Using Salinity Measurement, Tidal Correlation to Study Inflow/Infiltration in Lowland, Tidewater Areas

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Hallandale Beach is a community of 4.1 square miles and 18,000 households with a year-round population of approximately 34,000 people that swells to approximately 41,500 people in the winter season. The city is located in the southeastern part of Broward County, adjacent to both the Atlantic Ocean and the Intracoastal Waterway. It is approximately 1.5 miles north-south along the coast and goes approximately three miles inland to Interstate Highway 95.

The city produces its own water supply but pumps its collected sewage to the county's Southern Regional Wastewater Treatment Plant (SRWWTP) in the adjacent city of Hollywood. Hallandale Beach is a large-volume customer of that system with a total flow rate of 2.175 billion gallons per year, or 5.96 million gallons per day (mgd) average daily flow (ADF). The Golden Isles area (Pump Station Nos. 1 and 2's gravity collection basins) generates an ADF of 1.63 MGD, or 594 million gallons per year. Hallandale Beach's marginal cost to transmit and dispose of its sewage is approximately $2 per 1,000 gallons.

Normal design rules of thumb tell us that sewage flow in a mature collection system will be about 80 percent of domestic water flow. Modern design rates of 90-120 gallons per capita per day (gpcpd) for water supply are expected; a significant factor in the spread is whether or not potable water is used for irrigation. At these water-supply rates, only 80 gpcpd is expected for sewage.

As the sewer ages, infiltration and even illegal or accidental inflow connections will increase the flows somewhat, bringing the expected sewage-to-water ratio closer to 0.8-0.85. Citywide, Hallandale Beach has found that its sewage-to-water ratio is 1.49. In the eastern portion of the city, less the 3-Island residential area, the ratio was 1.7, or twice that which would normally be expected. The water component for these flows has been adjusted to take out the flows metered through irrigation meters. Also, while chloride concentrations in sewers inland, both in Hallandale Beach and further west, have been well below 100 mg/l, concentrations near the coast have been found to be in the 1,000-5,000 mg/l range. Abutting the coast, we will presume that where salinity values are reported, rather than chlorides, the two are approximately equivalent for practical purposes.

City officials have determined they have a problem with extraneous water entering their sewage system, both because of the sewage-to-water ratio and the elevated chloride/salinity values found. The city is under pressure to reduce these flows and saline intrusion for the following reasons:

- Paying to transmit and treat clean water is an obvious waste of tax and user-fee monies and should be eliminated or reduced where it is practical to do so.
- The SRWWTP, which is approaching its permitted flow rate, is under pressure to expand so that building activities in the user communities will not be limited. At the same time, the Florida Department of Environmental Protection and the U.S. Environmental Protection Agency are discouraging any increase in the flow allowed to be pumped through the outfall to the ocean. To permit an increase in total rated capacity, the SRWWTP has installed a reuse treatment facility and a reuse distribution network to use some of the effluent for irrigation. Reuse water with elevated chlorides kills the landscaping plants and grasses and can not be used, so Hollywood is pressuring its coastal volume customers and its own utilities department to reduce saline infiltration and thus lower the salt content of the effluent.
- Hallandale Beach is undergoing an intensification of its land use and density, which increases the demands on its infrastructure. Capacity in the sewers that is consumed by inflow/infiltration (I/I) flows can not be used for new-development flows. Also, Hallandale Beach has a cap on the volume of sewage the city is allowed to send to Hollywood. Reducing I/I is equivalent to adding piping, pumping, and treatment capacity.

The city's utility department has had an active, rigorous program of inflow location and elimination for many years. The I/I study described in this article has found that this control program has been highly effective, with only one study zone showing any impact from Hurricane Michelle. The city also is committed to begin a new sewer rehabilitation program to reduce infiltration and plans to perform I/I studies before and after the program to assess the effectiveness of the repair techniques utilized.

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The first zone to be studied and then rehabilitated is the greater Golden Isles area, along and toward the mainland side of the Intracoastal Waterway, south of the city's centerline. This area is composed mostly of 10 narrow, residential, lowland islands with detached, single-family dwellings and high-rise and low-rise condominiums, along with primarily residential, lowland areas on mainland streets closely abutting saline canals. An exception is a branch sewer of one of the two area master pump stations that runs north, away from the canals, and serves a mostly commercial area of strip malls and a major enclosed mall, but also some very large condominiums.

The several portions of the Golden Isles project area consist of approximately 27,000 linear feet of 6- to 30-inch gravity sanitary sewer (58+ inch-miles of pipe), approximately 110 manholes, three local lift stations and two master pump stations, plus the private system serving the large Gulfstream Race Track complex, which pumps into the study system and impacts the flows observed.

In South Florida, with its shallow, unsaturated soil zone to the groundwater table, a typical, thorough, upland area I/I study consists of dual wet- and dry-season monitoring to observe leakage patterns when the groundwater level is both seasonally high (typically August through mid-November) and relatively low (typically mid-January through April). This technique offers insight into the condition of the shallowest mainline sewers and also the service laterals.

The wet-season observations tell us about the maximum flows we are experiencing and the dry-season observations tell us about infiltration when shallow lines, particularly service laterals, are not submerged.

When the two results are compared, owing to the differences in groundwater levels, an estimate can be made of the relative magnitude of the leakage in the service laterals, which normally can be expected to account for perhaps half the total wet-season and rainfall-induced infiltration flows. This information will help guide where it is necessary to perform a lateral investigation and rehabilitation program, which is an expensive undertaking. Thus, we get insight into the magnitude of the problems we have with the service laterals.

In the first area to be studied, it is believed that the hydrogeology of the narrow islands and the near-shore streets offers very little opportunity for the groundwater to mound up during the rainy season and cause significant rainfall-induced infiltration. Instead, the tidal variation in the canals is thought to be the controlling dynamic impacting groundwater levels and infiltration. Since this hypothesis is proving accurate, the city will be able to gather the information it needs for approximately half the normal study cost because it will not need the additional season's data to monitor the leakage during the opposing season's groundwater level environment.

Normally, we see and attempt to estimate three classes of extraneous water flows entering the sanitary sewer system:

- **Inflow** is the direct runoff of rainfall into the sanitary sewer system from surface sources during and immediately after a rainfall event. Typical sources are open clean-outs, yard and roof drains, intentional or inadvertent cross-connections between storm inlets and their drainage pipes and the sanitary sewer lines, and open or leaky manhole frames and covers, especially in a street-flooding situation. Inflow usually produces a high spike of additional flow into the sewer that quickly fades after the rain event ends and the runoff dissipates.
- **Infiltration** is the direct leakage of groundwater into faults in the mainline sewer pipes, building-service lateral pipes, and manholes. Infiltration usually varies seasonally when prolonged or frequent wet weather elevates the groundwater table and the canal system, flooding sewer faults that are not submerged during the dry season and increasing the pressure on normally submerged sewer-system faults. Infiltration results in a relatively steady base flow.
- **Rainfall Derived Infiltration** is caused when a significant rain event temporally elevates the groundwater table, increasing infiltration. It occurs during both wet and dry seasons to differing degrees. Rainfall Derived Infiltration results in a prolonged increase in base-flow infiltration until the groundwater mound and/or canal levels drop to normal levels.
- We experienced very little rain during the observation month, except during Hurricane Michelle, and what rain we did experience had very little impact upon flows. Because there is little opportunity in our study area for rainfall to form a groundwater mound on the islands and the mainland areas abutting the waterway and its canals, a fourth mechanism became apparent: **Tidally Derived Infiltration**. The twice-a-day rise and fall of the tide varied the groundwater levels and, as we will see, had an impact upon nighttime flows (the impact upon daytime flows was masked by normal variations in sewage flows) and salinity observations. This mechanism allows us to learn, using one season's observations, what we would normally need dual seasons to accomplish in an upland community.

Our program can be seen as having two separate analysis phases: the conventional I/I phase and the tidally influenced flow and salinity analysis. In the conventional I/I program, as well as the current program in Hallandale Beach's Golden Isles area, the flow estimate is accomplished by first metering the rate of sewage flow, over time, while also measuring rainfall rates and groundwater levels.

URS Corporation was retained by the Hallandale Beach Utilities and Engineering Departments, which will be referred to as the Department, to conduct such I/I and sewer system evaluation surveys (SSES), as met the needs of the Department from time to time. The first such assignment under this contract was to assess the amount of extraneous flow entering the collection systems of Pump Stations 1, 2, 10, 11, and 15, located in the Golden Isles area.

The objectives of this study were twofold. The first objective was to provide a measurement of base conditions before the city undertakes cost-effective rehabilitation efforts to eliminate extraneous flow. After the rehabilitation program is complete, the flow measurement (I/I) protocol will be repeated to assess the effectiveness of the repairs.

The second objective was to locate and identify individual sources of infiltration and inflow and to provide direction and costs for a Phase II follow-up study. The Department's staff is conducting this task independently from the measurement task via smoke testing and CCTV in-sewer inspection. The objective of that SSES study is to investigate individual sources of I/I and provide remedial recommendations for I/I abatement.

URS and its subcontractors, Sewer System Evaluations Inc. (SSE) of Chicago and Video Industrial Services Inc. of Birmingham, Alabama, monitored the flows at five sewer locations, installed a local rain gauge to monitor precipitation, and also installed salinity monitors at all the sewage meter sites. In addition, a staff tidal gauge was installed and the city installed ground water pieziometers at selected manholes.

The sewage, rain, and salinity monitors recorded their data automatically and were periodically downloaded by the engineering team. The city periodically read the tidal staff gauge and the groundwater sight glasses. The staff gauge was used to standardize the predicted tidal levels available from Internet sources. Marsh-McBirney Flotote battery-powered, area-velocity type, open-channel,

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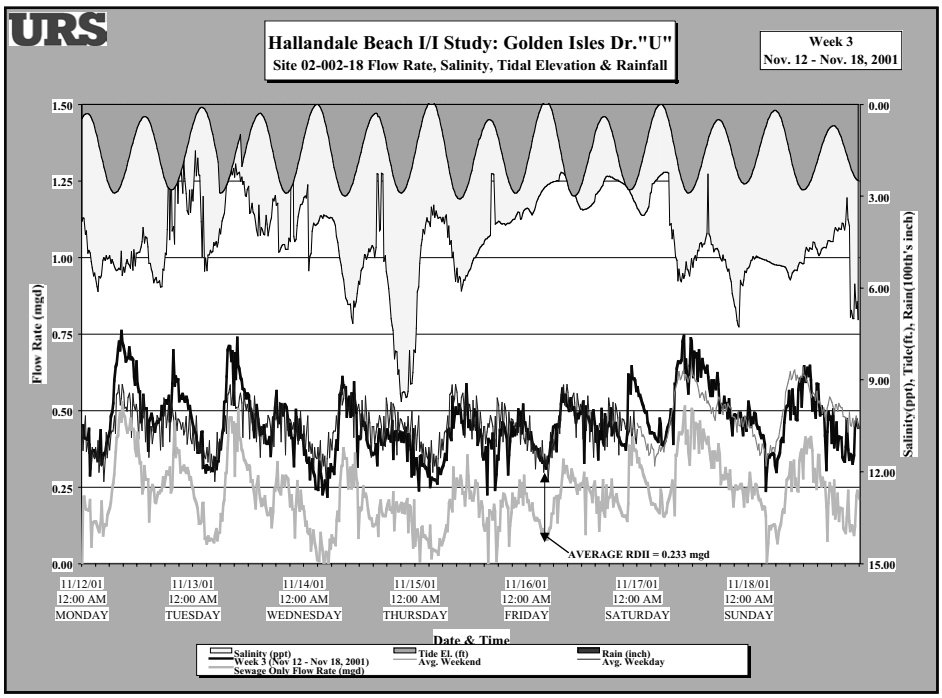


Figure 1

AREA	DESCRIPTION	LF	SALINITY (PPT)	INCH-MILES OF PIPE	OBSERVED INFILTRATION (MGD)	PRORATED RATE (GPIMD)
01-004:	All of PS 1 area, including PS Nos. 10, 11, 15 and + Gulfstream Racetrack PS; Not incl. Tennis Club PS or Beach Flow	5,605 + GFSTM system	Up to 14,000	17.01 + GFSTM system	0.289	16,966 less GFSTM footage
01-029	Sunset Drive: PS 10 & 15	6,850	Up to 6,600	10.83	0.025	2,308
02-001:	Diana Drive east of PS 2	2,100	Up to 7,500	3.18	0.030	9,434
02-002:-15	Hallandale Beach Blvd Commercial Area and Diplomat Pkwy Condos	16,170	Up to 9,200	27.62	0.185	6,698
02-002 -18	Golden Isles Drive Condos	3,350	Up to 9,500	10.44	0.233	22,318

Table 1

Inflow

Continued from page 31

flow-metering devices were used to calculate sanitary flow rates.

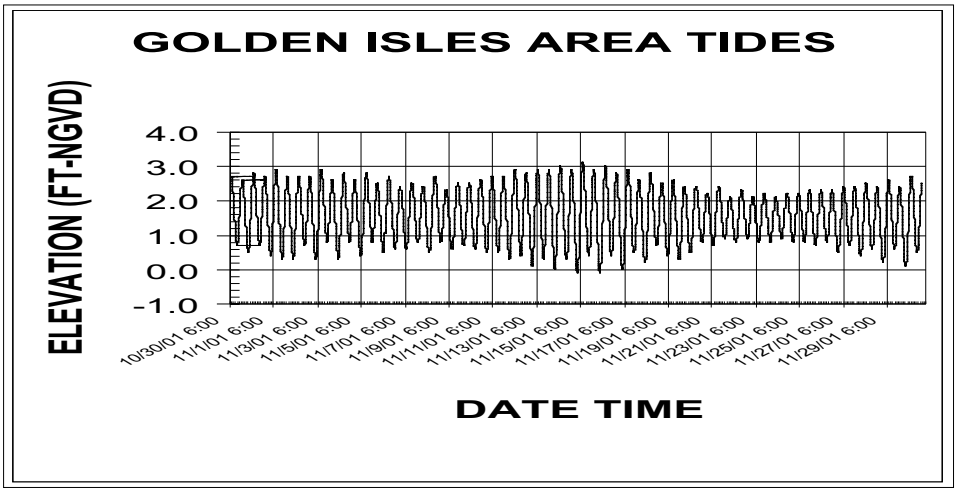
The meters were configured by SSE to calculate and record the average flow value every 15 minutes. The 15-minute time interval is used frequently for flow monitoring applications because it helps minimize real-time data fluctuations and significantly reduces the recorded data sets to a manageable size. This same recording interval is applied to the rainfall gauging activity so that recorded rain accumulation data and flow data corresponding to the same time frames can easily be compared.

A battery-powered "Ranger" data collector with a magnetic-contactor, tipping-bucket rain gauge was installed at Pump Station 1. The salinity probes were installed in each pipe so as not to interfere with the velocity sensors. Manufactured by Hydolab, the MiniSonde water-quality probe is a portable, water-analysis instrument. The battery-powered, self-contained probe was programmed to measure and record salinity every 15 minutes in parts per thousand (ppt) using the specific conductivity method.

Data were collected when the sewage flows were collected. All flow, salinity, and rain sensors were calibrated in place. The city also collected water-meter readings at the beginning and the end of the study period so domestic water consumption could be correlated with measured sewage flows.

Data were collected over 28 days from late October to late November 2001. First, the conventional I/I analysis was performed on the data. From that data (sewage flow, rainfall, tide levels, salinity, and water consumption), seven-day hydrographs were prepared for each week for each meter. **Figure 1** on page 31 is typical of those hydrographs.

Reading from the top, the dark-shaded sine wave is the tide elevations (scale in feet at right). The light-shaded area is salinity (scale in parts per thousand [ppt] at right). The thicker and thinner dark lines in the middle are the actually observed sewage flow rate (thick) and the monthly average daily diurnal flow hydrograph (thin) (scale for both in mgd at left). The last plot, the light line that is below and follows the actual flow curve, is the calculated, approximate "pure" sewage flow rate when all I/I is removed. The vertical distance between them is the average I/I rate for the month. In actuality, the I/I rate isn't constant, but varies with tidal level; however, this rate is very difficult to try to plot. In most areas, good correlation was seen between



MONTHLY AVERAGE FLOW AND SALINITY VALUES BETWEEN 2 AM AND 4 AM

Site		Flow (mgd)		Salinity (ppt)	
		High Tide	Low Tide	High Tide	Low Tide
01-004	Layne – Egret PS1	0.586	0.377	8.33	5.24
01-029	Sunset Drive, PS 10&15	0.052	0.032	3.58	3.61
02-001	Diana Drive, E/S PS 2	0.081	0.083	4.25	3.86
02-02-15	HBBE/Diplomat Pkwy, N/S PS 2	0.243	0.240	7.47	6.44
02-002-18	Golden Isles Dr "U, S/S PS 2	0.410	0.321	6.85	3.75

High Tide is when the water level exceeded +2.35 feet NGVD
Low Tide is when the water level was below +0.55 feet NGVD

Table 2

sewage flow, tidal level, and salinity, especially at night when most people are asleep.

For the five areas studied, the conventional portion of the study revealed that only one zone, 01-029, Sunset Drive, exhibited any response to rainfall (during the hurricane). One other area, 02-002-15, the northern commercial zone, suffered a flow-meter failure when debris in the sewer blinded the sensor and the first week's data was lost (also during the hurricane period). As for infiltration, both base and tidal derived combined, the results are summarized in **Table 1**.

The salinity concentration (ppt) in the Intracoastal Waterway was approximately in the mid to mid-high 20's during the first half of the study, when freshwater was being dumped at a high rate due to Hurricane Michelle, and around 30 ppt during the second half of the study. In western Broward County, well away from the ocean and Intracoastal Waterway, concentrations would be expected to be less than 0.1 ppt.

The areas were then examined for the nighttime flow patterns with respect to high and low tides. At first, all 24 hours of the day were examined in the database. Quickly it became apparent that the normal sewage flow variability during the day confused and masked the tidal effect, but when the examination was restricted to the early-morning hours, especially during the 2 a.m.-4 a.m. period, the effect was obvious in almost all cases.

It was first presumed that the tidal cycle could be arbitrarily broken up into three regimes: low tide, below elevation +1.0; high tide, above elevation +2; and mean tides. This division would allow a reasonable number of samples at the high-tide and low-tide regimes. In the tidal graph, the amplitude varies throughout the month; however, within these ranges, no clear flow differentiation could be observed. Therefore, the bars were raised and lowered, respectively, so that high tide was now elevation +2.4 and above and low tide was elevation +0.5 and below. Under these conditions, differential infiltrations were observable.

Following the tidal graph, **Table 2** shows the average infiltration and salinity of each sample point between 2 a.m. and 4 a.m. over the four-week period for the high-tide and low-tide regimes.

The islands and some of the areas abutting the waterway were created by dredging the Intracoastal's channel and using the dredge spoil as hydraulic fill. Typically this material is both compressible and of low permeability. While the low-permeability soils of the islands and the small tidal variation in the Intracoastal Waterway at this location made the use of this tidal/groundwater/infiltration investigative technique difficult, it was still possible to get meaningful results. It is believed that when this technique is employed to study the barrier beach, which is both sandy (and thus more permeable) and subject to higher tides and salinity concentrations from the ocean, clearer results will be achieved.

Conclusions

Among the areas under study, the Golden Isles Drive (Site 02-002-18) island, containing many condominiums of various sizes, exhibits significant leakage that is 4.5 times the Miami-Dade County guideline limit of 5,000 gpimd. This site shows a significant difference in both infiltration and salinity concentration at high and low tides. It is expected that both the mainline sewer and the service laterals are in need of further investigation and rehabilitation. Service lateral problems are anticipated.

The Layne Blvd./Egret area (Site 01-004) exhibits similar characteristics, if a somewhat lower infiltration rate, but this judgement is clouded by the absence of information at this time concerning the Gulfstream Race Track sewer system, which could have a significant lowering effect on the infiltration proration rate. It would appear to merit similar attention for further study and rehabilitation.

The commercial area/condo zone to the north (Site 02-002-15) exhibits excessive infiltration, although not to the extent of the first two zones. As expected, Site 02-002-15 does not have the same obvious high/low-tide relationship seen in the first two areas because, with the exception of the race track system, the commercial zone sewers are significantly away from the tidal surface waters. To understand the condition of the site's shallow pipes, such as service laterals, a dry-season, lower-groundwater observation would be needed.

The race track is away from the saline surface waters as well, which could mean that the balance of the Layne system, which is under the city's control, is exhibiting an even larger high/low tide leakage rate than the observed numbers indicate, due to the dilutional effect of the track's flow.

The Diana Drive system (Site 02-001), which abuts the waterway, also exhibits significant leakage overall, almost twice the 5,000 gpimd guideline, but doesn't exhibit a flow increase at high tide. It does show a somewhat increased salinity, however. There may not be a significant service lateral problem here.

Finally, the Sunset Drive, four-island system (Site 01-029), which is tributary to the Layne system, exhibits some infiltration and inflow, but no significant high/low tide differential values. Even the I/I rate of 2,300 gpimd rate is probably high, since it partially reflects the inflow during Hurricane Michelle. This area could benefit from a renewed inflow correction effort, but its magnitude wouldn't make it a high priority. Pipeline repairs in this zone shouldn't be a priority, either.