHOSPHATE			.80 *

11/15/86	LK #2	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.68	.52	.86 *
	AMMONIA		.47	.49
	PHOSPHATE			.76 *

11/23/86	LK #3	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.96 *	.35	.78 *
	AMMONIA		.41	.68
	PHOSPHATE			.13

12/06/86	LK #4	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.89 *	.66	.11
	AMMONIA		.82 *	.05
	PHOSPHATE			.39

12/21/86	LK #5	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.96 *	.94 *	.81 *
	AMMONIA		.93 *	.78 *
	PHOSPHATE			.88 *

1/08/87	LK #6	AMMONIA	PHOSPHATE	CHLOROPHYLL
	NITRATE	.91 *	.95 *	.27
	AMMONIA		.79 *	.40
	PHOSPHATE			.24

TABLE 12. CONTINUED

1/28/87 LK #7	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.91 *	.72 *	.59
AMMONIA		.81 *	.47
PHOSPHATE			.70 *

2/18/87 LK #8	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.84 *	.27	.34
AMMONIA		.37	.43
PHOSPHATE			.12

3/20/87 LK #9	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.81 *	.29	.32
AMMONIA		.21	.39
PHOSPHATE			.31

4/09/87 LK #10	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.85 *	.18	.04
AMMONIA		.11	.30
PHOSPHATE			.49

4/26/87 LK #11	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.68	.02	.31
AMMONIA		.45	.36
PHOSPHATE			.86 *

6/19/87 LK #12	AMMONIA	PHOSPHATE	CHLOROPHYLL
NITRATE	.63	.55	.37
AMMONIA		.93	.65
PHOSPHATE			.79 *

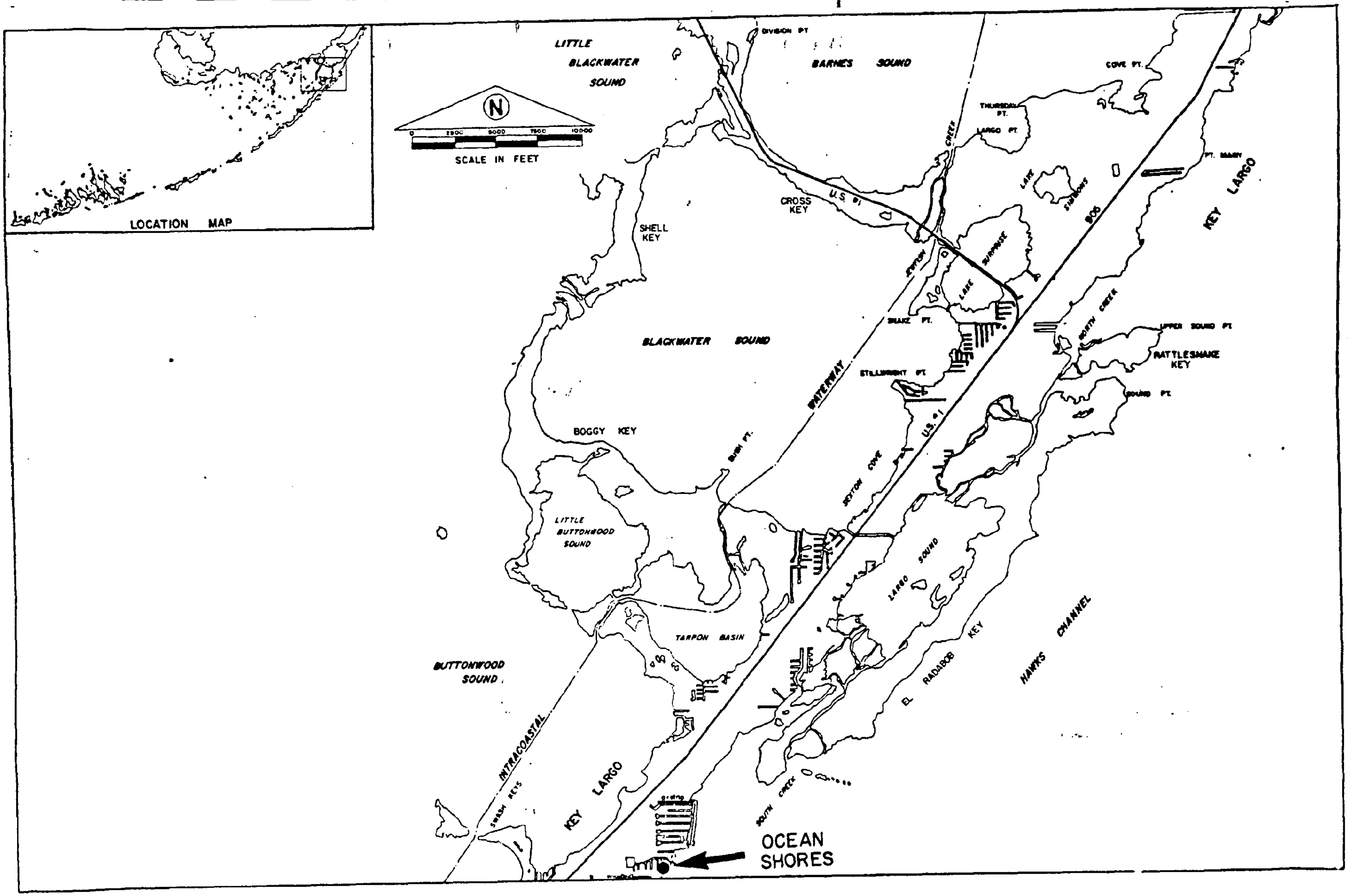


Figure 1. Location of groundwater monitor stations on Key Largo.

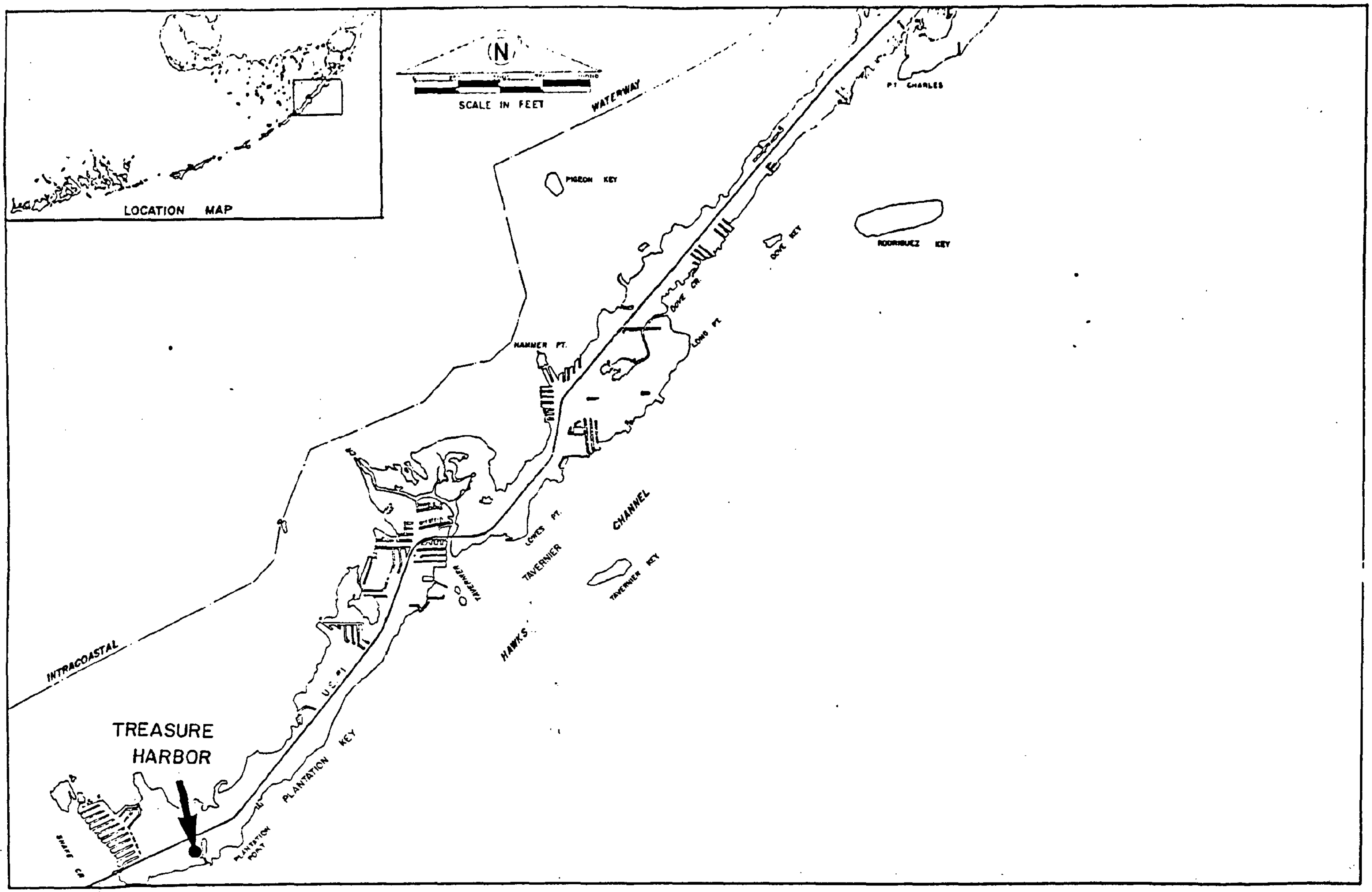


Figure 2. Location of groundwater monitor stations on Plantation Key.

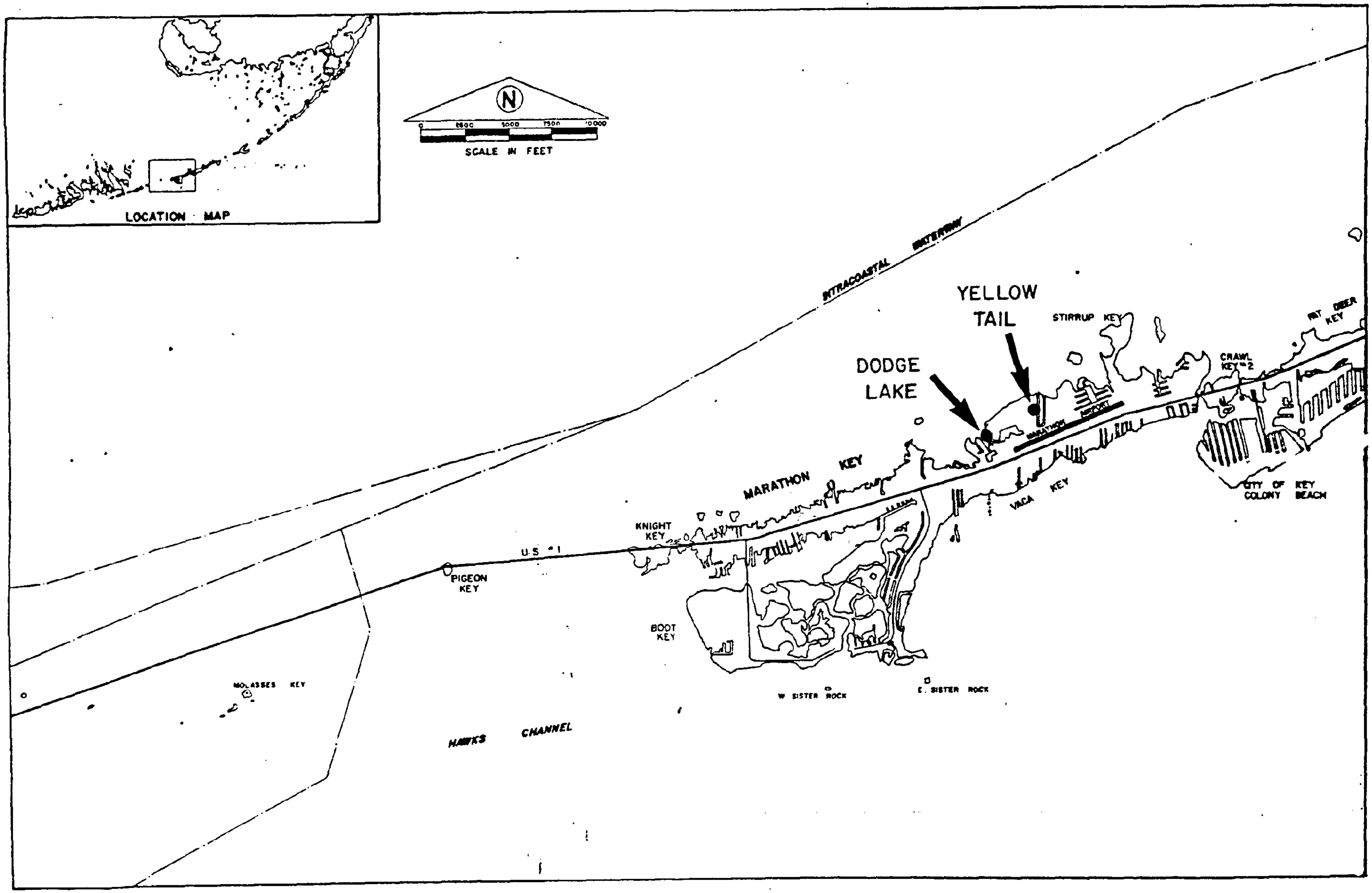


Figure 3. Location of groundwater monitor stations on Marathon.

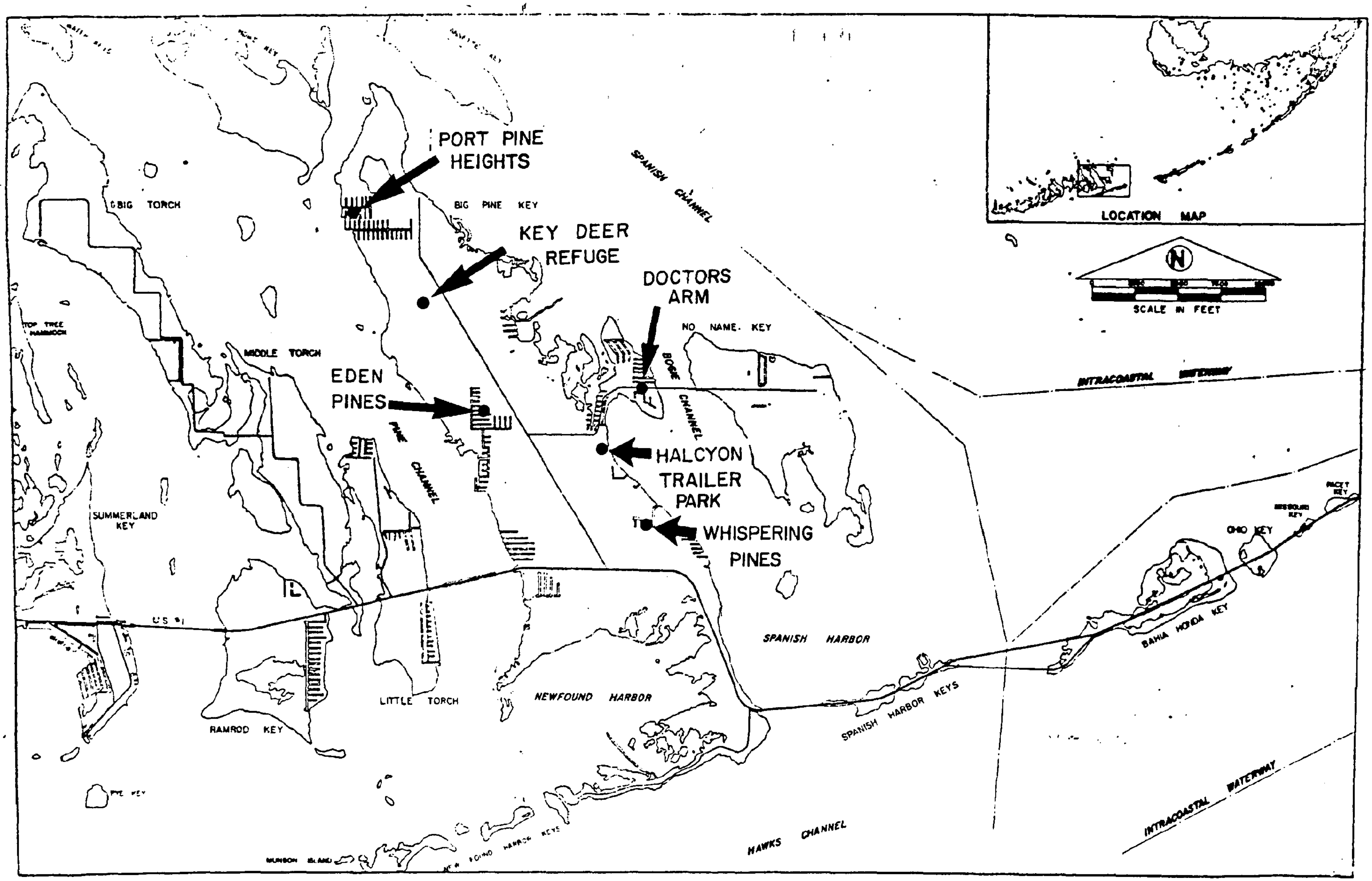
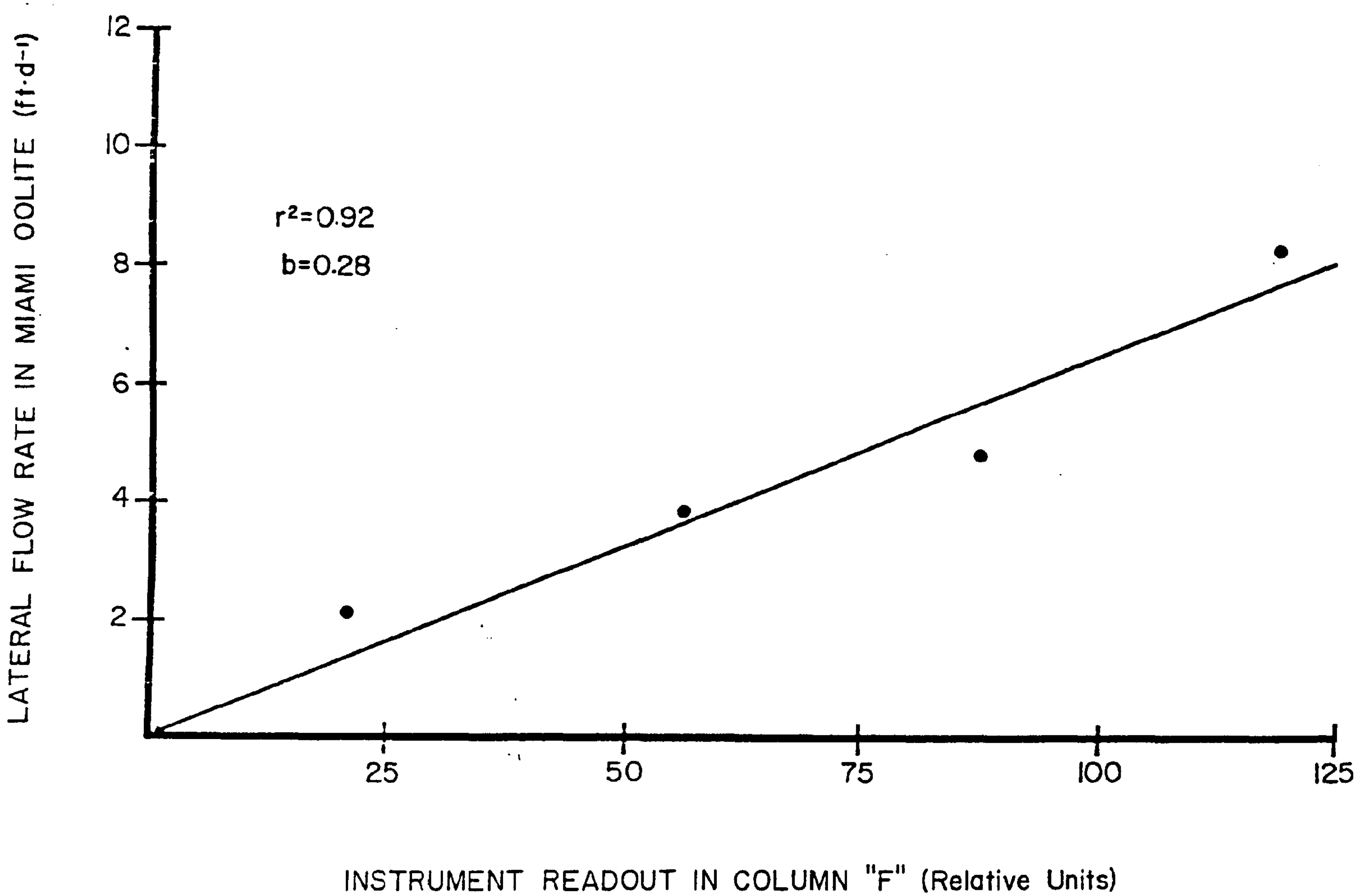


Figure 4. Location of groundwater monitor stations on Big Pine Key.

Figure 5. Calibration Curve for GeoFlow groundwater flow meter.



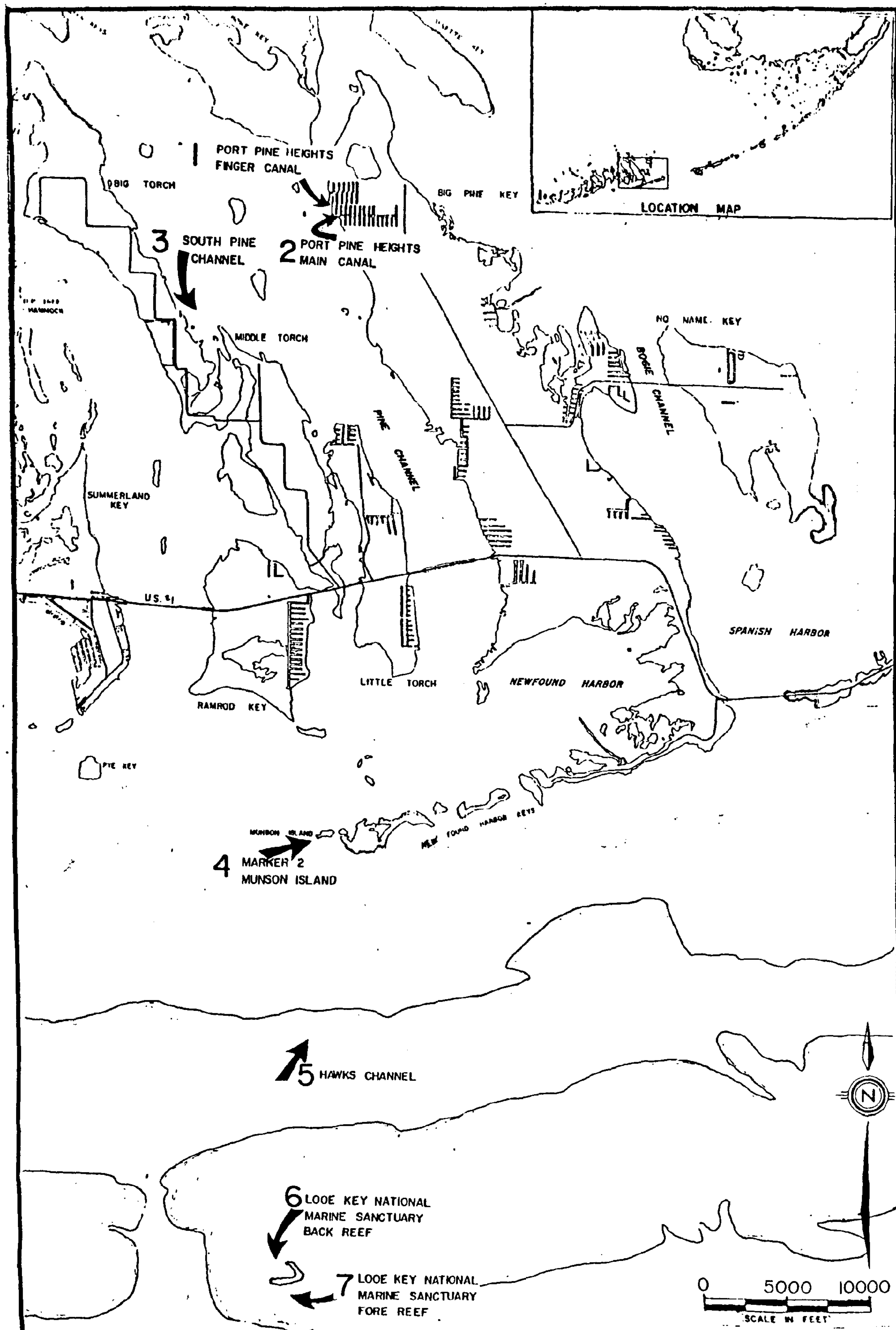


Figure 6. Location of hydrographic stations in nearshore waters of Big Pine Key.

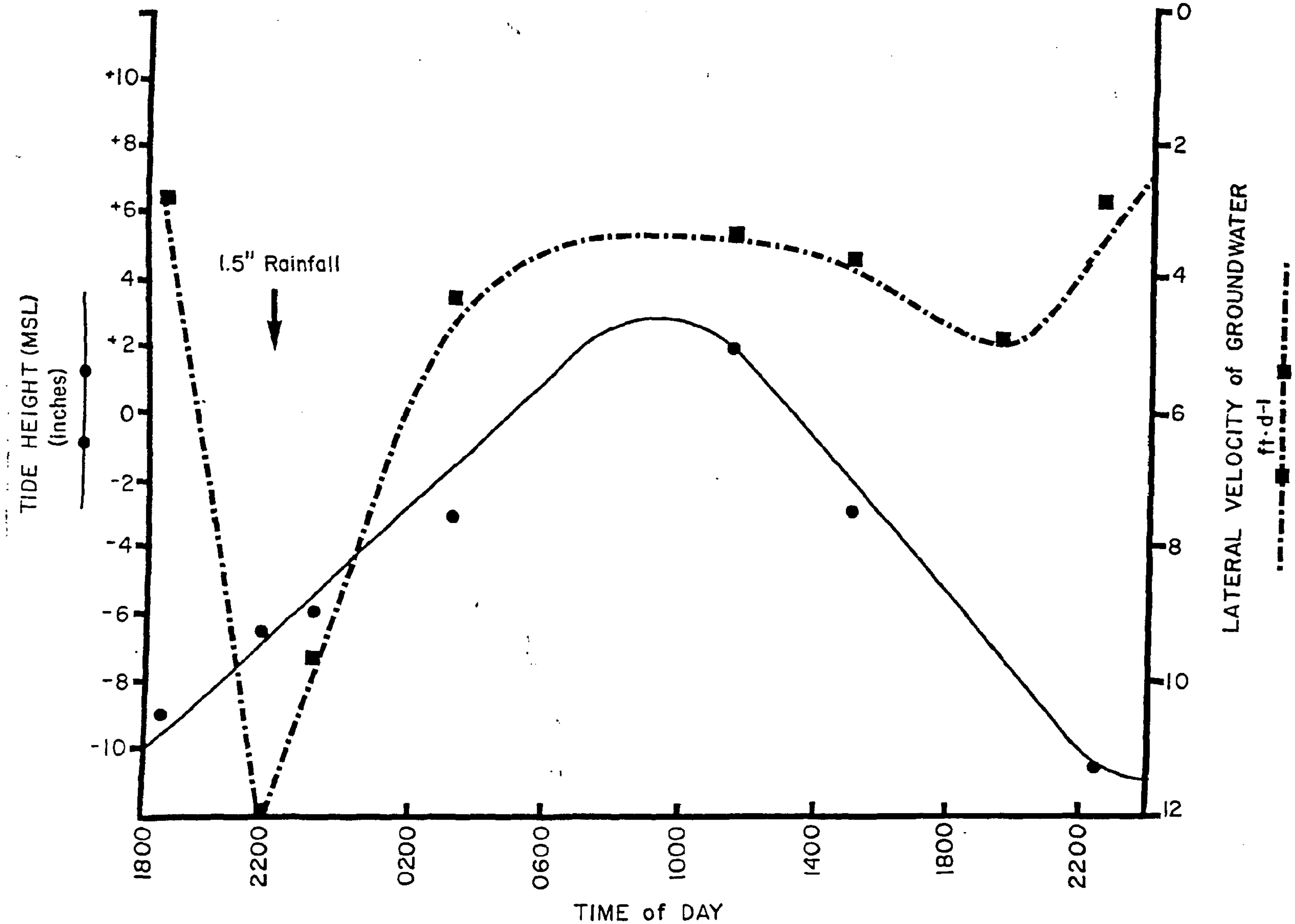


Figure 7. Groundwater flow rate in Port Pine Heights, Big Pine Key; ebbing tide.

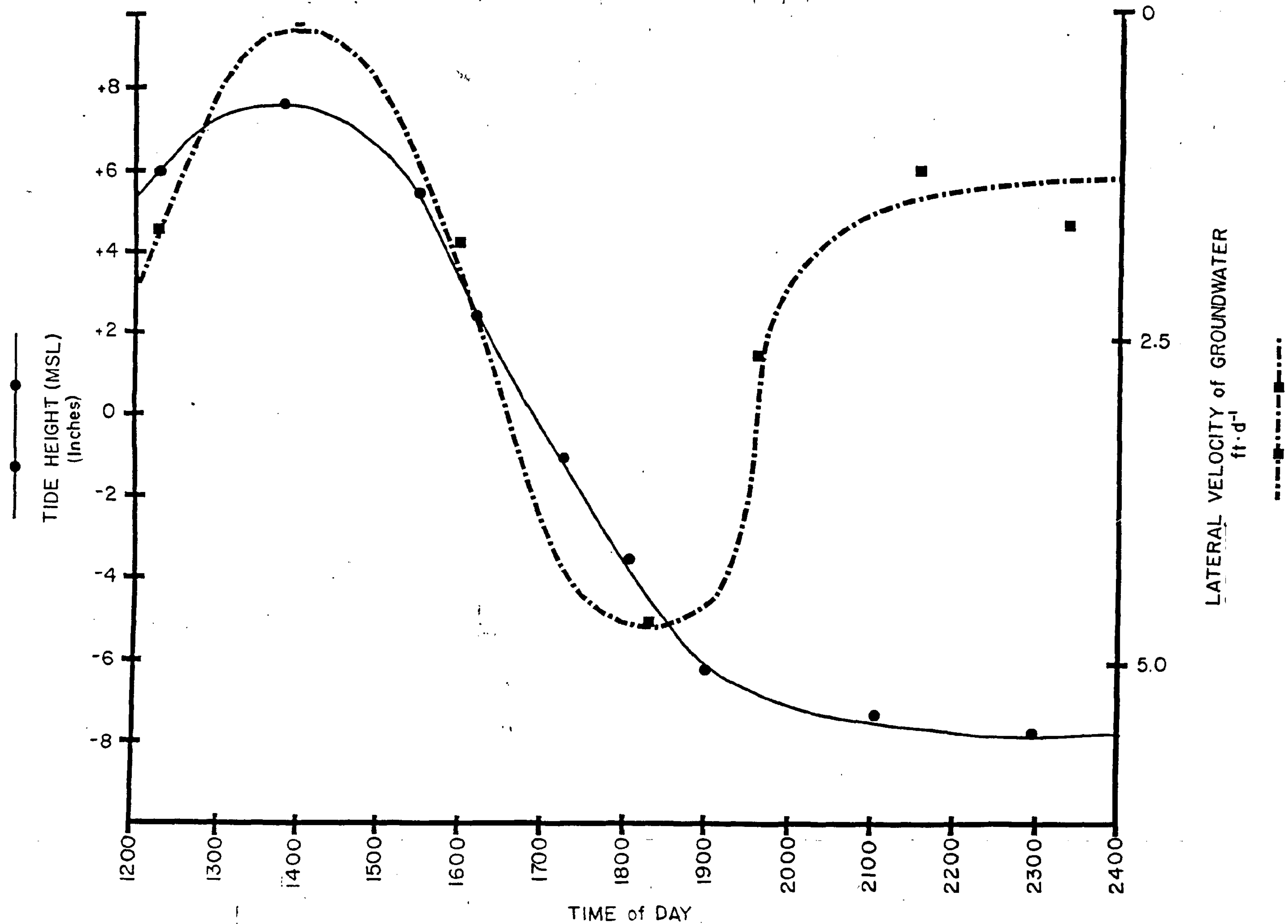


Figure 8. Groundwater flow rate in Port Pine Heights, Big Pine Key; flooding tide.

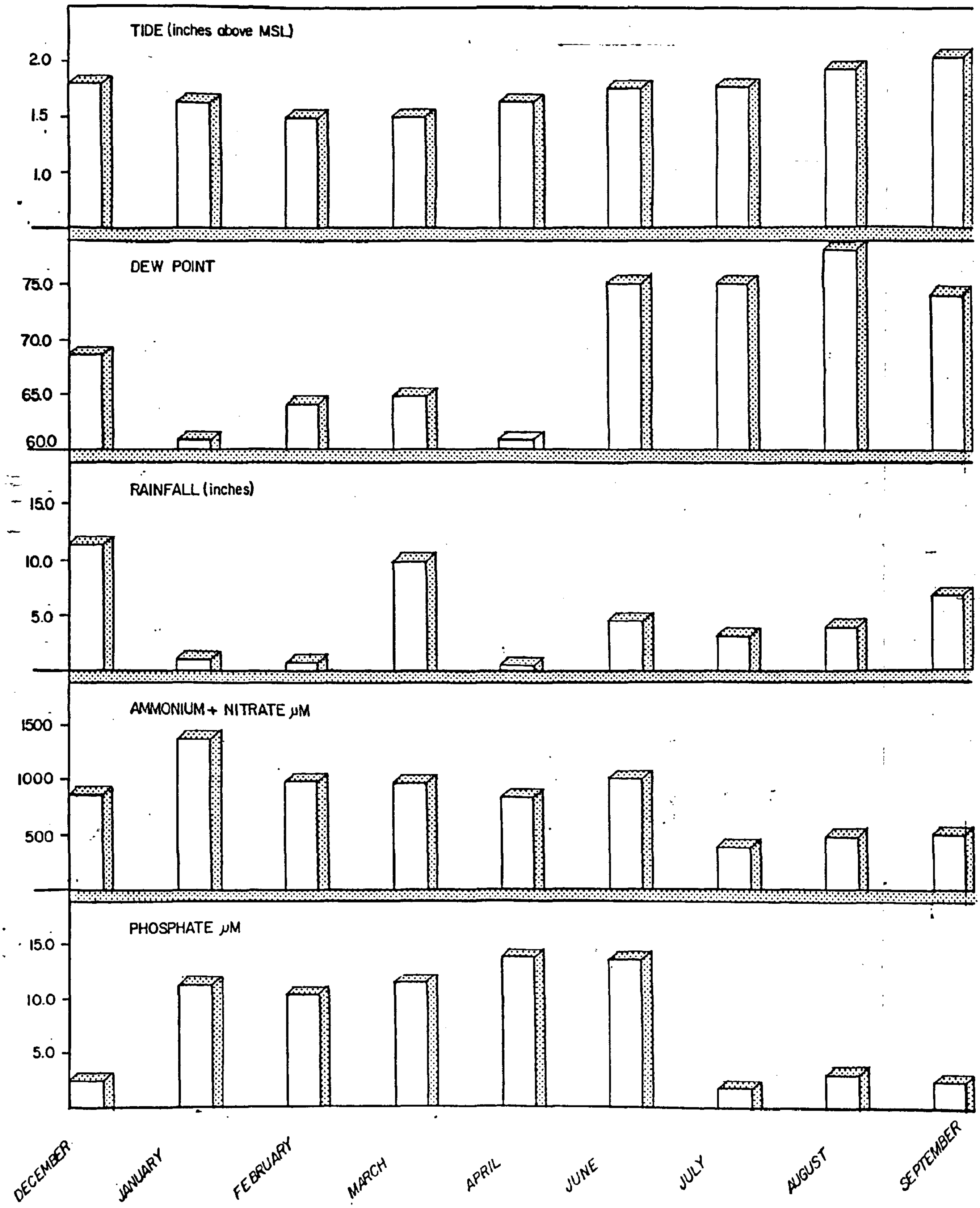


Figure 9. Mean monthly values of hydrological (high tide level, dew point, and rainfall) and nutrient (ammonium + nitrate and soluble reactive phosphate) data between December 1986 and September 1987.

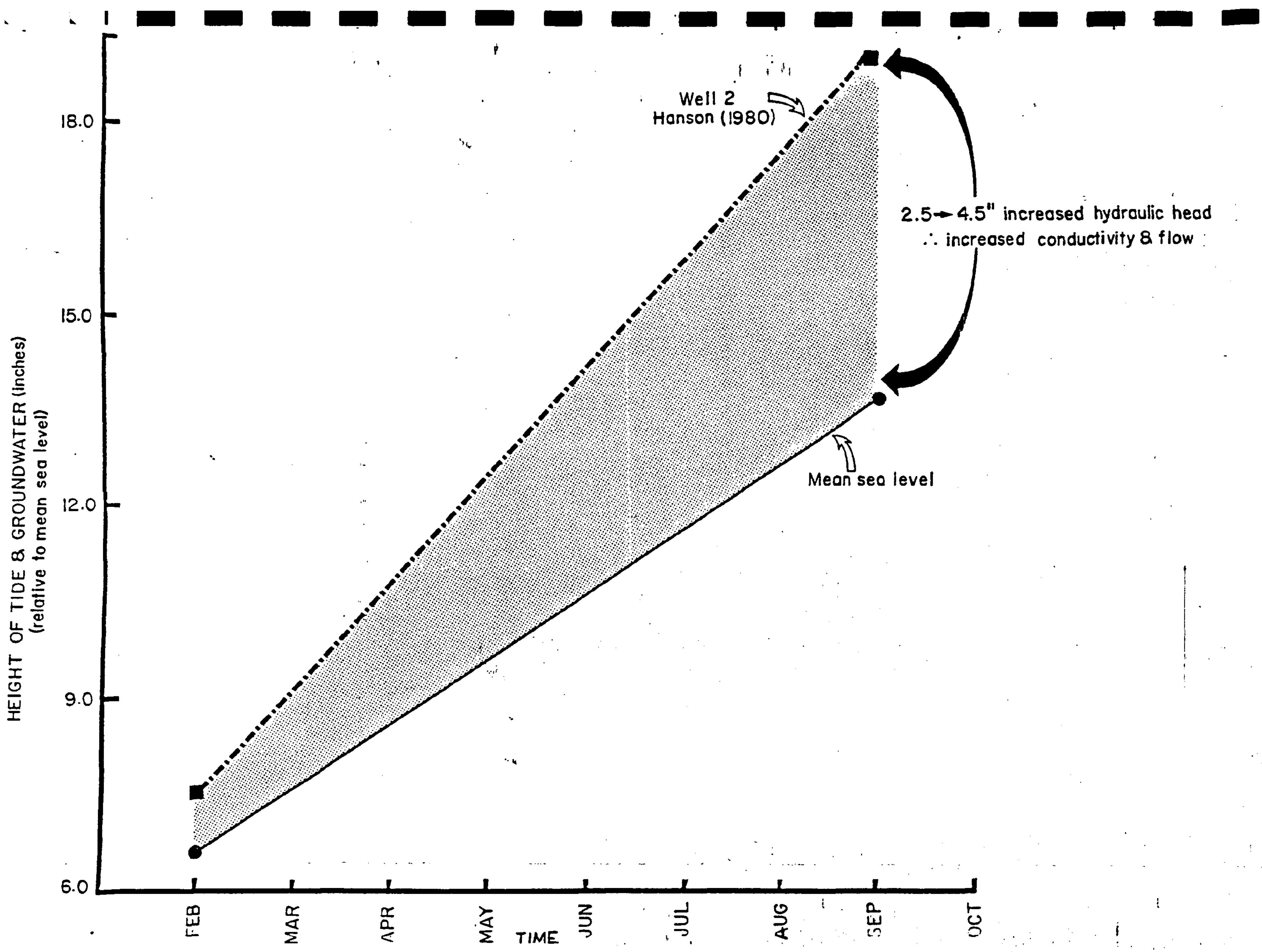


Figure 10. Seasonal trends in hydraulic head based on monthly average groundwater table height and mean sea level.