OSDS IMPACTS ON THE ST. LUCIE RIVER

AND INDIAN RIVER LAGOON
(Year II)

FINAL PROJECT REPORT
St. Lucie River Issues Team
(Contract OT060154)

Submitted To:
South Florida Water Management District

Submitted By Florida Tech Researchers:

Thomas V. Belanger, Ph.D., Principal Investigator

And

Thomas L. Price Jr., M.S., Co-Investigator

JANUARY 2007

Table of Contents

OSDS IMPACTS ON THE ST. LUCIE RIVER AND INDIAN RIVER LAGOON
(Contract: OT060154)

CONTACT INFORMATION:

Thomas V. Belanger, Ph.D., Principal Investigator
Professor, Department of Marine and Environmental Systems
Florida Tech
Melbourne, Florida 32901
Phone: (321) 674-7463
Fax: (321) 674-7212
e-mail: belanger@fit.edu

PROJECT OBJECTIVES:

In this FY 06 Issues Team OSDS (septic tank) study, four (4) sites were investigated through detailed field studies to determine their site-specific impacts on the St. Lucie River Estuary in Martin and St.Lucie Counties, Florida. These sites were investigated under a range of environmental and hydrologic conditions in 2006, and the collected data were used to help determine the probable importance of OSDS bacterial and nutrient loading to the St. Lucie River. These data were added to the database obtained during the FY 05 Issues Team OSDS study (in which other sites on the river were investigated), and the combined effort has provided needed data on the importance of OSDS loading to the St. Lucie River and estuary. These data will allow better management decisions regarding OSDS to be made in the future.

BACKGROUND AND GENERAL SITE DESCRIPTION:

The Indian River Lagoon (IRL) System is a vital biological and economic resource to eastern Florida, representing a biogeographic transition zone rich in habitat and fish and wildlife species. Because of this diversity, and the fact that it is home to approximately nine federally protected threatened and endangered species, it is recognized as an important commercial and recreational area. It appears the water quality of the lagoon is declining, however, and there are a growing number of biological impacts that seem to be caused by this water quality decline. For example, disease and tumors in fish, and increases in algal blooms, fish kills and invasive species have hinted at a system under stress. Many biological experts suspect poor water quality is responsible for these impacts, and septic tanks may be contributing greatly to the water quality degradation through nutrient and bacterial loading in the lagoon system. Nutrient enrichment also represents a very real threat to seagrasses, since the lagoon system is a seagrass based ecosystem that depends on the existence of thriving seagrasses. The nutrient levels required for optimum seagrass growth are extremely low, and elevated nutrient levels may cause more algae and harmful algal blooms (HAB’s) to proliferate with a concurrent reduction in seagrasses. A change to and an algal based system with continued nutrient loading would have disastrous ecological consequences to the system.

The St. Lucie River, in particular, is on the brink of crisis, exhibiting poor water quality, fish kills and high bacterial levels. Concern over the health of the river was evidenced by the numerous Treasure Coast newspaper articles published in the summer and fall of 2005 concerning the poor condition of the river. Some of these newspaper article titles are shown in Table 1. Although Lake Okeechobee water releases to the river estuary are certainly a large part of the problem, there are other nutrient and bacterial sources in the watershed, such as septic tanks (OSDS), that may be major contributors, as well.

There are more than 120,000 septic tanks along the IRL and at least 90,000 of the total are located in areas with bad conditions, such as a high water table, poor soil conditions, close proximity to the lagoon, etc. Past studies estimating groundwater seepage in the southern IRL region indicate rates are high and show the potential for high OSDS loading (Table 2). The Martin County area, in particular, has a high potential to impact the St. Lucie River and IRL due to high OSDS densities and poor soil conditions. In a study prepared by the Martin County Health Department for the SFWMD, it was estimated that at that time (early 90's) there were over 16,000 OSDS in the county located adjacent to the lagoon or one of its tributaries, with millions of gallons of effluent released to the soil in the area each day. Many of the OSDS are located in areas with poor site conditions, suggesting OSDS pollutant loading could be very significant (Kearney and Kroesen, 1995).

Several studies in other regions of the IRL have indicated OSDS nutrient loading is significant. In a study for the National Park Service (NPS) by Florida Tech on groundwater/surface water interaction in Mosquito Lagoon (northern IRL), groundwater sampling down gradient from the NPS headquarters septic tank indicated high mean phosphorus loading to the lagoon. A rate of 41.3 g m^2/day was found entering the lagoon behind the OSDS drainfield, compared to a control mean loading rate of 6.4 g m^2/day (Belanger et al., 1997). Another study near Florida Tech in the Crane Creek watershed, a tributary of the IRL, also indicated significant phosphorus loading from residences served by OSDS (Reznicek, 2003). In view of the paucity of past OSDS studies, as well as the sometimes conflicting results, additional field based studies which provide conclusive cause/effect data are needed and necessary for future lagoon management. The need for OSDS studies in the St. Lucie River Estuary watershed is summarized in Table 3. In view of the above information, it appears very possible that OSDS could be a significant contributor of nutrients and bacteria to the river and lagoon, and this project investigates that question in detailed field studies at selected OSDS sites.

Table 1. Selected Treasure Coast Newspaper Articles on the St. Lucie River Estuary.
Summer and Fall, 2005.

June 5 - Septic Tanks May Be Tainting River; Suspected Bacteria Source To Be Tested
July 14 - State Scientists Try To Narrow Search For Cause Of Bacteria
July 16 - North Fork Samples Still Testing Poor; River's Ill's Tied to Range of Sources
July 17 - St. Lucie River Becomes a Foul Dead Mess
July 23 - Three Sites Still Testing High For Bacteria
July 26 - SFWMD To Pay For St. Lucie River Tests; Number of Sick Fish Rising
Aug. 3 - Scientists Close In On River Pollution
Aug. 9 - St. Lucie River A "Mess"
Aug. 10 - Lasting Estuary Damage Feared
Aug. 11 - State To Step Up Fight To Save Estuary
Aug. 12 - Martin Commissioner Shows St. Lucie River Muck, Algae in Washington.
Aug. 13 - St. Lucie River in Crisis
Aug. 18 - Extensive Monitoring To Keep Tack of Algae Bloom; Nelson Takes a Look at St. Lucie River Algae
Aug. 18 - North Fork Water Tests Still Show Elevated Bacteria
Aug. 22 - Bait Shops: St. Lucie River No Longer A Love For Fishermen
Aug. 23 - St. Lucie Makes Pitch to Save Estuary
Aug. 24 - Martin County To Sue Over Poor River Conditions; Scientists Stir Up St. Lucie River Muck
Aug. 30 - St. Lucie Estuary Still Going Downhill
Sept. 8 – Fishing Clinic Moving over Estuary Health Concerns
Sept. 9 - Algae in St. Lucie River Creates Stink
Sept. 17 -State Scientists Track Contamination Sites of St. Lucie River
Sept. 22 -Scientists Think Septic Tanks Turning North Fork of St. Lucie Estuary Nasty
Oct. 1 - Testers Find Bacteria Hot Spots for River
Oct. 14 - Editorial: The latest Threat to the River? Leaking Septic Tanks
Nov. 2 - Lagoon is Safe; St. Lucie Estuary Isn't
Nov. 24 - St. Lucie Health Department Advises: Stay out of River's North Fork
Dec. 8 - Cause of Bacteria Bloom in St. Lucie River Still a Mystery

Table 2. Historical Data on Groundwater Seepage Rates in the Southern IRL.

Method	Mean Seepage (m day^{-1})	Comment	Reference
Seepage Meter	0.078	Several Measures	Zimmerman et al., 1985
Seepage Meter	0.077	Biweekly 7/88 – 1/89	Belanger and Walker, 1990
Finite Diff. Model	0.0003	MODFLOW	Montgomery, 1990
Finite Elem Model	0.00076 – 0.0026	GROSEEP	Pandit and El-Khazen, 1988
Link-Node	0.003	DYNTRAN	SFWMD, 1987
Seepage Meter	0.046	Bimonthly One year	Belanger et al., 2003
Seepage Meter	0.027	Bimonthly One year	Belanger et al., 2003
Seepage Meter	0.016	Bimonthly One year	Belanger et al., 2003

Table 3. Need for OSDS Studies in the St. Lucie Estuary Watershed.

St. Lucie Estuary and IRL are recognized as unique recreational and commercial resources and appear under stress.

High densities of OSDS exist adjacent to the St. Lucie Estuary and IRL.

Nutrient loading from OSDS has been found in a few other studies of the IRL, but data are sparse and site specific.

Modeling studies can be misleading and should be supported by field data.

Data indicate groundwater seepage in the St. Lucie Estuary and IRL is high.

Conclusive cause/effect data from representative OSDS sites are needed under a range of hydrologic conditions to in order to provide the basis for important OSDS management decisions in the watershed.

GENERAL APPROACH AND RATIONALE:

Four FY 06 OSDS test sites were established at locations on the North and South Forks of the St. Lucie River. The exact site location selections were established after consultation with the Martin and St. Lucie County Health Departments, and are shown in Fig. 1 with the previous FY 05 OSDS field sites. Control site locations were established in close proximity to the test sampling locations (near the drainfield), but away from OSDS influence. Although general neighborhoods were targeted for testing, the exact residence locations in each area were dependent on the willingness of the individual homeowners to allow us to study their OSDS installations. The sites in this study represent properly functioning OSDS and, although not selected in a statistically random fashion, they represent a range of site conditions (e.g. soil type, location of drainfield relative to river, high vs. low vertical and horizontal hydraulic gradient, bulkhead vs. natural slope, low vs high tank loading, etc.).

The four FY 06 study sites were located, from north to south (Fig. 1), at 2502 Isola Bella in Ft. Pierce (Smith residence, Site B2), 354 Surfside in Port St. Lucie (Forte Residence, Site C2), 701 N.W. Sunset Drive (Carl Residence, Site E2) in Stuart and 3679 S.W.St. Lucie Shores in Palm City (Murray Residence, Site D2). The Smith home (Site B2) was built in 1985, had four residents, and represents a low gradient natural site located on the north Fork of the St. Lucie River. The Forte residence (Site C2) was built in 1986, had four occupants, and has a bulkheaded backyard adjacent to a canal connected to the river's North Fork. The septic tank drainfield was located less than thirty feet from the canal. The Carl residence (Site E2) was built in 1970 and has had three to five occupants during that time (five people for the last ten years). The site represents a natural low gradient site and had a 1050 gallon septic tank with a 300 ft^2 drainfield up-gradient from the river's North Fork. The Murray residence (Site D2) was built in 1975, currently has four residents, and has a 750 gallon septic tank with a 200 ft^2 drainfield located in a bulkheaded backyard adjacent to the St. Lucie River's South Fork. Soil type, hydraulic gradient and other site characteristics are discussed later. Drainfield distances from the river were 117 ft, 22 ft, 68 ft and 200 ft for sites B2, C2, D2 and E2, respectively. Sampling dates in 2006 were 4/15, 6/18, 7/24, 7/27, 8/23/ and 9/6,however all sites were not always sampled on the same day due to time constraints.

This project involves the collection of water quality and hydrologic data three times from each site during 2006. Fecal coliform bacterial data were collected on a semi-annual basis (twice/yr). Groundwater samples were collected at each site from piezometers and PushPoint samplers located adjacent to and down gradient from the septic tank drainfield, to the edge of the water body. Water level measurements in piezometers allowed head differences and hydraulic gradients (vertical and horizontal) to be calculated during each sampling trip. The OSDS layout at each site was mapped and the sediment and hydrologic characteristics measured and documented. The general sampling scheme used at each site is shown in Fig. 2, and individual sampling site locations are shown in Figs. 3 through 6. Samples for conductivity, ammonia, soluble reactive phosphate, nitrate, dissolved oxygen, temperature, turbidity and bacteria analyses were collected from the groundwater and surface water sampling locations at each site (Figs. 3-6). Site characterization (soil characteristics, hydraulic gradients etc,) provided hydrogeologic data for use in data analysis.

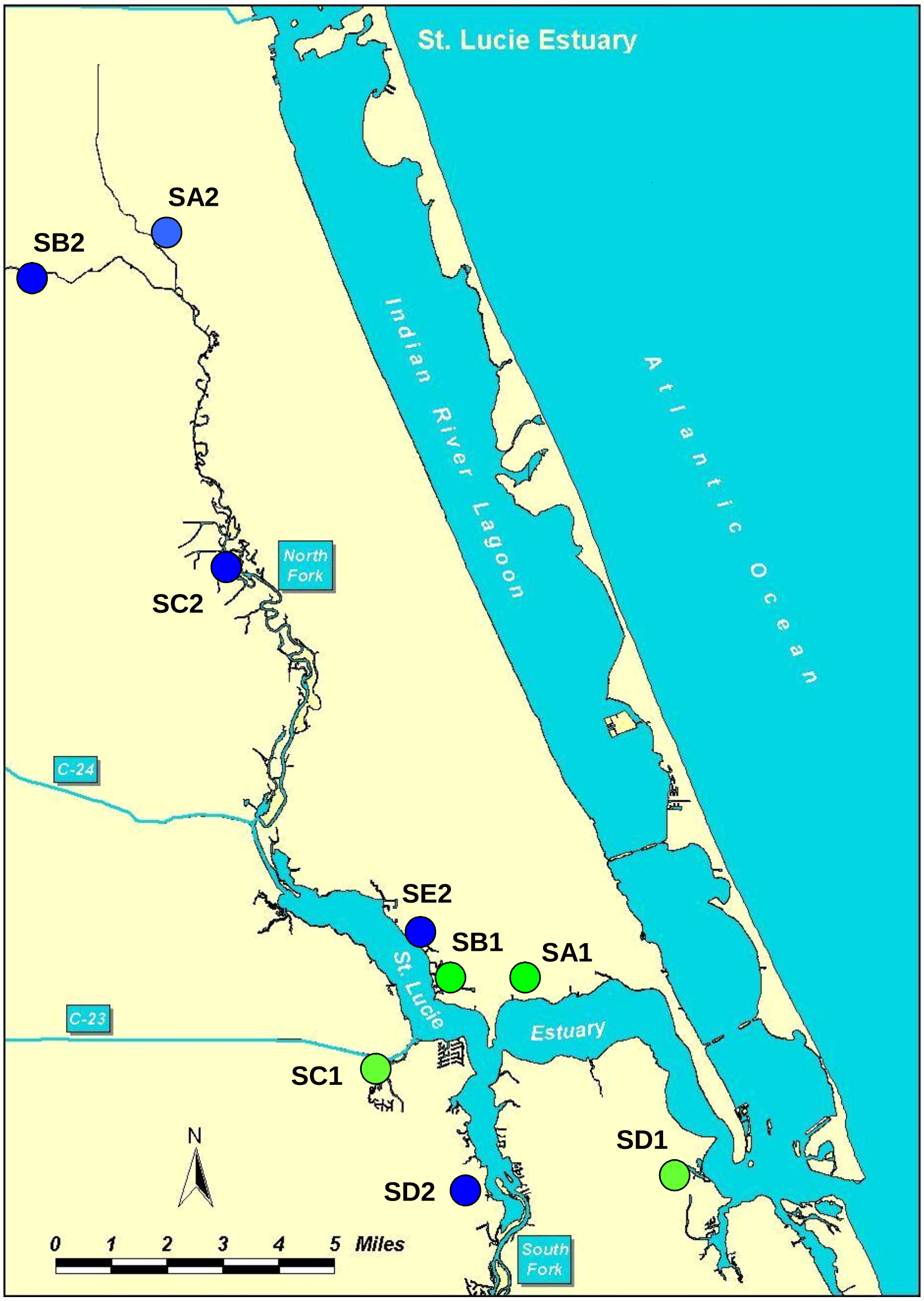


Figure 1. OSDS Site Locations, FY 05 in green, FY 06 in blue.

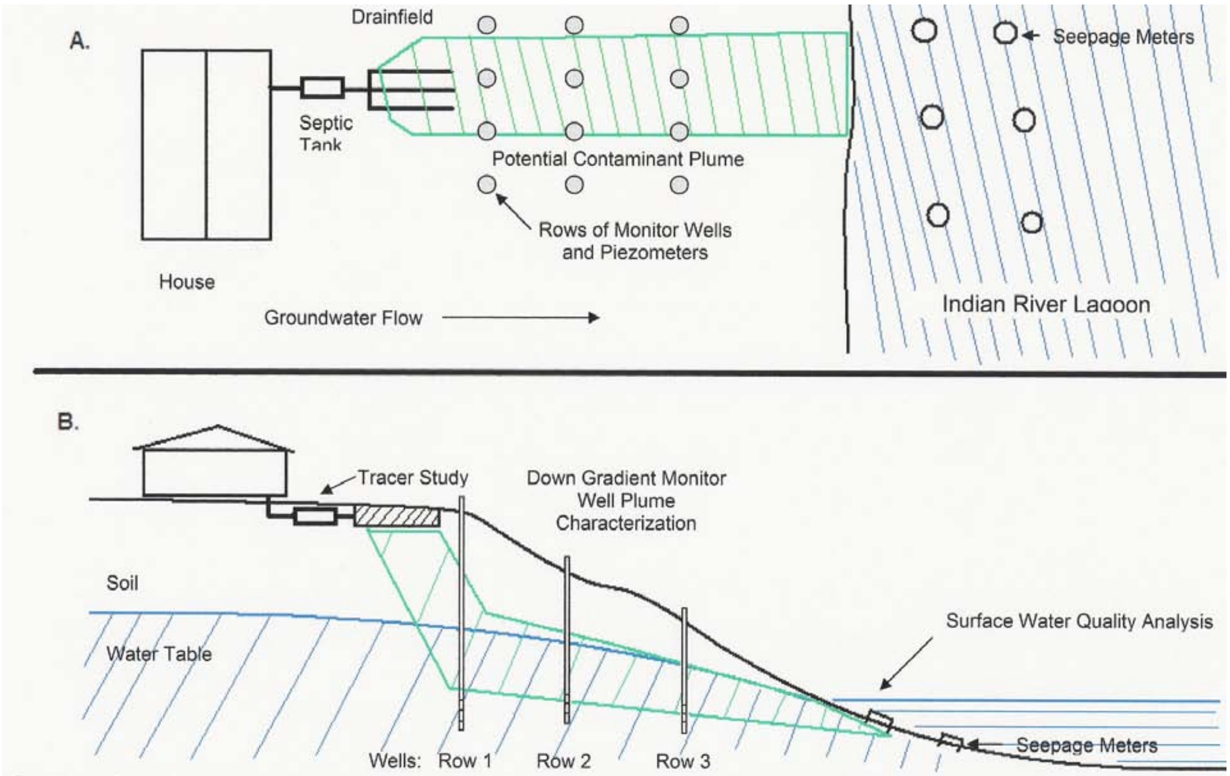


Figure 2. General Sampling Scheme for Study

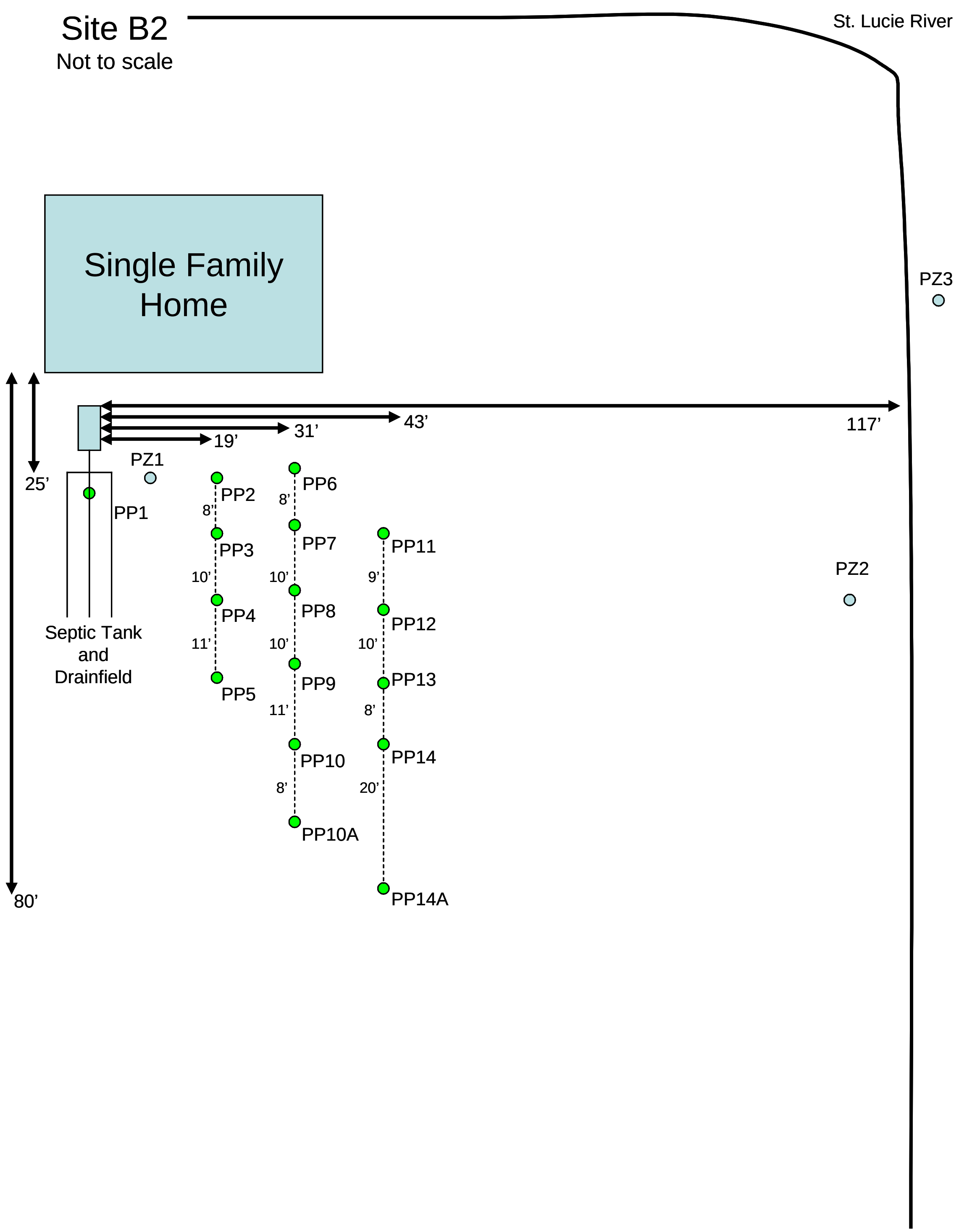


Figure 3. Site B2 Sampling Locations

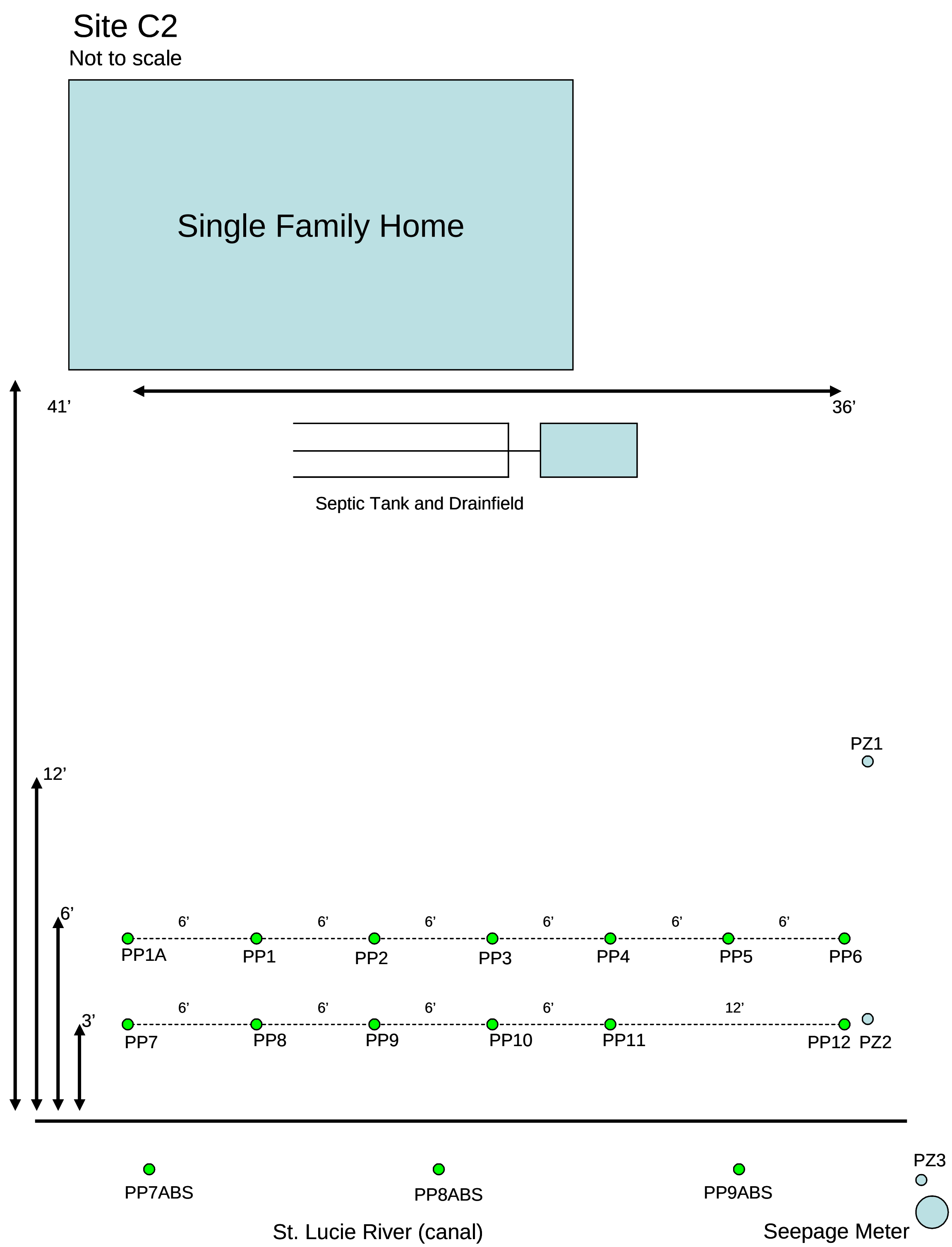


Figure 4. Site C2 Sampling Locations

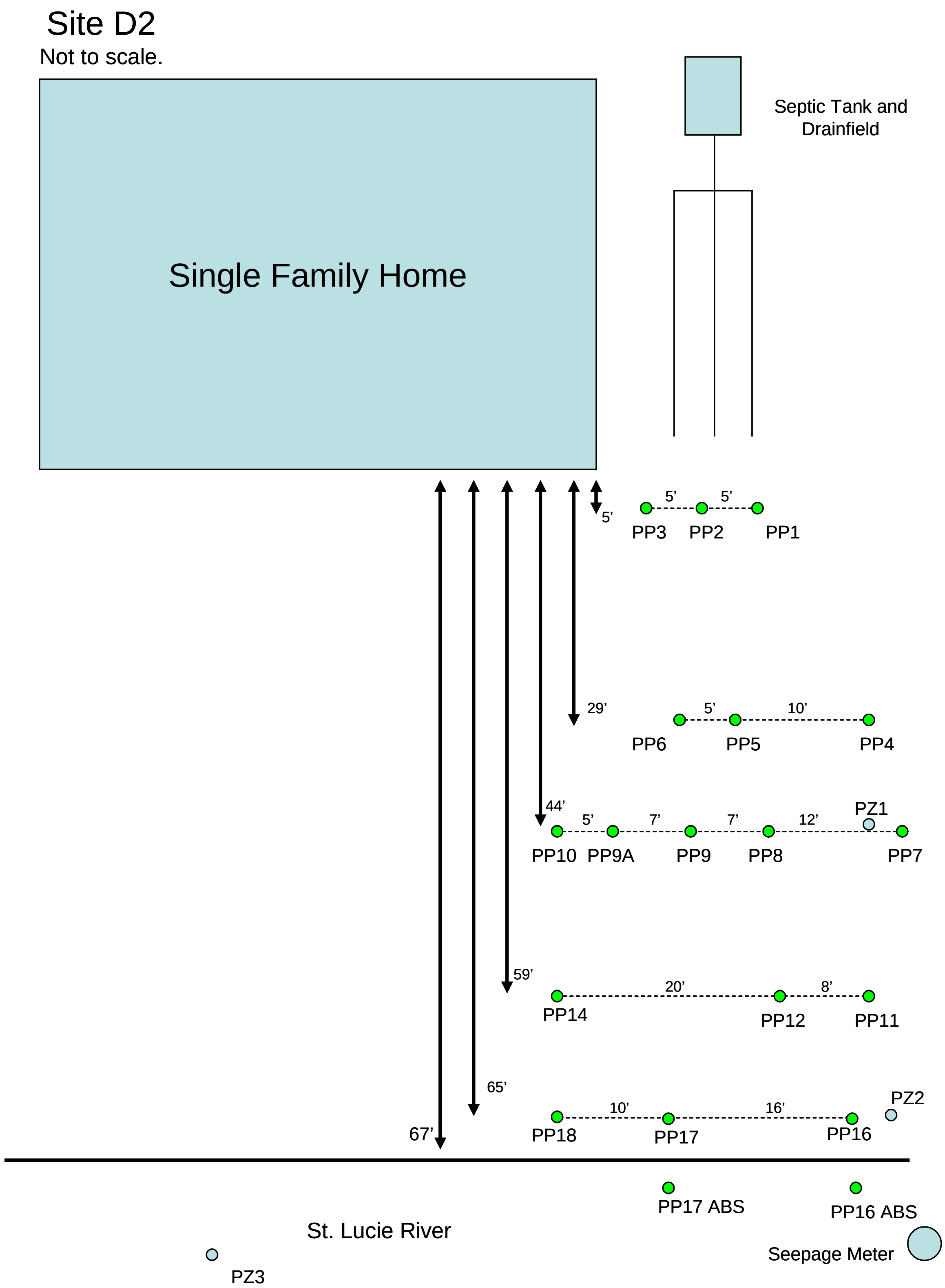


Figure 6. Site D2 Sampling Locations

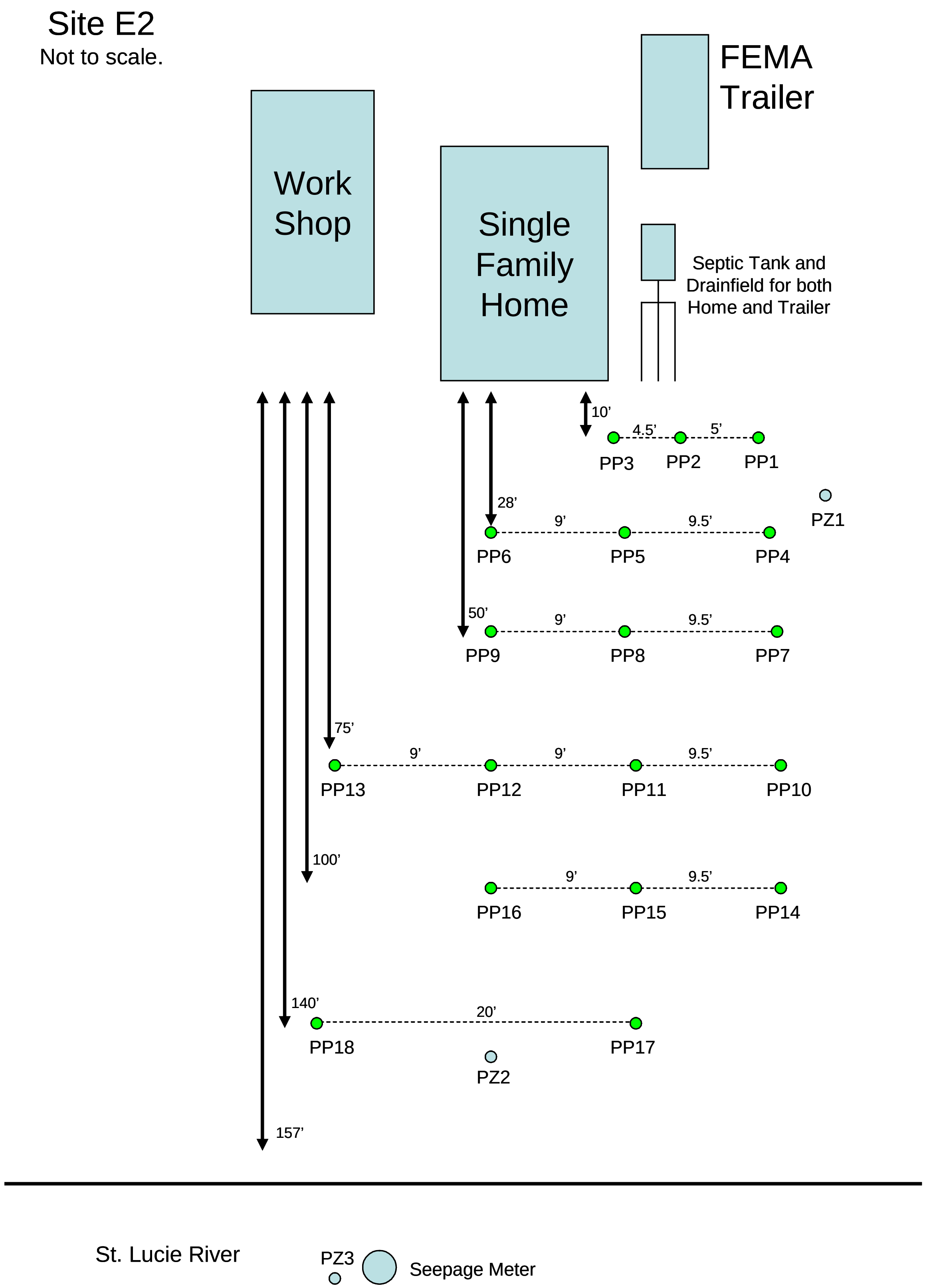


Figure 7. Site E2 Sampling Locations

GENERAL METHODS:

With the exception of Site B2 (Smith residence), one seepage meter was positioned near the shore at each site. Two, 2 inch piezometers were installed at each site--one up gradient from the drainfield and one or three down gradient near the edge of the river. These piezometers were used to establish site groundwater levels for use in calculating hydraulic gradients. One in situ ¾ inch piezometers was positioned near the shoreline and collected water level data were used to calculate vertical hydraulic gradients. Groundwater samples were obtained from 2 inch piezometers using bailers and M.H.E. PushPoint sediment pore water samplers using a peristaltic pump. Groundwater samples were collected 0.5 ft below the water table and at other depths at selected sites. Surface water samples were obtained from grab samples one to two feet below the surface. Figure 2 shows a generalized schematic of the sampling plan. Sampling protocols described in the District's Field Sampling Manual (12/01/02) were followed. Samples were analyzed for soluble reactive phosphate (PO_4), ammonia (NH_4-N), nitrate plus nitrite (NO_X-N), color and turbidity in the lab using EPA approved methods, while specific conductance, temperature and dissolved oxygen were measured in the field. Nutrients were analyzed using the CHEMetrics VVR water analysis system. All lab samples were kept on ice in the field and analyzed as soon as possible. Bacteria were collected in sterile jars provided by Harbor Branch, kept on ice and delivered to the Harbor Branch Oceanographic Institution lab for total and fecal coliform analysis with three to four hours of sampling. At Harbor Branch they were immediately analyzed using the EPA approved MPN technique (APHA, 1985).

SPECIFIC METHODS:

Seepage Meters

Water fluxes through the sediment interface were measured directly using a seepage meter positioned near the shore. The seepage meter technique is cited by EPA as one of the best methods for this purpose (USEPA, 1988). Seepage meters followed the design of Lee (1977), with slight modifications (Figure 7). Each meter consisted of a 55 gallon steel drum cut to produce a hollow cylinder, open at one end, with a surface area of 0.29 m^2. A hole in the top of the meter was connected to a plastic collection (reservoir) bag by a polyethylene tube fitted through a rubber stopper

Meters were installed without a reservoir bag and left undisturbed for a minimum of one day prior to measurement, allowing time for the initial flow disturbance to subside and the meter to settle into a fixed position. When the meter was ready, a reservoir bag with one L of water was attached and the change in volume in the bag was determined over a defined time period. If a meter was not located during sampling a new one was inserted and measured the next day, if possible. Similarly, when bags were lost, measurements were sometimes repeated, if time permitted. The seepage inflow or outflow was measured in change in volume per square meter per hour (mL/m^2-hr). These units are dimensionally equivalent to units of millimeters per hour (m/hr). Correction factors were applied to the data to correct for flow field disturbance and friction losses within the meter (Erickson, 1981; Cherkauer and McBride, 1988; Belanger and Montgomery, 1992).

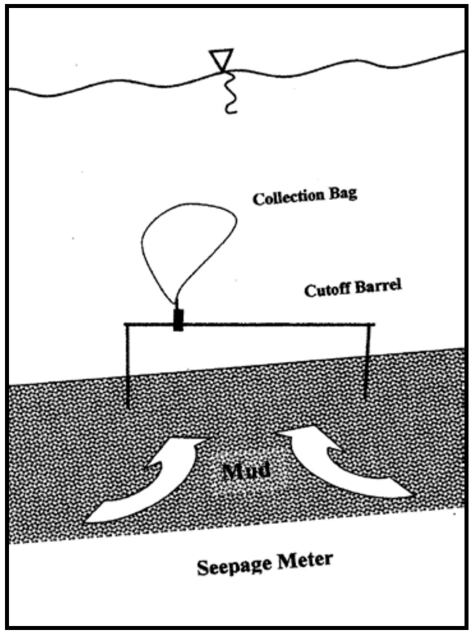


Figure 7. Diagram of a Seepage Meter.

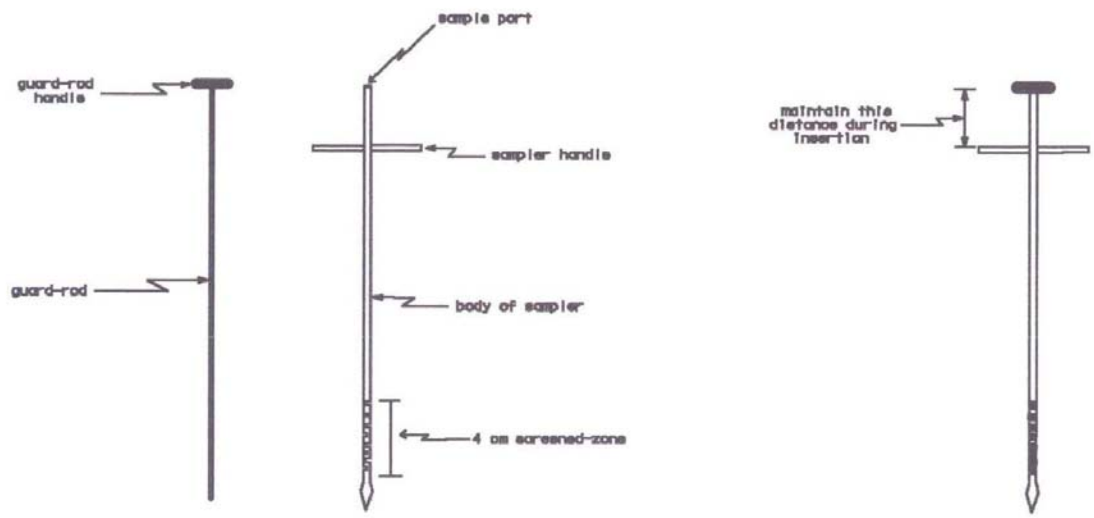
In Situ Piezometers

Shallow (2-5 ft) ¾ inch in situ piezometers were installed in the benthic sediment at nearshore sites (one per site) The piezometers had 1 ft screened intervals with 0.010 slot screen. The in situ river piezometers were installed by jetting in a 1 ¼ inch temporary casing outside the piezometer pipe with a 1½ h.p. Honda water pump connected to a 1 ¼ inch hose line. After the piezometers were allowed to settle and equilibrate for several days, the head difference between the surface water level (outside piezometer water level) and the groundwater (inside piezometer water level) was routinely measured (ΔH). The vertical hydraulic gradient can be obtained by dividing the ΔH by the depth of the screen below the sediment surface. The horizontal gradients were calculated by dividing the vertical difference in water level between two points (up gradient and down gradient piezometer) by the horizontal distance between the two piezometers or between a piezometer and the river water level. Both vertical and horizontal hydraulic gradient units are dimensionless (ft/ft).

PushPoint Samplers

The M.H.E. PushPoint sampling tool allowed us to rapidly and accurately locate and sample groundwater; in essence map and track contaminated groundwater movement in the area down gradient from OSDS. The PushPoint device is a very simple, precisely machined tool consisting of a tubular body fashioned with a screened zone at one end and a sampling port at the other (Fig.8). The bore of the PushPoint body is fitted with a guard rod that gives structural support to the PushPoint and prevents plugging and deformation of the screened zone during insertion into sediments. The PushPoint is made of 316 stainless steel and comes in various lengths. In this study we primarily used 36 inch length and ¼ inch diameter PushPoints. The screened-zone consists of a series of interlaced machined slots that form a short screened-zone with approximately 20% open area.

A.



B.

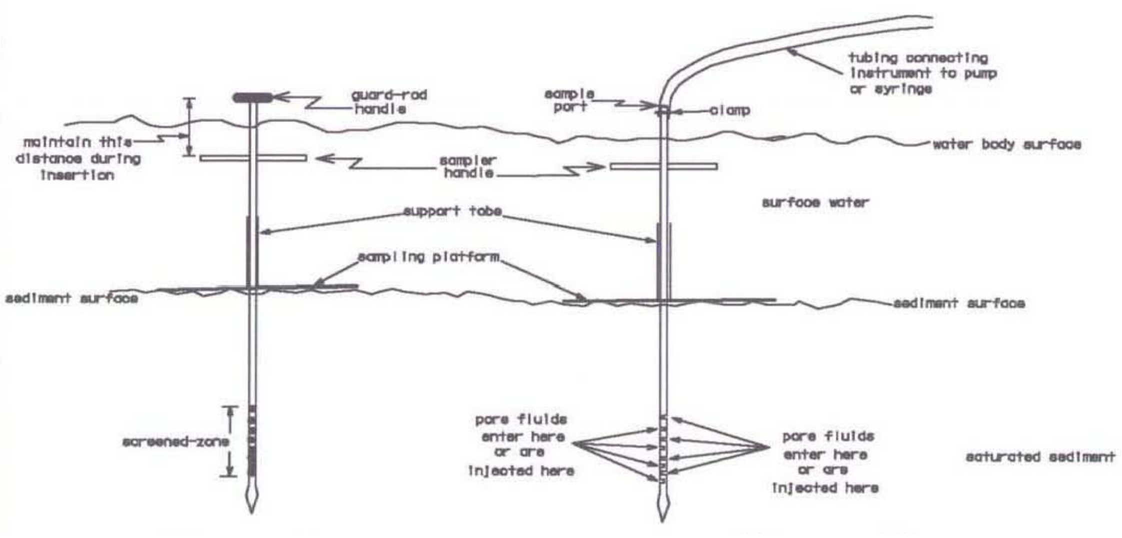


Figure 8. PushPoint Sampler Design (A) and Sampling Configuration (B).

The device is held in a manner that squeezes the two handles towards each other to maintain the guard-rod fully inserted in the PushPoint body during the insertion process. With the device held in this manner, the PushPoint was pushed into the sediment to the desired depth using a gentle twisting motion. When the desired depth was reached the guard-rod from the PushPoint body was removed without disturbing the position of the deployed sampler. A GeoPump peristaltic pump was attached to the PushPoint sample port (see Fig. 8) via Tygon tubing and water was withdrawn at a low-flow sampling rate (50-200 ml/min.). The first 20-50 ml of groundwater is generally turbid and this "development" water is discarded. Once non-turbid aliquots have been withdrawn, representative samples are collected for on-site and off-site analysis. Several depths from the same location can be sampled by pulling the PushPoint up to successively shallower sediment depths. This was done at selected locations.

Sediment Analyses

Percent sediment particle size analyses were completed on mixed auger sediment sample sat up gradient (near the drainfield) and down gradient (near the river) samples using standard sieving techniques, and silt/clay, very fine sand, fine sand, medium sand, coarse sand and granule or larger fractions were recorded. Percent organic matter (O.M.) was also determined by combusting the sample at 550 degrees C in a muffle furnace. Procedures are outlined by Belanger et al. (1993).

Field Measurements

Field water level measurements were made in the piezometers with a Herron “Little Dipper” water level measurement pressure transducer and used for horizontal and vertical gradient calculations. Specific conductance and temperature were measured with a YSI Model 33 SCT conductivity meter that was frequently calibrated with a KCL standard. Dissolved oxygen was measured with a YSI Model 57 meter that was routinely air calibrated and occasionally calibrated against Winkler oxygen titrations.

RESULTS AND DISCUSSION:

Hydraulic Gradients, Groundwater Seepage, Sediment, Rainfall and Field Data.

Field data collected from the various OSDS sites between 4/15/06 and 9/6/06, sites are shown in Table 4. Groundwater dissolved oxygen content measured in the 2 inch piezometers, was low at all sites (< 1.6 mg/L). Mean DO levels from sites B2, C2, D2 and E2 were 0.70, 0.67, 0.80 and 0.58 mg/L, respectively. Groundwater temperatures ranged from 25.0 to 29.0 degrees C during the study. Groundwater specific conductance averaged 485, 986, 85 and 575 umhos/cm for Sites B2, C2, D2 and E2, respectively. Surface water dissolved oxygen levels were generally fairly high and always greater than 6.5 mg/L, with very high levels (> 11.4 mg/L), occurring at site E2, located near the north fork entrance to the St. Lucie Estuary. Noticeable algal blooms were present at this site.

Mean surface water dissolved oxygen levels for Sites B2, C2, D2 and E2 were 6.9, 6.5, 7.8 and 11.6 mg/L, respectively. The surface water specific conductance values were related to the proximity of the individual sites to the inlet, averaging 950, 693, 9600 and 10500 umhos/cm, respectively, for sites B2 to E2, respectively. The higher conductance values at Sites D2 and E2 reflect their close proximity to the inlet (higher salinity).

Hydraulic gradient, groundwater seepage and rainfall data for the FY O6 OSDS test sites are presented in Table 5. Although data are limited, vertical gradients were highest at Site D2 and lowest at Site E2, with mean values of 0.06 and –0.02, respectively. Horizontal hydraulic gradients were an order of magnitude higher at Sites C2 and D2 (with bulkheads) than Sites B2 and E2 (natural sites with little fill and no bulkheads). Groundwater seepage was not high at any site, compared to other locations in Florida, but the low measured values may be a function of meter location and could increase at other locations short distances away because the sediment depth and type was variable at most sites. The hydraulic conductivity and depth of the sediment influences groundwater seepage rates, and these parameters can change greatly from site to site. Because of this, we feel nutrient loading estimates using the measured seepage rates represent underestimates. Ideally, the seepage rates should be measured at numerous shoreline locations over several tidal cycles. In this study groundwater seepage rates ranged from 0 to 162 $mL/m^2/hr$, but measurements were limited due to bag leak and meter displacement problems. Because of this, loading estimates were not calculated and only concentration data at the shoreline are presented.

Table 4. Field Data Collected From Various OSDS Sites, By Date.

Location	Parameter	Unit	4/15/06 B2	4/15/06 C2	6/17/06 B2	6/17/06 C2	7/23/06 C2	7/24/06 D2	7/24/06 E2	9/6/06 C2	8/23/06 D2	8/23/06 E2
MW1	Depth[1]	ft	5.55	6.50	6.50	7.20	7.14	3.67	2.62	6.52	4.69	3.55
	DO	mg/L	0.7	0.7	0.4	1.2	0.5	0.5	0.5	0.4	0.5	0.7
	Temp	°C	-	-	25.0	26.2	26.0	26.2	29.0	26.7	26.5	29.0
	Cond	umhos/cm	550	700	700	820	750	-	70	750	-	900
MW2	Depth	ft	4.00	4.24	4.50	5.11	5.30	4.20	1.95	4.38	4.27	2.58
	DO	mg/L	1.3	0.8	0.4	0.6	0.5	1.6	0.4	0.3	0.6	0.7
	Temp	°C	-	-	26.4	25.5	26.5	27.0	28.2	26.6	27.5	27.0
	Cond	umhos/cm	190	720	340	1850	1200	-	380	1100	85	950
PZ	Depth in[2]	ft	3.08	-	-	n/a	-	4.21	4.37	1.65	4.11	4.00
	Depth out[3]	ft	3.70	-	-	n/a	-	4.70	4.10	1.65	4.38	4.00
SW	DO	mg/L	7.2	8.3	6.5	6.7	-	7.6	11.8	4.4	8.0	11.4
	Temp	°C	-	-	30.0	30.2	-	30.5	34.5	27.2	29.5	32.0
	Cond	umhos/cm	850	680	1050	350	990	6200	8000	750	13000	13000
Seepage	mL/hr		-	-	-	-	15.0	-	-	42.5	7.3	-

Notes:
1. Monitor well measurements are depth to water in feet.
2. in situ piezometer inside depth to water in feet.
3. in situ piezometer outside depth to surface water in feet.
4. "-" indicates not sampled

Table 5. Hydraulic Gradient (Δ H), Groundwater Seepage and Rainfall Data From OSDS Sites.

Date	Site B2			Site C2			Site D2			Site E2			Previous	Previous
	Vertical ΔH	Horizontal ΔH	Seepage (mL/m^2-hr)	Vertical ΔH	Horizontal ΔH	Seepage (mL/m^2-hr)	Vertical ΔH	Horizontal ΔH	Seepage (mL/m^2-hr)	Vertical ΔH	Horizontal ΔH	Seepage (mL/m^2-hr)	24 hr rain (in)	96 hr rain (in)
4/15/2006	0.070	0.003	-	-	0.013	-	-	-	-	-	-	-	0.00	0.00
6/17/2006	-	0.000	-	-	0.033	-	-	-	-	-	-	-	0.00	0.00
7/23/2006	-	-	-	-	0.061	58	-	-	-	-	-	-	0.00	1.16
7/24/2006	-	-	-	-	-	-	0.070	0.103	-	-0.030	0.008	-	0.00	1.14
8/23/2006	-	-	-	-	-	-	0.040	0.056	32	0.000	0.006	0	0.25	0.26
9/6/2006	-	-	-	-	0.027	162	-	-	-	-	-	-	0.38	2.39

Notes: Missing Δ H data (-) due to malfunctioning pressure transducer, or not sampled.
Missing seepage data (-) due to bag leaks, meter displacement or missing meter.

Normally, a significant inverse relationship is found between tide height and groundwater seepage, but from the limited seepage data collected in this study prevented a statistical comparison. Horizontal hydraulic ΔH gradients were much higher at Sites C2 ($\bar{x}$ = 0.033) and D2 ($\bar{x}$ = 0.080), than at Sites B2 ($\bar{x}$ = 0.002) and E2 ($\bar{x}$ = 0.007,), as shown in Table 5. The higher horizontal hydraulic gradient sites (C2, D2) represent sites with bulkheads, while the lower horizontal gradient sites (B2, E2) represent low gradient natural sites with very little fill. Horizontal and vertical hydraulic gradients were not statistically ($P<.05$) related to water quality (groundwater and surface water).

Sediment percent particle size and organic matter data are presented in Table 6 for Sites B2, C2, D2 and E2. Up gradient and down gradient sediment samples were collected near the OSDS drainfield and near the river, respectively, at each site. At each site, up-gradient and down gradient sediment data were very similar (Table 6). The two natural river sites, Sites B2 and E2, were very similar with medium and fine grained (combined) sand averaging 83.3 and 81.3 % of the sediment at these sites, respectively. At Sites C2 and D2, which were characterized by bulkheads and more fill, medium and fine grained sand comprised a lower percentage than at natural Sites B2 and E2, with averages of 71.4 and 73.5 %, respectively. Sites C2 and D2 also exhibited much higher percentages of very fine grained sand (Table 6). Percentages of organic matter at the four sites were low, averaging 2.43 0.35, 2.48 and 1.19 %, respectively, for Sites B2, C2, D2 and E2.

Table 6. Sediment Particle Size and Organic Matter Data.

Sediment	Site B2		Site C2		Site D2		Site E2	
Percent	Upfield	Downfield	Upfield	Downfield	Upfield	Downfield	Upfield	Downfield
Very Coarse	0.29	0.52	0.08	0.06	0.79	0.59	0.32	0.55
Coarse	4.33	11.45	1.77	2.04	8.95	4.28	8.44	10.48
Medium	45.74	47.36	18.23	18.22	33.16	29.07	54.21	48.07
Fine	37.93	35.54	51.11	55.13	42.95	41.86	28.38	31.96
Very Fine	11.19	4.93	27.89	23.99	13.49	22.43	7.98	8.53
Silt/Clay	0.53	0.20	0.92	0.57	0.66	1.77	0.67	0.42
% Organic	0.91	3.95	0.21	0.48	2.27	2.69	0.86	1.52

Site B2 Water Quality

The Site B2 residence was built in the 1980’s by the current occupants and has four residents (two adults and two teenage children). This flat, natural site is surrounded by water on three sides making it difficult to determine the exact flow path from the OSDS drainfield. Sampling locations covered a large area due to this fact, but all nutrient data were low, indicating very little down gradient movement (Table 7). However, because of the flow path uncertainty, the site was abandoned after the second sampling event. No bacteria samples were taken at this site.

Table 7. Nutrient and Turbidity Data for Site B2.

Site Location	NH_4-N (mg/L) 4/15/2006	6/18/2006	NO_X-N (mg/L) 4/15/2006	6/18/2006	SRP (mg/L PO_4) 4/15/2006	6/18/2006	Turbidity (NTU) 4/15/2006	6/18/2006
BPP1	0.00	0.10	0.05		0.15		400	
BPP1A				0.09		0.05		17
BPP2	0.00	0.90	0.05	0.12	0.00	2.10	324	>500
BPP3		0.40	0.15	0.11	0.15	0.80	150	95
BPP4	0.00		0.04		0.00		500	
BPP5	0.00	0.40	0.10	0.06	0.00	0.05	425	96
BPP6			0.07		0.85		150	
BPP7			0.07	0.06	0.55	0.30	>1000	87
BPP8			0.08	0.04	0.20	0.00	275	>500
BPP9			0.07	0.05	0.05	0.15	100	>500
BPP10		0.60	0.12	0.24	0.05	0.00	>1000	>500
BPP11	0.94		0.04	0.18	0.00	0.15	225	>500
BPP12	0.60	0.00	0.02	0.06	0.05	0.05	200	85
BPP13			0.00		0.00		>1000	
BPP14		0.05	0.07	0.11	0.00	0.00	150	78
BSW	0.00	0.00	0.01	0.10	0.00	0.25	25	5

Notes: > = over range

Site C2 Water Quality

This site was sampled four times, and data reflect a range of rainfall and groundwater level conditions. This residence was built in 1986 by the current occupants (two adults) and the septic tank and drainfield are located very close (< 20 ft.) to a canal (Figure 4). Nutrient, turbidity and bacterial data are presented in Table 8.With the exception of sampling locations CPP4 and CPP5 on 4/15/06, NH_4-N was generally low at upland sampling locations. Reducing conditions existed in the sediment near offshore piezometer sampling locations (CABS 7-11), and high NH_4-N levels were encountered. The high offshore levels were not influenced by OSDS loading, however. Extremely high NO_X-N levels ($\bar{x}$ = >6.80 mg/L) were consistently found at up-gradient sites CPP1 and CPP2, as well as CPP3, CPP4, and CPP5 on 9/6/06. NO_X-N levels were elevated at the seawall (> 6.0 mg/L) at Sites CPP9 and CPP10 on 6/23/06 and 9/6/06, respectively, 45 feet down gradient from the drainfield. Offshore NO_X-N levels were low (< 1mg/L) as would be expected in a low redox environment. SRP levels were consistently high at Site CPP1 ($\bar{x}$ = 2.5 mg/L), and remained high down gradient to the seawall at Site CPP7 (2.8 mg/L). Very high SRP levels were found at CPP3 (Fig. 4). Highest SRP levels were found at Sites CPP3 (17.80 mg/L) and CPP4 (4.85 mg/L) on 9/6/06. Highest SRP concentrations generally occurred on 9/6/06 at most sites, rather than other dates, and this is likely due to the higher rainfall occurring at that time (Table 5). Fecal coliform bacteria levels were high at stations CPP11 and CPP12 on 7/23/06, with levels of 50 and 20 colonies/100 mL, respectively, but these levels appear unrelated to OSDS loading and are probably of animal origin.

Table 8. Nutrient, Turbidity and Bacteria Data for Site C2.

Site	NH_4-N (mg/L)				NO_X-N (mg/L)				SRP (mg/L PO_4)				Turbidity (NTU)				Fe.Coli.(col/100ml)	
Location	04/15/06	06/18/06	07/27/06	09/06/06	04/15/06	06/18/06	07/27/06	09/06/06	04/15/06	06/18/06	07/27/06	09/06/06	04/15/06	06/18/06	07/27/06	09/06/06	07/27/06	09/06/06
CPP1	0.05	2.10	0.45	0.45	1.37	9.40	>7.0	14.50	2.70	1.55	2.65	3.05	50	2	0	0	<2	<2
CPP1A		0.35		0.00		8.00		6.65		0.45	0.75	0.75		4		0		<2
CPP2	0.05	0.40	1.30	0.80	5.40	0.86	8.50	>7.0	0.35	0.15	0.65	1.45	25	5	7	0	<2	<2
CPP3	1.95	0.80			0.30	0.10	>7.0	9.95	0.30	0.00	0.65	17.80	25	13	11	40	<2	<2
CPP4	>7.0	0.00	0.40	2.50	0.50	0.20	0.41	2.06	0.15	0.05	0.00	4.85	0	43	10	0	2	<2
CPP5	1.10	0.00		2.45	0.00	0.14		8.55	0.06	0.05		0.15	125	21		5		
CPP6	1.65	0.75			0.55	0.10	0.06	0.15	0.11	0.05	0.05	0.25	50	11	>500	20	2	
CABS7		8.20	2.55			0.18	0.39			0.00	0.00			67	65		<2	
CPP7	0.75	1.70	0.50	0.15	1.70	8.50	5.10	>15.0	11.30	2.20	2.45	2.15	0	72	21	10	<2	<2
CPP7T			0.45				>7.0				2.40	0.45			10		<2	
CABS8		3.90	>7.0	12.60		0.09	0.53	0.22		0.05	0.50	0.45		62	55	10	<2	<2
CPP8	0.60	0.40	0.60	0.35	2.58	2.14	OR	1.53	0.44	0.45	2.65	3.35	100	5	0	15	2	<2
CPP8T			1.45				OR				0.85				5		<2	
CABS9		4.00		7.75		0.43	0.20	0.19		0.10	0.05	0.15		59	63	5	<2	
CPP9	0.40	0.20	0.80	0.25	0.13	0.24	6.00	ORX5	0.30	0.95	2.80	0.45	150	4	0	60	<2	<2
CABS10			1.80				0.53				0.05				31		<2	
CPP10	1.15		0.55	0.55	0.04		>7.0	>7.0	0.15		0.25	0.45	50			80	<2	<2
CABS11				22.60				0.41				0.00				85		<2
CPP11	1.70	0.65	0.45	1.40	0.05	0.14	0.74	0.31	0.20	0.05	0.05	0.10	50	3	3	5	50	<2
CPP12	0.20		1.05	3.60	0.03		0.23	0.70	0.15		0.20	0.15	150			15	26	<2
CSWSW	0.15	0.75	0.45	0.90	0.01	0.43	0.23	0.20	0.05	0.05	0.15	0.55	50	2	2	10	50	1300

Notes: > = over range

Site D2 Water Quality

The home at Site D2 was built in 1975 and has had four residents since 2003.This bulkheaded site exhibited the highest horizontal and vertical hydraulic gradients of any site, with mean values of 0.080 and 0.06, respectively. Nutrient, turbidity and bacterial data for Site D2 are presented in Table 9.With only a few exceptions (DPP9, DPP10 DPP17), NH_4-N was generally low at Site D. NO_X-N, however, was high at Sites DPP1-6 located within 30 ft. of the drainfield (>5.20 mg/L), but levels dropped off significantly down-gradient. SRP concentrations were also high at Sites DPP1-6, averaging 15.40 mg/L, and levels down gradient at the seawall (stations DPP17 and 18) remained high ($\bar{x}$ = 4.5 mg/L). These sites were 66 ft. from the septic tank (76 ft. from drainfield) and indicated SRP loading to the estuary was occurring. Except for an extremely high fecal coliform level of 2400 col/100 mL at station 9 on 7/24/06, levels were low and did not indicate OSDS loading of bacteria to the estuary. Reasons for the extremely high value at station 9 are not known, but could be due to animal feces. The residents owned several dogs and they could be the source of the fecal coliform bacteria.

Table 9. Nutrient, Turbidity and Bacteria Data for Site D2.

Site	NH_4-N (mg/L)		NO_X-N (mg/L)		SRP (mg/L PO_4)		Turbidity (NTU)		Fe.Coli.(col/100ml)	
Location	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06
DPP1	0.00	0.00	0.20	>15.0	45.00	24.30	35		<2	<2
DPP2	0.35	0.35	13.30	>7.0	0.20	19.50	32		<2	80
DPP3	0.00	0.00	5.20	>7.0	5.75	22.00			<2	50
DPP4	0.00	0.15	0.23	>7.0	1.90	12.80	55		<2	<2
DPP5	0.00	0.15	0.45	0.16	>7.0	15.30	8		<2	
DPP6	2.50	0.30	0.20	>7.0	18.80	12.00	50		<2	80
DPP7	0.00	0.45	2.36	0.20	2.90	1.30	30		<2	2
DPP8	0.85	0.50	0.22	0.22	0.65	4.55	20		<2	<2
DPP9	0.10	2.95	0.26	0.17	3.00	13.80	12		2400	
DPP9A		0.40		0.30		4.20				220
DPP10	5.20	0.95	0.14	0.23	19.30	1.20	31		4	8
DPP11	0.77	0.45	0.17	0.20	3.10	0.75	11		<2	<2
DPP12	0.15	0.25	0.22	0.22	0.50	2.20			<2	2
DPP14	0.00	0.60	0.25	0.25	4.30	9.25	23		<2	7
DPP15	0.09	1.70	0.27		1.20					
DABS16	1.50	2.95	0.13	0.14	0.40	0.30	11		<2	
DPP16	1.50	1.70	0.19	0.17	3.75	2.65	12		<2	2
DABS17	1.60	>7.0	0.18	0.15	0.15	2.40			<2	
DPP17	>7.0	0.80	0.23	0.18	3.65	0.10	25		<2	4
DPP18		1.70		0.21		9.75				2
DSW	1.60	0.50	0.19	0.19	0.30	0.60	0		22	50

Notes: > = over range

Site E2 Water Quality

Site E2 represents the oldest residence (built in 1970) and the highest number of occupants (3-5), but was characterized by a low gradient, natural topography and appeared to have no fill material. The horizontal and vertical gradient at this site were very low, averaging 0.007 and –0.02, respectively. Nutrient, turbidity and bacterial data for Site E2 is presented in Table 10. NH_4-N was fairly low at all Site D stations. NO_X-N was very high at EPP3 ($\bar{x}$ = >9.55 mg/L) and EPP6 ($\bar{x}$ = 8.65 mg/L), but levels decreased rapidly down gradient. These two locations (EPP3 and EPP6) were approximately 35 and 53 ft. from the septic tank, respectively, and approximately 5 and 23 ft. respectively from the drainfield. SRP concentrations were also elevated at these same two sites with mean levels of 13.30 mg/L and >12.8 mg/L, respectively. SRP was high at down-gradient location EPP9 ($\bar{x}$ = 4.35 mg/L), located 45 ft. from the drainfield, but was low at all other sampling locations. Conclusive cause/effect fecal coliform loading from the septic tank was not demonstrated at Site E2, as levels were low on 8/23/06 and sporadic on 7/24/06, with no definite contamination plume being found. High levels at selected locations on 7/24/06 are probably due to animal feces, with migration enhanced by high rainfall at that time (Table 5).

Table 10. Nutrient, Turbidity and Bacteria Levels for Site E2.

Site	NH_4-N (mg/L)		NO_X-N (mg/L)		SRP (mg/L PO_4)		Turbidity (NTU)		Fe.Coli.(col/100ml)	
Location	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06	07/24/06	08/23/06
EPP1	0.70	0.70	2.49	0.26	2.00	0.30	0		<2	<2
EPP2	0.00	0.05	>15.0	1.64	3.80	3.20	0		<2	<2
EPP3	0.35	0.25	12.10	>7.0	13.30	13.30	0		<2	
EPP4	0.00	0.30	0.09	0.16	0.15	0.50	0		<2	
EPP5	0.60	0.10	0.12	0.20	2.00	0.25	0		2	<2
EPP6	0.00	0.20	15.00	2.29	18.50	>7.0	0		<2	
EPP7	1.30	1.00	0.04	0.17	0.30	0.45	0		300	<2
EPP8	0.00	0.40	0.15	0.27	0.15	1.95	0		<2	2
EPP9	1.20	0.85	0.15	0.17	0.60	4.35	0		80	<2
EPP10	0.00	0.00	2.66	0.16	0.05	0.15	0		23	2
EPP11	0.25	0.70	0.02	0.19	0.05	0.15	0		<2	<2
EPP12	0.20	0.30	0.01	0.14	0.20	0.15	0		<2	
EPP13	0.00	0.60	0.05	0.42	0.10	0.10	0		2	<2
EPP14	0.10	0.00	0.20	0.61	0.00	0.10	0		23	<2
EPP15	0.05	0.34	0.05	0.22	0.25	0.10	0		300	<2
EPP16	0.00	0.70	0.09	0.12			0		2	<2
EPP17	1.80	0.15	0.23	0.09	0.25		0		2	<2
EPP18	0.60	0.55	0.07	0.15	0.00		0		7	<2
ESW	1.75	0.00	0.04	0.11	0.30		0		70	11

Notes: > = over range

SUMMARY AND CONCLUSIONS:

This FY O6 study has provided information on the nutrient and bacterial impact of selected OSDS sites on the St. Lucie River Estuary. Data were obtained that determined contaminant plume migration distances at the various sites. The OSDS sites are representative of properly functioning systems, not failing systems, and are therefore typical of most OSDS in the watershed. Although Sites C2 and D2 appeared to discharge very high nutrient loads (NO_X-N, SRP) to the surface water, whether or not loading to the river occurs at any site depends on the actual distance of the OSDS drain field from the river as well as a variety of other factors. Data are presented that show nutrient and bacterial travel distances at the various sites, each with different sediment, hydraulic gradient, age and OSDS loading characteristics. These data are summarized in Table 12.

Exact site locations are shown in Figure 1. At Site B2, a natural, low gradient site, we found no nutrient or bacterial movement from the OSDS drainfield, but there was some uncertainty concerning the direction of groundwater flow at this site and therefore the site was abandoned midway through the study. Site C2, a high gradient site with a bulkhead and the septic tank drainfield located very close to a canal (15 ft.), showed NO_X-N and SRP loading to the canal, however no bacterial loading was observed. Site D2, an older bulkheaded residence (> 30 yrs) with high hydraulic gradients (vertical and horizontal) , exhibited SRP loading to the South Fork of the St. Lucie River Estuary from the septic tank drainfield (76 ft.distance), while NO_X-N had migrated approximately 30 ft. No significant fecal coliform movement was detected at this site, however. Site E2, an older (>35 yrs) low gradient natural site (no fill), exhibited high NO_X-N 23 ft. from the drainfield and high SRP concentrations at a distance of 45 ft. from the drainfield. No fecal coliform migration was detected. The shorter migration distances of NO_X-N and SRP at site E2 versus Site D2 are primarily due to the lower hydraulic gradients at that natural site compared to the high hydraulic gradient (bulkhead) Site D2. Sediment particle size and organic matter content was not a significant factor in explaining the water quality data, as the sediment data was similar for the four sites

This FY O6 study shows that SRP from 30-40 year old OSDS systems was capable of migrating 45 to 76 feet from properly functioning OSDS, while NO_X-N was found to move distances of 20 to 30 ft. At Site C2, NO_X-N and SRP had moved approximately 15 ft. to the seawall in 21 years, but conditions at that site were conducive for much greater movement had the septic tank been father from the canal. Although the sites selected in this study are considered representative, other OSDS locations may differ, as obviously site specific soil, hydraulic gradient, rainfall and loading characteristics are important in determining plume migration distances. Fecal coliform bacteria data were not highly definitive, and were only occasionally found in elevated numbers at locations near the OSDS drainfields. It appears the sandy soil is an effective filter for bacteria, but not for nutrients. In general, our studies indicate the OSDS can be important contributors of nutrients (NO_X-N, SRP) to the St. Lucie Estuary and its tributaries, given the right site conditions (e.g. high hydraulic gradients, older system, highly loaded, high percentage of sand, etc.), but that most properly functioning systems are not contributing significant fecal coliform bacteria.

Table 11. OSDS Site Characterization

Parameter		FY 2005 Site A1	FY 2005 Site B1	FY 2005 Site C1	FY 2005 Site D1	FY 2006 Site B2	FY 2006 Site C2	FY 2006 Site D2	FY 2006 Site E2
Year Built		1950's	mid 1970's	1984	2003	1985	1986	1975	1970
Current # Residents		2	2	2	4-6	4	2	4	4
Maximum # Residents		4 (until '96)	unknown	3 (until '91)	4-6	4	2	4	5
Mean Vertical Δ H		0.11	-0.01	0.14	0.29	0.07	-	0.06	-0.02
Mean Horizontal Δ H		0.022	0.018	0.055	0.024	0.002	0.033	0.080	0.007
Cumulative Seepage (mL/m^2-hr)		-172	9	122	-	-	162	32	0
Mean % ≥ Medium Sand		70.52	55.24	20.07	-	54.84	20.20	38.42	61.03
Mean % ≤ Fine Sand		29.47	44.76	79.43	-	45.16	79.80	61.58	38.97
Mean % Organic Matter		0.47	2.80	0.41	-	2.43	0.35	2.48	1.19
Estimated Nutrient Migration	NH_4-N	-	55	65	-	-	-	44	-
	NO_X-N	≥ 76	55-63	65	-	-	≥ 15	30	23
	SRP	52	55-85	65	-	-	≥ 15	≥ 76	45

Notes: Nutrient migration values of ≥ indicate nutrients have reached the river or canal, site dependent.

Nutrient and bacterial movement can increase in pulses with rainfall events. Our sampling schedule was fixed in advance and did not necessarily occur after individual rainfall events or after weeks of heavy rain, and therefore our data do not represent worst case scenarios. Although we did sample under a range of rainfall and other conditions, we would expect nutrient and bacteria levels to travel farther with higher rainfall and soil saturation conditions.

Eight specific OSDS sites were investigated in the combined FY O5 and FY O6 Issues Team Studies (4/yr). When the data for these two studies are combined, plume migration distances can be determined under a great range of environmental and OSDS conditions. Nutrient and bacterial travel distances for the two studies are summarized in Table 11, along with other pertinent site data. Although three of the eight sites were shown to be contributing nutrients to surface water, the nutrient migration distance data are more instructive since the OSDS installations were located various distances from the St. Lucie River Estuary and its tributaries. In the combined studies, NO_X-N traveled > 55 ft. at three sites (1.6 – 3.0 ft/yr), NH_4-N traveled > 55 ft. at two sites (1.1 – 3.0 ft/yr), while SRP migrated > 45 ft. at five of the eight sites (0.95 – 2.7 ft/yr). Aerobic conditions in and near the drainfield at most sites prevented high NH_4-N concentrations from occurring. From our data, it appears that residence age and horizontal hydraulic gradient are very important factors in determining plume migration distance (Table 11). Our data indicate nutrient travel distances (SRP, NO_X-N) are generally in the 1-3 ft/yr range at all sites. Sediment type can be a very important factor, but our sites exhibited similar sediment and therefore cause/effect sediment impacts were difficult to determine. The sandy (primarily medium/coarse grain) calcareous soils characteristic of the area are not particularly effective in adsorbing phosphate, as significant SRP travel distances were measured at the majority of the OSDS sites. Although slightly elevated fecal coliform bacteria levels were measured 28 to 55 ft. down gradient at two sites, the soil generally appears to be an effective bacterial filter. Our studies indicate that OSDS nutrient loading is a greater threat to the St. Lucie River Estuary than bacterial loading, unless the OSDS installations are failing.

LITERATURE CITED

American Public Health Association. 1985. Standard Methods for the Examination of Water and Wastewater. 15th Edition.

Belanger, T. V.,H. H. Heck, M. Sohn and P. Sweets. 1993. Sediment Mapping and Analysis in Crystal River/Kings Bay and Lake Panasoffkee. Final Report to SWFWMD. 230 p.

Belanger, T.V., H.H. Heck, and M.S. Andrews. 1997. Groundwater Flow Characteristics of the Mosquito Lagoon, Fl. Final Report, Project Number: CANA-N-027.000. Submitted to the Water Resources Division, National Park Service.

Belanger, T.V., H.H. Heck, C. Gefvert and S. Krupa. 2003. Seepage Meter Program for the St. Lucie River and Indian River Lagoon. Final Report submitted to the SFWMD (Contract Number: C-11835). 73 p.

Belanger, T. V. and R. A. Walker. 1990 Groundwater Seepage in the Indian River Lagoon, Florida. AWRA Proceedings of International Symposium on Tropical Hydrology. H. Krisha, V Quinones – Aponte, F. Gomez – Gomez and G. Morris, Editors. 367 – 375.

Belanger, T. V. and M. E. Montgomery. 1992. Seepage meter errors. Limnology and Oceanography. 37(8). 1787 – 1795.

Cherkauer, D. A. and M. S. McBride. 1988. A remotely operated seepage meter for use in large lakes and rivers. Ground Water, 26, 165 – 171.

Erickson, D. R. 1981. The hydrology of Williams Lake, Minnesota with special emphasis on quantification of littoral ground water contributions using seepage meters and wells. MS Thesis, University of Minnesota. 153 p.

Kearney, G. and B. Roesen. 1995. Indian River Lagoon Septic Study for Martin County. Report prepared for the SFWMD by the Martin County Public health Unit. 50 p.

Lee, D. R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnology and Oceanography, 22, 140-147.

Montgomery, M., 1990. A comparison of direct and indirect methods for estimating seepage in the Indian River Lagoon, Florida. M.S. Thesis. Florida Institute of Technology, Melbourne, Fl.

Pandit, and C. C. El-Khazen. 1988. Modeling of Water Exchange Between the Indian Lagoon and Surficial Aquifer in Port St. Lucie, Florida. Department of Civil Engineering, Florida Institute of Technology, Melbourne, Florida. 145p.

Reznicek, M. 2003. An investigation of direct measurement methods to estimate groundwater nutrient loading to water bodies. M.S. Thesis. Florida Tech. Melbourne. 109 p.

South Florida Water Management District. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. Technical Publication 87-1, SFWMD, West Palm Beach, Fl.

U.S. Environmental Protection Agency. 1988. Internal Working Draft, Oct. 6. A review of methods for assessing non-point source contaminated groundwater discharge to surface waters and their relevance to waste local allocations. Office of Groundwater Protection.

Zimmerman, C.F., J.R. Montgomery, and P.R. Carlson. 1985. Variability of dissolved reactive phosphate flux rates in nearshore estuarine sediments: effects of groundwater flow. Estuaries, (2B): 228-236.