AN EVALUATION OF THE HYDROGEOLOGY OF MARATHON, FLORIDA, AND THE EFFECTS OF SHALLOW WELL EFFLUENT DISPOSAL

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EXECUTIVE SUMMARY

I have prepared this report at the request of FOLKS – Friends of the Lower Keys, to evaluate the fate and transport of sewage effluent disposed by the City of Marathon, Florida. I am a licensed Professional Geologist in the State of Florida with more than 35 years of experience as a geologist, engineer, and well driller in evaluating and documenting subsurface fluid flow, geochemical alteration, and the fate and transport of contaminants. I have performed work associated with this case, and prepared this report, on a pro bono basis, in order to add my support to the protection of the Florida Keys ecosystem.

The City of Marathon uses 12 shallow sewage wells at five sewage treatment plants to inject approximately 1 million gallons a day of partially treated sewage effluent into the groundwater beneath the island. The straight-line distances traveled by injected effluent to surface waters in Marathon range from 130 to 750 feet. The location of the City of Marathon is provided as Figure 1 in Appendix A.

The rock underlying Marathon has both primary and secondary natural preferential pathways (tunnels and high permeability zones) that allow rapid (up to 100 feet per hour) lateral and vertical migration of groundwater and any associated contaminants. There is no significant duricrust layer that impedes vertical flow from the wells to the groundwater table and surface water. Site-specific evidence documents migration of the effluent plume up to the water table, and to a distance of more than 400 feet from the injection wells. The vast majority of injected effluent moves through preferential pathways and reaches surface water in a matter of days or, at most, of weeks. A smaller portion of the injected effluent moves through smaller pores in the rock matrix. For this portion of the effluent, travel-time is slower.

There is minimal, if any, degradation, adsorption, renovation, or change in the majority of effluent chemical constituents before the effluent is discharged into surface water. Comparison of injected and groundwater concentrations of nutrients and inorganic parameters confirms that the groundwater contamination plume has the same chemical characteristics as the injectate. The effluent maintains its identity as sewage effluent in the plume when it discharges to surface water. The combination of effluent buoyancy and preferential tunnel pathways in the karst limestone, together with the gradients formed by injection and tidal variation, results in rapid transport and minimal changes to the effluent prior to its discharge to surface water. The effects of dilution in the subsurface are likely on the order of 10 times, and may range from 2-to-50 times depending upon the location. At the farthest end of this range, however, even 50 times dilution is not sufficient to prevent subsurface discharges of phosphorous and nitrogen from reaching surface water at concentrations in excess of surface water Strategic Targets set by the EPA to protect the Florida Keys National Marine Sanctuary waters.

The estimated nutrient flux to surface water is approximately 343 pounds/month total nitrogen and 90 pounds/month total phosphorous, with average concentrations released to surface water on the order of 0.15 mg/L for nitrogen and 0.04 mg/L for phosphorous (using 10 times approximate dilution).

In short, the Florida Keys consist of highly porous karst limestone riddled with "preferential pathways"—voids, tunnels, caves and conduits through which groundwater moves rapidly. Accordingly, I conclude that most of Marathon's sewage effluent reaches the surface waters of the surrounding Florida Keys National Marine Sanctuary quickly, in a matter of days or weeks. The majority of the pollutants that are characteristic of this sewage effluent, e.g., nutrients, sucralose, pharmaceuticals, hormones, and plastics, are not significantly affected by their short travel through the subsurface and are not held permanently in the rock. The injected sewage effluent, and the vast majority of its constituent contaminants, including nitrogen and phosphorous, are released to surface water.

A deep well is a geologically feasible improvement to Marathon's shallow injection wells. Such a well can be drilled, and they have been drilled in other parts of the Keys. Geology suggests it will be effective in eliminating discharge of effluent contamination to near shore waters.

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APPENDICES

I. BACKGROUND AND EXPERIENCE

I am a licensed Professional Geologist in the State of Florida, and have more than 35 years experience as a geologist, hydrogeologist and environmental engineer. I hold Master's and Bachelor's degrees in geology from Rensselaer Polytechnic Institute. My areas of expertise include evaluating and documenting subsurface fluid flow, geochemical alteration, and the fate and transport of contaminants. My Curriculum Vitae, including a list of depositions and trial appearances, is provided in Appendix B. I have performed work associated with this case, and prepared this report, on a probono basis, in order to add my support to the protection of the Florida Keys ecosystem.

I was asked by the counsel for Plaintiff Friends of the Lower Keys (FOLKS) to collect and evaluate data and information in regard to the injection of partially treated sewage effluent into the limestone karst below the City of Marathon. I was asked to calculate or estimate travel time as well as the fate and transport of nitrates, phosphorous and other contamination between the City of Marathon's shallow gravity injection wells used for partially treated sewage disposal and nearby surface waters. I was also asked to prepare an expert report summarizing my findings and conclusions, and to testify regarding those findings and conclusions

In estimating flows, fate, and transport of partially treated sewage effluent from the injection wells, I relied on my education, decades of relevant experience, professional studies and papers by others, observations of local bedrock outcrops, and collection and analyses of surface water samples. I was assisted by volunteers in the collection of samples. The documents and information I relied upon are provided in appendices to this report. The work I performed and the data, documents and information I considered, are of the type typically and reasonably relied upon by geochemists, hydrogeologists and geologists to evaluate chemical fate and transport in the subsurface.

The expert opinions presented in this report were reached by applying accepted methodology in the fields of geochemistry, hydrogeology and geology. The opinions expressed in this report are my own and are based upon the data and facts available to me at the time of writing. I hold these opinions to a reasonable degree of scientific certainty. Should additional relevant information become available, I reserve the right to supplement the discussion and findings presented in this report.

II. INTRODUCTION

There are five sewage treatment and disposal facilities operated by the City of Marathon, Florida (see Figures 2 through 7 for locations), referred to as the Area 3, 4, 5, 6, and 7 plants. Twelve Class V Group III shallow injection wells with existing Florida Department of Environmental Protection (FLDEP) permits serve as the sole method of disposal for partially treated effluent at this time. The injection wells are 6 to 12-inch nominal diameter, drilled to approximately 90-120' and cased to approximately 60'. Under these permits, every month, the City of Marathon submits "discharge monitoring reports" ("DMRs") to FLDEP reporting the volume of effluent injected at each sewage plant and the concentration of nitrogen and phosphorus in the discharge. Table 1 below presents summary statistics on Marathon's selfreported discharges between 2007 and 2022 based on collection and tabulation of the DMRs including average flows and nutrient concentrations injected at each of the five plants as well as distances from the injection wells to surface water. Appendix D is a table of the month-by-month data as reported in the DMRs.

In recent years, from 2018 to 2022, the City of Marathon average effluent injection rate is approximately 0.9 million gallons per day (MGD). The injected sewage contains, on average, approximately 343 pounds/month total nitrogen (TN) and 90 pounds/month total phosphorous (TP). The average concentrations of nitrogen and phosphorus in the injected effluent over the same time period are 1.50 mg/L nitrogen and 0.39 mg/L phosphorus.

Table 1: Summary of the City of Marathon Partially Treated Effluent Injection Wells								
Beginning of Injection to 2022								
Area	**Year Injection Began**	**Approx. Distance Inj. Well to Surface Water**	**Average Monthly Nitrogen Concentration and Calculated Load**	**Average Monthly Phosphorous Concentration and Calculated Load**	**Average Monthly Flow (MG)**	**Total Flow (MG)**	**Total Load of N (Tons)**	**Total Load of P (Tons)**
3	2012	700-750 feet	2.14 mg/L; 0.040 tons/month	0.81 mg/L; 0.016 tons/month	4.45	578.6	5.20	2.10
4	2010	700 feet	1.76 mg/L; 0.045 tons/month	0.46 mg/L; 0.012 tons/month	6.55	982.0	6.71	1.79
5	2007	750 feet	1.94 mg/L; 0.049 tons/month	0.34 mg/L; 0.009 tons/month	6.71	1,261.3	9.17	1.71
6	2009	130-160 feet	1.94 mg/L; 0.016 tons/month	0.42 mg/L; 0.004 tons/month	2.26	352.3	2.53	0.62
7	2012	700 feet	1.80 mg/L; 0.009 tons/month	0.22 mg/L; 0.001 tons/month	1.29	153.6	1.10	0.13
All Areas Combined						**3,327.8**	**24.71**	**6.35**
2018 to 2022 Only								
			Average Monthly Nitrogen Load	**Average Monthly Phosphorous Load**	**Average Monthly Flow (MG)**	**Total Flow (MG)**	**Total N (Tons)**	**Total P (Tons)**
All Areas Combined			**0.171 tons/month** **(343 lb/month)**	**0.045 tons/month** **(90 lb/month)**	**27.27**	**1636.4**	**10.29**	**2.69**
Average Concentrations (All Areas)			**1.50 mg/L**	**0.39 mg/L**	(Calculated from Total N and Total P and Total Flow, above)			
Sources: Florida Department of Environmental Protection Permits and DMRs; Appendix D; USGS Topographic Maps - Marathon and Grassy Key Quadrangles. "Tons" = U.S. Tons.								

Partially treated sewage effluent is municipal sewage that has been processed by advanced wastewater treatment plants in an effort to reduce the nitrogen, phosphorous and pathogenic constituents to the maximum limits allowed by the permits. The acceptable discharge concentrations of pharmaceuticals, metals, and other non-nutrient constituents are not defined in the permits. Allowable average annual nutrient concentration discharges are permitted up to 5 parts per million (ppm) biological oxygen demand (BOD); 3 ppm total nitrogen, and 1 ppm phosphorous. (Source: FLDEP permits).

The allowable permit discharge limits for the sewage treatment plants are 300 times greater than the EPA developed surface water Strategic Targets of 0.010 ppm nitrogen and 130 times greater than the Strategic target of 0.0077 ppm phosphorous (as calculated using the wastewater permit limit and target limit for nitrogen). (Source: FKNMS 2017 Annual Report).

Samples were collected at Area 3 in autumn 2022 from the partially treated effluent prior to its injection into the ground. These samples were analyzed for nutrients, sucralose, metals, pharmaceutical compounds and other analytes. The sampling field notes and analytical reports are appended to this report. Table 2 provides a summary of the detected compounds.

Table 2: Summary of Compounds Detected in Area 3 WWTP Effluent, Autumn 2022, Prior to Injection

PPCPs*	Results (ng/L)	Nutrients	Results (mg/L)
Penicillin G	H 7.55	Total Nitrogen	8.5
Dehydronifedipine	4.48	Total Organic Nitrogen Calc	0.73
Diphenhydramine	1.64	351.2 Total Kjeldahl Nitrogen	0.73
Fluoxetine	13.1	353.2 Nitrogen, NO2/NO3 pres.	7.8
Thiabendazole	2.96	365.4 Phosphorus, Total	0.9
Cotinine	75.7	Phosphorus, Total (as P)	0.9
Metformin	1.21	Metals**	Results (mg/L)
Oxycodone	0.619	Barium	0.0095 I
Alprazolam	1.67	Nickel	0.0022 I
Benzoylecgonine	144	Vanadium	0.0015 I
Cocaine	0.344	Zinc	0.042
DEET	199	PFAS	Results (ng/L)
Metoprolol	2.43	PFBA	17.7
Norfluoxetine	1.81	Perfluorobutanesulfonic acid	35.5
Sertraline	0.818	Perfluoroheptanoic acid	8.6
Theophylline	16.9	Perfluorohexanoic acid	22.1
Valsartan	356	Perfluorohexanesulfonic acid	16.0
Diatrizoic acid	98	Perfluorononanoic acid	11.1
Iopamidol	4360	Perfluorooctanoic acid	32.9
Metronidazole	11.6	Perfluorooctanesulfonic acid	161.0
Estriol	32.9	PFPeA	38.6
		Sucralose***	Results (ng/L)
		Area 3 effluent sample	35,710

Sources: Appendix C; Pace Analytical Services (PFAS, Nutrients, and Metals results); Environmental Analysis Research Laboratory (EARL) at Florida International University Lab Report M2209C (Sucralose results); SGS AXYS Analytical Services (PPCPs Results)

Note: Samples for nutrients, metals, and sucralose were collected on September 20, 2022. The PFA sample was collected December 7, 2022

*Certifying lab reports that the letter "I" denotes: "The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit."

** Certifying lab reports that the letter "H" denotes: "concentration is estimated."

*** Certifying lab reports that "The sample [from Area 3, tested for sucralose] presented sucralose concentration above the upper limit of quantification, i.e. the highest concentration of the calibration curve (2000 ng/L), and had to be diluted in order to preserve the method accuracy. The sample was also analyzed for salinity using a refractometer."

III. GEOLOGY

Transport of the partially treated effluent in the subsurface is primarily controlled by the geology, injection rate, location, depth, and tidal variation in the receiving surface waters. Evaluation of the geology is needed to identify preferential pathways and the characteristics of the rock which control groundwater flow. In particular, these characteristics include the size, locations, connectivity and shape of the pore spaces and fractures in the rock.

The Florida Keys is a chain of small limestone islands which extends from near Miami to Key West. The geology less than 200 feet below Marathon's ground surface includes one main formation of Pleistocene age—the Key Largo Limestone. The Key Largo is primarily coral reef rock, but also includes rocks formed and reformed as beaches, mud flats and the islands. The Key Largo Limestone is the surface rock at Marathon and has a maximum thickness of over 200 feet (Hoffmeister, 1964 and 1968; Halley, 1997).

The Key Largo bedrock below the Keys was formed over hundreds of thousands of years; during that time the sea levels have fluctuated wildly, increasing and then dropping by hundreds of feet. Graphs of sea level changes for the past few hundred thousand years are provided as Figures 8 and 9 (USGS, 2017; Lidz, 2006). The horizontal X-axis on these graphs is time, extending from present day on the left, to the geologic past on the right. The vertical Y-axis is water depth/sea level elevation relative to the present time. These graphs show sea level changes of hundreds of feet, with low sea levels during periods of continental glaciation, and high sea levels during warmer periods like the present. In general, the rock was formed as coral reef, sand and mud during periods of higher sea level. As originally deposited, the coral reefs contained myriad intersecting tunnels, caves and other pore spaces, the sands had intergranular porosity (like the space between grains of sand at the beach) and the mud flats were perforated vertically by boring animals and roots. The solution holes, weathering and calcite precipitation in nearby outcrops, and the cores and well logs indicate historical dissolution of the limestone during previous low sea level conditions consistent with karstification of the rock. The Key Largo Formation has often been compared to Swiss cheese riddled with conduits and interconnected pore spaces, allowing for rapid transport of substances in the subsurface (Dillon, 2007).

As shown on Figure 9, at least five low seawater periods have been identified in the past 145,000 years which resulted in the rock beneath Marathon being exposed as islands more than 100 feet high. These five periods are identified in layers as Q1 through Q5 (earliest to latest) (Muller, 2002). During those low sea level periods, the rock was exposed and was dissolved by fresh rainwater, forming sink holes and expanding the pre-existing pore spaces into larger, interconnected networks ideal for the fast transport of groundwater. In some cases, the infiltrating water became saturated with the limestone carbonate minerals dissolved above the water table, and re-precipitated caliche or similar rock at or near the elevation of the water table at that time. Throughout its history, burrowing animals and tree roots penetrated and fractured the rock, encouraging water to flow vertically, even through the "Q" layers.

One basic principle of geology is "the present is the key to the past." This rule of thumb means that one can examine the current deposition, alteration and similar processes, and apply them to those that occurred in the past to create similar rocks. An examination of exposed Key

Largo Formation rock outcrops was performed with this in mind, and a summary is provided herein. Figure 10 is a photograph of the Key Largo Formation at Windley Key State Park, showing the primary coral porosity and secondary porosity caused by rainwater dissolution, tree roots and other factors. Photographic examples of primary porosity include Figure 11 (an eel in a coral cavern, and Figure 12 (coral). Figures 13 and 14 are photographs of the bedrock at Sombrero Beach in Marathon, showing the multitude of holes in the limestone, including those currently being used and expanded by mangrove tree roots. Figures 16 and 17 are at Crane Point on Vaca Key, and show secondary porosity including 10-foot and greater diameter solution sink-holes, and numerous holes which are being expanded by storm action, animals and plant roots. Similar evidence of porosity in the limestone is provided in Figure 18 showing characteristics of the bedrock at Bahia Honda State Park, located west of Marathon, and in Figure 19 showing a 5/8-inch vertical hole through a limestone fragment.

In addition to the evidence from nearby bedrock outcrops, there are a large number of geologic and driller's logs of borings and nearby wells in Marathon, including the well and coring locations shown on Figure 20. These logs indicate that the rock includes caverns, tunnels, and karst (limestone rock with multiple voids or holes in it formed by the historic flow of water underground through the rock). Such rock has high permeability and hydraulic conductivity (Geologic Logs: Sickle, 2008 through 2019, Florida Geologic Survey, 1995 and 1999, Applin, 1937 and Muller, 2002). Included with those data is Test Boring B-1, which has a photographic log from Marathon's Area 3 (Universal Engineering Sciences: UES, 2021 City of Marathon Improvements Data Report). Test Boring B-1 was drilled to 150 feet below ground surface for the City of Marathon in support of their recent permit application to almost double the capacity of the Area 3 treatment and disposal system. As shown on Figure 21, photographs of the Area 3 B-1 core show ubiquitous pore spaces (holes) and fractures (cracks through the rock). Additionally, there are many intervals where the B-1 core recovery was less than 50%, indicating the probable presence of large karst caves, conduits, or tunnels).

Concerning the possible presence of widespread duricrust Q layers, available data indicate that such layers are not present to a significant extent below Marathon and Area 3 as documented by the multiple boring and well logs referenced above. For instance: Attachment 2 to Marathon's August 13, 2021 communication to FLDEP states: "No definite duricrust zones were identified. … Testing is required to determine the permeability. Weathering of the limestone is suggested by the chalky nature of the sediments. This is particularly true from the uppermost sample to approximately 30 ft. Other zones may exhibit some weathering." (WEC; 2022 and 2022a). Additionally, monitoring well data in the vicinity of the Area 3 shallow effluent injection wells show the ubiquitous presence of the effluent plume at 10 feet below ground surface, above any hypothetical Q impeding layer (Ingalls, 2021 and 2022).

In addition, Area 3 B-1 core photographs (appended) show minimal recovery of core in the negative 13 to negative 20 feet elevation interval (approximately 16-23 feet below ground surface (fbgs)) including: 9% recovery of broken pebble-sized rock fragments between 10-15 fbgs, and 30% recovery of broken rock fragments between 15-20 fbgs (UES, 2021). The lack of core recovery suggests the presence of caverns in those intervals, not a horizontal impeding layer.

Furthermore, reports from logs of wells at Key Colony Beach indicate the thickness of the Q3-4 layer boundary is less than a foot and approximately 18 feet deep (Muller, 2002).

Other well logs from the area do not indicate that the boundary was observed at all (see attachments). Such thin and discontinuous layers are insufficient to provide significant vertical barriers to groundwater transport, particularly given the multiple vertical tunnels produced by benthic biota and mangrove roots (as shown in outcrop and core photographs; Figures 10 through 21).

Geologic logs are also available from the Applied Geoscience Services Section of the Florida Geological Survey for borings near Area 3 (including Wells #W-2, #W17918 and #W16738; locations of wells are provided on Figure 20). These documents do not describe black or brown cores typical of Q boundaries, but instead indicate that the rock is fossiliferous and coral limestone, and is porous and honeycombed at some depths (Florida Geologic Survey, 1999), has a possible high permeability (e.g. ability to transport water and effluent), and is poorly cemented in some zones. No aquitards or laterally continuous impermeable layers are noted down to depths below 120 feet in these logs. (Source: email and borehole reports provided by FLDEP; see Appendix E). Additional Geologic Logs were provided from regulatory@dep.state.fl.us in a September 6, 2019 e-mail in response to a public records request. Several of these well records documented tunnels and caves, including “cavernous limestone” (Class V Well Completion Reports dated 11/05/08, 11/25/08, 3/8/10).

IV. HYDROGEOLOGY - CHEMICAL FATE AND TRANSPORT

As discussed above, the Key Largo Formation karst limestone contains connected pore spaces, holes and voids which form a network of interconnected branching tunnels, conduits and caves. This section of my report explains the key factors that control how groundwater and injected effluent move through this geology.

To summarize briefly, the well log geologic descriptions, combined with outcrops and the well-known and documented depositional history of the Florida Keys, indicate that the rock has both primary and secondary natural preferential pathways (tunnels and high permeability zones) that allow rapid lateral and vertical migration of groundwater - on the order of 10-100 feet per hour. Most of the injected effluent below Marathon will migrate to surface water through the largest tunnels; as one would expect, more water flows through the bigger “pipes.” The flow in the larger tunnels is also faster than the flow though smaller pore spaces.

Based on consideration of the factors below, including the results of prior hydrogeology and chemical fate and transport investigations conducted in Marathon and at other locations in the Keys, most of the injected wastewater effluent travels from Marathon’s wells to surface water in a matter of days or weeks and will be subject to only minimal reduction in the pollution conveyed. This conclusion is further supported by site-specific data and on-site sampling. The subsections below explain how each of the key factors regulating the flow of groundwater and the chemical fate and transport of pollutants in groundwater supports this conclusion.

A. Porosity and Hydraulic Conductivity

Porosity is a critical factor in groundwater transport, particularly connected porosity such as tunnels, conduits, or caves. Extreme porosity variation has been reported throughout the limestone; a good example is the pair of borehole photographs of the Biscayne Aquifer in southeast Florida shown in Figure 22 which shows a large vertical conduit in the right-hand boring, and relatively solid rock in the lefthand boring (USGS, Water Resources Investigations Report 03-4208). Because wells are generally drilled vertically, some will not penetrate vertical conduits, even if the conduits are prevalent, as they are below Marathon.

Groundwater flow occurs in the pores (holes) in the rock, and is controlled by hydraulic conductivity (a measure of the connectedness, size and shape/tortuosity of the pores); the groundwater gradient (or slope); and the porosity (the relative volume of open holes or cracks in the rock). Most of the volume of groundwater flow occurs in large, connected pores, conduits, tunnels and/or caves if they are present.

As illustration, consider a water tank with two holes in the bottom, one the size of a garden hose, and the other a 12-inch sewer pipe. Most of the water in the tank will drain out the sewer-pipe sized hole. Similarly, most of the injected effluent below Marathon will migrate to surface water through the largest tunnels.

The Key Largo Formation has order-of-magnitude varying measured hydraulic conductivities and porosities, as is expected in karst, depending upon whether the monitoring well in question intersects one of the connected tunnel, conduit, or cave systems. The hydraulic conductivity has been measured up to 39,000 feet per day (fpd) in field-scale aquifer tests. (Water Science Associates, 2015, Reich, 2001, Briceño, 2015; GeoHydros, 2015; Paul, 1995; Shinn, 1999; Dillon, 2001).

Although, as discussed above, the Key Largo Formation is known to have five “Q” layers (also referred to as “duricrust layers”), there is no evidence that the uppermost of these duricrust layers are laterally extensive under Marathon or that they are preventing upward plume migration from Marathon’s injection wells to surface water.

B. Tracer Tests Demonstrate Rapid Movement of Injected Effluent

Because groundwater flows preferentially through the largest pathways in the rock, one of the most reliable ways to confirm discharge locations and develop a range of travel times is the use of a tracer test. In such a test, a tracer (a non-toxic chemical or biological substance) is injected into the well and groundwater is monitored for the presence of the tracer at multiple locations. Multiple tracer tests have been conducted in the Florida Keys, and many have shown highly variable transport times and preferential pathway migration (through tunnels or caves) resulting in rapid transport of effluent with little reduction in nutrient concentrations (Dillon, 2000 and 2003; Griggs and Kump, 2002; Paul, et. al., 1995; Dillon and Chanton, 2007; Chanton, et. al., 2001).

Tracer tests tend to predict a very wide range of travel times, but the majority of the groundwater flow moves in the largest pathways represented by the fastest (shortest) travel times observed. This is because, in any tracer test, only a few of the monitoring locations actually intersects the preferential pathway tunnels/caves. Those monitoring wells that do intersect preferential pathways show fast transport times, (which would result in minimal decrease in nutrients), while other wells at similar distances to the point of injection that do not intersect a tunnel show much longer transport times. Thus, if one drills and performs tracer tests on several wells, with some wells intersecting tunnels and others not, measured travel times vary by orders of magnitude (i.e. by a factor of 10, 100, or even 1,000) as shown in the horizontal transport rate column in Table 3 below. The fastest travel times presented in the last column of the table also represent the majority of the groundwater flow, since more water travels through the bigger pipes and tunnels. It is notable that all of the tracer tests had minimum transport times under six days for 750 feet of travel.

Table 3: Groundwater Velocities Measured in Nearby Studies

Study Author, Study Date	**Study Location**	**Horizontal Transport Rate in feet per day (m/hr)**	**Minimum Transport Time for 750-foot Distance**
Paul, 1995	Key Largo	45-1,912 (0.57-24.2)	<½ day
Paul, 1997	Key Largo	197-2,765 (2.5-35)	<1/3 day
Dillon, 1999	Key Largo	16.6-259 (0.21-3.28)	3 days
Elliot and Kump, 1999	Key Colony Beach	21-241 (0.27-3.05)	3 days
Dillon, 2000	Long Key	0.24-174 (0.003-2.20)	4 1/3 days
Chanton, 2001	Long Key	6.3-137 (0.08-1.74)	5 1/2 days
Briceno, 2014	Cudjoe Key	72-1,824 (2.74-23.17)	<½ day

In six of the studies, wells were drilled into the Key Largo Formation (the same geological formation that underlies Marathon). In the case of the Cudjoe Key study, the injection and monitoring wells were reportedly completed in the Miami Formation, but the borehole logs indicate that the aquifer material was heterogeneous and fossiliferous, and that dissolution cavities were common, similar to the Key Largo (Briceño, 2015 and 2017; GeoHydros, 2015; Water Science Associates, 2015; Zednek, 2015).

C. Hydraulic Gradients

Migration of the effluent plume in groundwater is controlled not only by porosity and hydraulic conductivity as described above, but also by the hydraulic gradient, or slope. In Marathon, the gradient/slope is generally controlled by tides on both sides of the islands. NOAA predictions of tides near Area 3, both on the Florida Bay side and in Boot Key Harbor south of Vaca Key, are available online. The upper half of Figure 23 shows the tidal variation on both sides, and the offset in time between the tide peaks. Normal tidal variation on the Florida Bay (north) side is 1-1.5 feet, while it is 1.5-3 feet in Boot Key Harbor. The NOAA data indicate a lag in the high-low tide peak times between the Bay and Boot Key Harbor stations. This natural change in gradient causes groundwater to flow first in one direction, and then the other on a daily basis. The graph also illustrates the diurnal and lunar variation in tides. Seasonal variation has been documented in the Florida Keys as well, and alters contaminant transport, although groundwater migration from Florida Bay towards the Atlantic Ocean appears to be dominant (Santos et. al., 2008). The gradient between the Bay and Boot Key harbor is shown on the lower half of Figure 23; when the purple line is above the horizontal zero, the gradient is towards Boot Key Harbor.

Another source of hydraulic gradients is the injection itself. When effluent is injected into the ground, it raises the elevation of the groundwater table in the vicinity of the injection well. This increases the water level around the well and creates a “groundwater mound” and increased hydraulic gradient, which in turn pushes the injected effluent away from the well.

Figure 24 shows a conceptual cross section of the direction of effluent migration from an injection well to surface water during varying tidal conditions.

Changes in tides, changes in the injection rates, and seasonal changes alter the effluent plume in groundwater. The plume oscillates back and forth with the tides, and changes in size and concentration. However, since the effluent injection is continuous, as is the variation in tides, the plume does not disappear, but is kept in a state of "dynamic equilibrium."

As described above, the gradient/slope of groundwater based on measurements of the groundwater levels in the injection well, monitoring wells, and surface water are critical to predicting and evaluating plume migration. As of April 2023, Marathon has not provided data regarding the water levels or size of the groundwater mound at Area 3 (or the other areas), however a well injection test in the Key Largo Limestone on Cudjoe Key caused a measured 4-5 feet of water level rise, and a similar order-of-magnitude rise is likely in Marathon (Geohydro, 2015).

Due to the groundwater mounding at the injection well, the hydraulic gradient will always be away from the well, driving the effluent plume towards surface water. However, the tidal variation creates a "dynamic equilibrium" in the contaminant plume as described above, in which it oscillates back and forth in response to tidal variation and "tidal pumping." That is, the majority of the effluent discharge to surface water occurs at low tide, on one side of the island or the other. When the tides change, a portion of the effluent plume contamination remains in the groundwater, and then migrates further with the next change in tides. Figure 25 shows a conceptual model for this pulsed migration (National Academies of Sciences, Engineering and Medicine: Characterization, Modeling, Monitoring, and Remediation of Fractured Rock, 2020).

Another driving force causing migration of the injected effluent plume is buoyancy. The injected water is generally "fresh", compared to the saline groundwater. Since fresh water is less dense, it rises and floats over the saline groundwater to the water table, likely within 50 feet of the injection well, through the preferential vertical pathways. Initial data from Area 3 indicate that the effluent salinity is about 1 to 1.5 parts per thousand, while the groundwater salinity is 35 parts per thousand (or about the same as seawater) (Ingalls, Nov 2021). The Area 3 geophysical data in Figure 26 show a buoyant effluent plume near the Area 3 injection wells (Ingalls, Nov 2021).

The data presented above and in Figure 26 on the salinity of Marathon's effluent and surrounding groundwaters is based in part on information from Pennsylvania State University (PSU) professors and their graduate students who have conducted multiple studies of groundwater hydrogeology and contaminant transport in the Key Largo Limestone of the Florida Keys. Recently, Professor Lee Kump, Professor Miquela Ingalls and others from PSU received a grant from the EPA to quantify the impact of shallow wastewater injection on groundwater nutrient fluxes to surface waters in the Florida Keys National Marine Sanctuary. This ongoing study is being conducted at the Marathon Area 3 treatment plant and effluent injection area.

The research team from PSU is using a variety of tools and measurements to study the flow of fluids through and around Marathon's Area 3 injection wells. While their experiments are not complete, early data provide information about the salinity and chemistry of effluent and groundwater, measurements of electrical resistance and conductivity in the subsurface, and other factors that help to characterize subsurface flow in this part of Marathon. Previously, Professor Kump conducted studies at Key Colony Beach near Marathon in the 1990s and early 2000s (Griggs and Kump, 2003; Elliot and Kump, 1999).

D. Dilution and Dispersion

Contaminant concentrations injected into groundwater can be reduced as the plume migrates by dilution (mixing with groundwater) and by dispersion (spreading of the contaminant plume). For a one-time release, spreading of the contaminant plume through dispersion reduces concentrations with distance. However, dispersion is relatively unimportant in terms of concentrations entering surface water during long term effluent injection such as the continuous injection of partially treated effluent that is occurring in Marathon. During long term injection, the mass and concentration of pollutants is continually renewed, resulting in a broad contaminant plume with similar concentrations to that of the injected liquids.

Dilution does not decrease the total mass of contaminants released to surface water; it is merely mixing the effluent with the saline groundwater. For Marathon, dilution is minimized because of the buoyancy effects from the low salinity injected effluent. The salinity differences inhibit mixing of the two liquids. The buoyant effluent rises rapidly and creates a “lens” of low salinity liquid floating on top of the naturally saline groundwater. This “freshwater lens” phenomenon is well known in coastal environments, where naturally occurring floating rainwater in the subsurface often provides potable water for islands and near-shore communities.

The conduit flow common in karst cave and tunnel environments also inhibits dilution in the subsurface. The injected effluent preferentially flows through the larger conduits, under pressure from the groundwater mound created by injection. The increased pressure (head) in the conduit prevents intrusion by the natural saline groundwater, and relatively unmixed and undiluted contaminants are released to nearby surface waters.

E. Degradation, Mineralization and Sorption

Other mechanisms that can potentially reduce contaminant concentrations are generally included in the term “attenuation”. Attenuation means a reduction in the contaminant plume concentration, generally through the processes of biological or chemical degradation, mineralization/precipitation and adsorption.

All of these processes take time to occur. Attenuation of an effluent plume generally correlates inversely with the time spent in the subsurface. The longer the contaminant plume spends in the subsurface, the more opportunity there is for nitrogen to be biologically transformed, and for phosphorous to be temporarily adsorbed or mineralized. Short transport times and periods of only days or weeks in the subsurface are generally insufficient for substantial attenuation to occur.

Nitrogen is transformed via a variety of biochemical processes, many of which are dependent upon the oxygen levels in the subsurface. Many of the biological processes are dependent upon aerobic (air breathing) bacteria. Low oxygen levels are not conducive to aerobic bacteria. The addition of nutrients to groundwater often causes biochemical changes in the groundwater chemistry, including depletion of oxygen. As a result, initial rapid denitrification is followed by reduced transformation rates as the groundwater chemistry is altered by long term effluent injection (Chanton, 2001). Figure 27 includes vertical profiles, or slices through the aquifer at Key Colony Beach, and maps the nitrogen concentrations with distance from the injection well (vertical line on the profile). As shown in the profile in the lower left of Figure 27, nitrogen migrates more than 500 feet eastward to the Atlantic side of the Key with virtually no reduction in nitrogen concentration.

Phosphate theoretically can be adsorbed to limestone or captured by precipitation or mineralization (incorporation of phosphorous into a solid phase). Phosphorous adsorption is a reversible process and there is a maximum limit of sorption.

Phosphate adsorption to limestone could be compared to static electricity, say while doing laundry. If you wash a fluffy towel with a permanent-press shirt, the lint particles stick to the shirt because their concentration is high in the wash water, and they are attracted to the shirt by static electricity. However, as when cleaner groundwater or seawater contacts limestone with high adsorbed phosphate, it desorbs, if you rewash the shirt in clean water, the lint particles are mostly removed, and are flushed away down the drain. In the case of phosphate, each incoming tide brings cleaner water in contact with the limestone; the phosphate is desorbed and dissolved into the water and is then carried further from the injection well source to surface water.

Some studies indicate that long term effluent injection will eventually expand the plume of elevated phosphorous concentrations all the way from the injection well to surface water via pulsed migration (Dillon et. al., 2007). During continuous injection, phosphate is remobilized from the near-injection surface sites, as the system evolves toward equilibration with phosphate-free ambient groundwaters. This desorption reactivates the near-injection surfaces, allowing for rapid scavenging of phosphate from subsequent injections. The remobilized phosphate is dispersed further from the point of injection. Studies show that the rate of phosphate attenuation reduces over time, likely as adsorption sites are filled, so the initial attenuation of phosphate will not continue over the long term, and eventually the phosphate will desorb back into solution. Experiments conducted at the Keys Marine Laboratory showed a rapid removal of phosphate initially, followed by a much slower rate of uptake which declined over time (Chanton, 2001). As shown by the lab data, phosphorous adsorption can take months, and is susceptible to desorption (Ingalls, Nov 2021).

Additional data support the conclusion that continuous effluent injection creates dynamic equilibrium or "steady state" conditions under which nutrients are no longer significantly attenuated, particularly in preferential pathways. Following are some quotations from the 2001 Chanton et. al. study and additional investigation reports describing those limitations.

- "Relative concentration changes monitored over time indicated that both phosphate and nitrate acted non-conservatively in the subsurface. Phosphate showed an initial rapid uptake followed by a slower removal, possibly caused by adsorption-desorption reactions. …" "<u>However, these experiments were conducted at a relatively small facility (2.6 m^3 wastewater injected per day), while some facilities in the Keys inject as much as 750 m^3 per day. Saturation of available adsorption sites and organic substrate availability may limit the efficiency of wastewater nutrient removal under such conditions.</u>" … "Perhaps the available sites for phosphate adsorption were saturated near the point of

> injection more quickly during the first (more concentrated, October) experiment, allowing further transport of measurable phosphate concentrations."… "De Kanel and Morse (1978) observed a rapid initial uptake followed by a slow decreasing rate of phosphate uptake with time. They attributed the differences to either lower phosphate concentrations or different mechanisms operative in seawater and freshwater. Uptake of phosphate observed in our experiments showed almost identical trends to those of De Kanel and Morse (1978). During both experiments conducted at the Keys Marine Laboratory, a rapid removal of phosphate was initially observed followed by a much slower rate of uptake which declined over time."… "It is apparent that after 5 and 2 days for the October, 1996 and June, 1998 experiments, respectively, that the phosphate SF6 ratios have reached a steady state. Calculated desorption rates ranged from 0.0007 hr-1 in Well# 1-13.5 to 0.007 - 0.012 hr-1 in Well# 1-18 for both tracer experiments."…."However, this calculation does not account for desorption, which probably occurs after the initial rapid uptake. Phosphate is remobilized from the near-injection surface sites between injections, as the system evolves toward equilibration with phosphate-free ambient groundwaters. This desorption reactivates these near-injection surfaces, allowing for rapid scavenging of phosphate from subsequent injections. The remobilized phosphate is dispersed further from the point of injection"… ."our nitrate results indicate an initial rapid denitrification rate at depth (within the first few hours), when nitrate and oxygen-rich wastewaters are mixing with the surrounding reducing saline groundwaters potentially producing a redox gradient, thus facilitating denitrification. This rapid removal is then followed by very little change in the nitrate, other than dilution, over time." (Chanton, et. al.,2001 and 2001a, underlining added)
>
> - "Results from the dual-tracer experiment showed rapid initial 3,2-PO^4 uptake followed by a slower rate of uptake. Other studies have also observed rapid phosphate removal followed by a much slower rate of uptake which declined over time by KLL (Key Largo Limestone)" … "This phosphate-equilibrated plume will most likely continue to expand with additional phosphate loading. It is difficult to predict the rate at which this will occur without additional column experiments." (Dillon et. al., 2003)

Multiple theories have been advanced as to the rate and processes of nutrient attenuation in the Key Largo Formation; however, to date, no repeatable field experiments have been conducted, primarily due to the complexity of seasonal and tidal effects on plume transport. In several studies, reductions in phosphorous and nitrogen at the margins of the contaminant plume have been reported, but those studies also show rapid conduit-flow towards some monitoring wells with little or no attenuation. For instance, in a PSU April 2021 Technical Advisory Committee (TAC) presentation, the discussion of Key Colony Beach testing stated: "Nitrate and phosphate were effectively removed from the slower velocity flow path margins by microbial N cycling and phosphate adsorption onto karst at Key Colony Beach, but nitrogen loads remained high in the central, faster flow paths."

Advanced treatment systems for municipal sewage generally rely upon aerobic biological processes in the sewage treatment system tanks. These treatment processes are basically enhanced forms of the natural biological degradation that may occur in the subsurface, and their efficiency is limited in regard to man-made pollutants, such as pharmaceuticals, sucralose, etc. So generally, significant reductions of sucralose mass do not occur either during treatment or in the subsurface (NCBI, 2022 Sucralose Fate from PubChem online downloaded 11-18-2022).

F. Summary of Chemical Fate and Transport

It is clear that fluids injected through shallow Class V wells in the Keys quickly discharge into the nearby surface waters through the highly porous and cavity-riddled limestone karst conduits. The rapid lateral and vertical migration of injected fluids – up to hundreds of feet per hour –mean that any injected contaminants discharge to surface water with minimal dilution or attenuation.

V. SITE-SPECIFIC DATA

This section discusses site specific data for Area 3, Area 4, and Area 6 collected by the City of Marathon, Pennsylvania State University, and from my own work. The site-specific data for Area 3 correspond to the explanations discussed above: that injected effluent travels swiftly and without much dilution or attenuation into the mangroves and surface waters of Boot Key Harbor and Florida Bay. I conclude that these results are generally applicable to all of Marathon's injection wells, since all of them discharge to surface waters at similar distances of 750 feet or less in a matter of days or weeks.

A. Area 3 Test Boring RC-1/B-1

The City of Marathon conducted drilling to obtain rock cores from Area 3 in 2021 (UES, 2021). As discussed above in Section III, the cores demonstrate that, as would be expected, the ground near the injection wells is a limestone karst of the type described above, that caverns and tunnels are present, and that no "duricrust" layer or other layer that would trap injected fluids and prevent vertical migration is present. The geology is exactly as expected and described above. As explained above, in these conditions most of the injected effluent is likely to move rapidly through preferential pathways into surface waters.

The porous, cavernous nature of the subsurface is documented by the Area 3 on-site B-1 rock core. Per the March 30, 2021 Geotechnical data letter report from Universal Engineering Sciences to Edward Castle, The Weiler Engineering Corporation: "The 150 feet of rock cored in 2021 at the Marathon Area 3 RC-1 test boring consisted of interbedded sandy to fossiliferous, vuggy limestone and medium to fine sand layers to the termination depth of 150ft below ground surface. The thickness of the sand layers was variable with multiple coring runs yielding no material recovered."

The lack of rock core recovery from many intervals suggests the presence of caverns and tunnels in the subsurface. Attachment 2 to the City of Marathon Area 3 Permit Application August 13, 2021 RAI Response states: “No definite duricrust zones were identified.” The weathering, porosity and calcite precipitation described in the core indicate historical dissolution of the limestone during previous low sea level conditions consistent with karstification of the rock.

B. Pennsylvania State University Studies

As discussed above, PSU has collected site-specific data for Area 3 to support ongoing research. This includes geophysical and water quality data showing a low salinity plume extending from the Area 3 injection well (Figures 26, 28 and 29). Wide-spread plumes from a single ongoing source, as documented in the PSU data, are expected due to the fractal branching nature of the preferential pathway tunnels, caves and connected pores in the rock.

In 2021, PSU installed multiple monitoring wells around the Area 3 injection wells as shown on Figure 28. Additional wells were installed in 2022. In total, PSU installed nine clusters of monitoring wells at distances of approximately 150-1,650 feet from the Area 3 injection well. Most clusters include 3-4 wells screened at approximately 10, 20, 50 and 90 fbgs.

The PSU monitoring well data show a low salinity effluent plume at 10 and 20 fbgs near the water table around the Area 3 injection well and extending in all directions, including north to Florida Bay as shown in Figure 29. The PSU salinity data demonstrate the presence of the effluent plume to more than 400 feet from the injection point. Slide 18 of the PSU November 2021 update concludes that the impact of shallowly injected wastewater on the subsurface system is clear, based upon observations in the monitoring wells hundreds of feet from the injection that: a. Salinities are depressed and b. Nutrient indicators are elevated. The presence of the injected effluent plume in the PSU shallow groundwater data confirms that there is no widespread horizontal “Q” “duricrust” impeding layer that prevents or slows the effluent from reaching the water table and surface water.

PSU states in their October 2022 report that: “The 20’ wells yielded salinities of 8.5 to 15.4, reflecting wastewater-groundwater mixtures approximately 25-50% wastewater.” That is, dilution of the injected effluent was measured on the order of two-to-four times. Other monitoring well data confirm insignificant dilution. For example, 2021 total phosphorous concentrations in well MN1-20 were 0.611 ppm, compared with 1.435 ppm in the injected effluent, confirming the migration of contaminants approximately 250 feet with less than three times attenuation, and exceeding the Strategic Target for surface water of 0.0077 ppm by multiple orders of magnitude.

Another way of presenting the water quality data is provided in Figure 31, which shows graphs of concentration versus distance for sucralose and the nutrients nitrogen and phosphorous. These graphs were prepared using the data from the PSU October 2022 progress report. Distance is on the horizontal axis, with the injection well on the left. Concentrations are shown on the vertical axis, and generally decline to the right with distance from the injection well. The presence of preferential pathways intersected by some monitoring wells is evident by the variation in concentrations at similar distances in all three graphs. The wells with higher concentrations (marked by + symbols in the Figure) represent tunnels/conduits intersecting specific wells, and the concentration of the majority of the effluent plume. The other data, shown as dots, represent slower moving portions of the plume where conduits were not intersected by the wells. Comparison of the initial effluent concentrations and change in concentration with distance for the conduit/tunnel wells is provided by the dashed line best fit natural log curves. The solid line curves are fit to the entire data set in each case.

Since sucralose is essentially non-reactive, it acts as a tracer, and can be used to measure dilution due to migration of the plume. Using the best fit curves in Figure 31, and the 750-feet distance to nearest surface water (Boot Key Harbor), attenuation to ~18% of the injection concentration due to dilution is measured. That is, an injected concentration of 100 will result in a concentration of ~18 being released to surface water. Comparison of the best-fit curves and measured attenuation for nitrogen provides a range of 17-33% of the injection concentration at 750-feet distance. If denitrification were significant, one would expect lower concentrations of the nutrients, but that is not the case. Comparison of the phosphorous data indicates a concentration of 2.5-33% of that injected at the 750-foot distance. These data suggest that phosphorous is being adsorbed in the zones of lower velocity, but passes through without significant attenuation in the caves and tunnels. In summary, the data show that minimal dilution and insignificant attenuation of nutrients is occurring in the preferential pathways and conduits that transport the majority of the effluent plume to surface water.

PSU also reported concentrations of minor elements in groundwater including calcium, potassium, magnesium, phosphorous, strontium, sulfate, bromine, chloride and sodium. PSU reported that monitoring well MN1-20, located hundreds of feet from the injection well, had concentrations of chloride, sulfate and bromine very similar to those injected. The relative percent difference between the monitoring well and injected concentrations were all less than 12%, indicating minimal dilution or dispersion in the subsurface. Many of these data collected from monitoring wells located hundreds of feet from the injection well were very similar to data from the injection wells, indicating minimal dilution or dispersion in the subsurface and documenting that the effluent plume identity is consistent during subsurface transport. A diagram showing the similarities between injection effluent and monitoring well chemistry is provided as Figure 32. Each well is shown as a separate graph. For each well, the left side of the graph portrays the injected effluent chemistry, and the right side portrays the chemical composition in the well. If the graph is a “mirror image” the chemical composition is similar (wells MS1-20, MW2-20 and MN1-20). If the left and right sides of the graph do not match, then there are significant chemical differences between the injected influent and that well (MW1-20 and deeper wells MS1-90 and MN1-50). These data confirm the fact that the composition of the effluent plume in the shallow groundwater hundreds of feet from the injection well has the same characteristics as the injected effluent.

Preliminary results of a 2022 tracer test performed as part of PSU’s larger study at Area 3 are presented in a PSU graduate student’s poster (Vipond, 2022). The data suggest horizontal transport rates of 5.6-16 feet per day (1.72 to 4.99 meters per day) to the north and east of Area 3 (i.e., no data was available measuring transport southeast towards the closest surface water in Boot Key Harbor). The data suggest that detection of the dye may be suppressed: “We suspect that high levels of organic matter are interfering with fluorescence measurements” (Vipond, 2022). Suppression of the dye would result in underestimates in transport velocity and overestimates of the travel time. Additionally, City of Marathon discharge monitoring reports indicate rates for Area 3 in June and July during the period of the tracer testing were about half those of historical rates, or even the rates a month before the testing commenced. The effect of reduced rates during the test would be longer estimated travel times.

C. Sucralose Testing

Another line of site-specific data comes from surface water samples. On behalf of FOLKS, I have participated in the collection of surface water samples from areas within Marathon's nearshore surface waters in proximity to several of the City's wastewater treatment plants. Documentation for this sampling and analyses is appended to this report.

The surface water samples collected on behalf of FOLKs were analyzed to determine levels of sucralose, a man-made artificial sweetener that is present in treated sewage but not in nature. Sucralose is excreted mostly unchanged from the human body, flows down the drain, and is discharged into the environment through wastewater treatment plants. Due to its ubiquitous occurrence and persistence, sucralose is used as a tracer of wastewater contamination in groundwater, landfill leachate, and drinking water. Sucralose has been reported in wastewater treatment effluent at 29.6 ppb, nearly the same concentration as the municipal wastewater influent. Less than 2% removal of sucralose by the wastewater treatment was reported. (Subedi and Kannan 2014 and 2014a).

Figures 33, 34 and 35 show locations of sucralose samples collected between 2019 and 2022 at Areas 3, 4 and 6, respectively. Table 4, below, provides the analytical results.

The data show high concentrations of sucralose in surface waters at Crane Point (proximal to Area 4) and in Boot Key Harbor (proximal to Area 3). FOLKs also detected elevated sucralose concentrations in surface water proximal to Area 6. The sucralose concentrations of surface water collected nearest the injection wells were generally one to two orders of magnitude higher than background samples collected further away.

Some of the Crane Point samples, collected about 1,200 feet from Marathon's Area 4 wastewater treatment plant, were collected from a visible plume of discolored water with an obvious odor, that was observed and recorded on multiple different days (DeMaria, 2019 and 2021). The presence of this plume containing high concentrations of sucralose demonstrates the transport of wastewater effluent to surface water. Samples for sucralose analysis collected from the center and margins of the visible grey water plume in 2019, and confirmation samples collected in 2021, had sucralose concentrations well above background conditions and high enough to indicate "human influence" in the surface waters (COAST, 2022).

Table 4: Sucralose Sample Analysis Results

Latitude (Decimal °)	Longitude West (Decimal °)	Sample Name	Area	Concentration (ng/L)	Date
24.72015	81.07335	1A	Crane Point - Area 4	264.8	10/05/2021
24.72037	81.07180	2B	Crane Point - Area 4	163.3	10/05/2021
24.72262	81.07180	3C	Crane Point - Area 4	104.6	10/05/2021
24.72027	81.07318	X	Crane Point - Area 4	121	7/15/2019
24.71960	81.07327	Y	Crane Point - Area 4	145	7/15/2019
24.72020	81.07277	Z	Crane Point - Area 4	89	7/15/2019
24.72027	81.07318	X	Crane Point - Area 4	157	7/22/2019
24.71960	81.07327	Y	Crane Point - Area 4	196	7/22/2019
24.72020	81.07277	Z	Crane Point - Area 4	54.1	7/22/2019
24.71185	81.08523	BKH A	Boot Key Harbor - Area 3	2838	3/1/2022
24.71058	81.08473	BKH B	Boot Key Harbor - Area 3	724	3/1/2022
24.70897	81.08528	BKH C	Boot Key Harbor - Area 3	215	3/1/2022
24.71185	81.08523	BKH A	Boot Key Harbor - Area 3	2650	3/1/2022
24.71058	81.08473	BKH B	Boot Key Harbor - Area 3	718	3/1/2022
24.70897	81.08528	BKH C	Boot Key Harbor - Area 3	100	3/1/2022
24.71185	81.08523	BKH A	Boot Key Harbor - Area 3	2930	3/1/2022
24.71058	81.08473	BKH B	Boot Key Harbor - Area 3	746	3/1/2022
24.70897	81.08528	BKH C	Boot Key Harbor - Area 3	189	3/1/2022
24.71185	81.08523	BKH Inlet	Boot Key Harbor - Area 3	1036	12/9/2021
24.37065	81.00321	S1	Area 6 - East	793	4/26/2022
24.37065	81.00321	S5	Area 6 - East-Duplicate	792	4/26/2022
24.37443	81.00271	S2	Area 6 - background	77.8	4/26/2022
24.73063	81.00486	S3	Area 6 - West	246	4/26/2022
24.71185	81.08523	BKH A	Boot Key Harbor - Area 3	1121	9/20/2022
24.71058	81.08473	BKH B	Boot Key Harbor - Area 3	676	9/20/2022
24.70897	81.08528	BKH C	Boot Key Harbor - Area 3	250	9/20/2022
24.70985	81.09015	A-1	Boot Key Harbor - Area 3	404	9/20/2022
24.70880	81.09007	A-2	Boot Key Harbor - Area 3	308	9/20/2022
24.70755	81.09055	A-3	Boot Key Harbor - Area 3	192	9/20/2022
24.71187	81.08303	B-1	Boot Key Harbor - Area 3	310	9/20/2022
24.70990	81.08273	B-2	Boot Key Harbor - Area 3	324	9/20/2022
24.71125	81.08243	B-3	Boot Key Harbor - Area 3	467	9/20/2022
24.71250	81.08722	Area-3	Injection well	35710	9/20/2022
24.70822	81.09058	A3-192	Boot Key Harbor - Area 3	192	11/28/2022
24.70897	81.08528	BKHC-250	Boot Key Harbor - Area 3	255	11/28/2022
24.70880	81.09007	A2-308	Boot Key Harbor - Area 3	293	11/28/2022
24.70985	81.09015	A1-404	Boot Key Harbor - Area 3	323	11/28/2022
24.71058	81.08473	BKHB-676	Boot Key Harbor - Area 3	354	11/28/2022
24.71125	81.08243	B3-467	Boot Key Harbor - Area 3	393	11/28/2022
24.70990	81.08273	B2-324	Boot Key Harbor - Area 3	493	11/28/2022
24.71185	81.08523	BKHA-1121	Boot Key Harbor - Area 3	631	11/28/2022
24.71187	81.08303	B1-310	Boot Key Harbor - Area 3	906	11/28/2022
24.71033	81.08297	B2-324Extra	Boot Key Harbor - Area 3	1742	11/28/2022

At all three areas, the sucralose levels are highest closest to shore and proximal to the injection wells. The concentrations in surface water generally decrease with distance from the injection wells. These data suggest that the sucralose in surface water is originating from bedrock discharge of the treated injected effluent. Additional data supporting a discharging bedrock source of sucralose is provided by samples and photographs of a visible plume observed in Boot Key Harbor in 2022 and 2023 (Figures 36-38). The visible plume is located in depressions at the bottom of the water column and appears to include clay-sized particles. Confirming evidence of a bedrock discharge of effluent at this location is provided by the elevated 1,742 ng/L sucralose concentration from sample (B2-324Extra), collected near the sediment surface from within the visible plume.

Additionally, I have reviewed the results of similar surface water sampling conducted by others, including COAST, an independent nonprofit that is not party to this case and that describes itself as "a registered 501(c)(3) nonprofit, based in Florida . . . dedicated to advancing the stewardship of oceans, estuaries, and coastlines using scientific research, education and innovative technologies." (www.coastecology.org/about). COAST described its sampling efforts, field observations, lab results, analysis and conclusions in a short report available on its website and appended to this report. (http://www.coastecology.org/science/wastewater.html#science-nav-bar). COAST reports: "There is a serious concern that partially-treated wastewater from shallow injection wells at a nearby wastewater treatment facility are likely the source of these unusually high concentrations of sucralose." (COAST, 2022).

The sucralose surface water data support the PSU groundwater data documenting minimal dilution of the injected effluent prior to discharge to surface water. The approximate 0.8-3 ppb surface water maximum sucralose concentrations near Areas 3 and 6 were approximately 1/10 to 1/40 of the 35 ppb reported in a sample collected from Area 3 effluent (COAST, 2022; FOLKs, 2022). The 35 ppb concentration of sucralose detected in the Area 3 effluent, in turn, appears consistent with results from other waste treatments plants, which report sucralose at concentrations of about 30 ppb. (Subedi and Kannan, 2014 and 2014a)

The lack of nutrient attenuation documented by PSU, combined with the ten-times dilution implied by the ratio of sucralose concentrations in surface water to effluent suggests that effluent from the injection wells is reaching surface water with nutrient concentrations approximately an order of magnitude above acceptable concentrations in surface water, whether using the observed annual average concentration of 1.5 ppm nitrogen or the maximum permitted concentration at any time of 3 ppm nitrogen (versus the surface water Strategic Target of 0.010 ppm).

D. Area 3 Effluent Sampling

Samples were collected from the effluent being injected at Area 3 on September 20 and November 29, 2022. The samples were collected and shipped on ice under chain-of-custody for analysis. The results of the analyses are provided in Table 3 above; and supporting documentation and laboratory reports are provided in Appendices C and D.

E. Personal Field Observations

I have examined multiple outcrops in the vicinity of Marathon. As shown in the photographs provided as Figures 13-19, at many outcrops the rock resembles a colander, with prolific vertical tunnels. I have found numerous sinkholes and vertical tunnels that extend beyond 4 feet in length in the bedrock outcrops near Marathon.

I have examined and sampled surface water in the vicinities of Areas 3, 4 and 6. I found much of the near-shore substrate in these areas to be limestone, not soft muck or sediment. In some areas near to the injection wells I found filamentous algae completely covering the turtle grass. I observed visible surface water plumes that were present over extended periods (months) and contained elevated sucralose concentrations relative to other locations further from injection wells.

I have examined the Area 3 sewage treatment plant and collected samples of its effluent for laboratory testing. Based upon the relative heights of the chlorine contact chamber overflow and the ground surface at the injection wells, the gravity-fed effluent may enter the well with an elevation head of 6.5 feet above ground surface. An in-line pump on the effluent pipe is reportedly not in use (personal communication with Mike Olivera, operator).

F. Velocity and Travel Time Calculations

A simple formula, the Darcy Equation, is a porous media calculation routinely used as an initial approximation of groundwater flow, and as a "reality check" for more complicated groundwater model results. Although the porous media approximation is not entirely valid for the karst geology, the equation provides an order-of-magnitude estimate. The equation is:

V=Ki/Phi
Where:
V is the groundwater flow velocity in feet per day
K is the aquifer hydraulic conductivity in feet per day (use same value as submitted by City of Marathon in permit support materials)
i is the groundwater hydraulic gradient in feet/feet (assume a three-foot injection induced groundwater mound based upon Cudjoe data and two feet tidal variation)
Phi is the aquifer porosity in volume/volume (use 30-40%, similar to the values submitted by City of Marathon in permit support materials)

Applying the Darcy Equation to the Area 3 effluent disposal area, and using K = 4,500 fpd, i = 0.007 (5 feet water groundwater difference divided by 750-feet distance to surface water), and porosity = 0.3 to 0.4; the resulting order-of-magnitude groundwater velocity is 75-100 feet per day. This estimate is similar to (but slower than) most of the Table 3 times projected based upon the tracer tests at nearby Keys This estimate is expected to be slower than the actual velocity for the following reason: The Darcy Equation assumes a uniform porous media (like sand); while the karst limestone below Marathon has preferential tunnels and conduits while act as pipes to transport contaminants more quickly than a tortuous intra-granule pathway.

It is critical to understand the limitations of porous media models, including the Darcy calculation discussed above. The Key Largo Formation is not a uniform porous media; it is not like beach sand, or a gravel bar. The rock beneath Marathon is karst limestone, riddled with interconnected caves, conduits and tunnels. As noted earlier, water preferentially flows through the largest of these pathways, and flows faster than would be the case in a uniform sand or gravel layer. Therefore, transport, velocity and attenuation estimates based upon the inaccurate porous media assumption will be underestimates, perhaps by orders of magnitude. As indicated by USGS Scientific Investigations Report 2016–5116: “Simulation of contaminant transport that does not account for preferential flow through conduits or extremely permeable zones in any approach is ill-advised.” (Kuniansky, 2016)

Low tide occurs twice a day, and transport towards one side of the island is limited to low tide periods unless the groundwater mound created by injection is larger than the tidal variation. In the absence of any on-site data regarding the height of the mound, and conservatively assuming transport to surface water on one side of the island one quarter of the time, this porous media formula predicts an order-of-magnitude travel time of approximately 4-6 weeks to Boot Key Harbor from the Area 3 injection well, excluding the “pipe flow” along preferential pathway tunnels and connected caves. As noted above, the presence of preferential conduit pathways will result in actual travel times much faster than that calculated by the Darcy Equation.

VI. MARATHON’S PLAN TO INCREASE INJECTION RATES

Marathon has applied for a permit to almost double the discharge of partially treated sewage effluent in Area 3 to almost 0.5 million gallons per day (annual average) using larger diameter injection wells. Increases in injection will increase the rate and mass (total amount) of nutrients, pharmaceuticals, and other contaminants released into surface water. Increases in the injection rates will not improve attenuation (will not cause decreases in concentrations in the subsurface), but instead are likely to shorten travel times to surface water, reduce any limited attenuation which is currently occurring, and increase loads and concentrations entering surface water.

The proposed increase in the rate of Area 3 effluent injection will result in a corresponding increase in the mass of nitrogen and phosphorous released to near shore and Halo Zone surface waters. The actual Area 3 effluent travel time of days to weeks to surface water is insufficient to provide sufficient attenuation of the effluent relative to surface water quality.

VII. REMEDY – DEEP WELL

Impacts to surface water from the excess nutrients and associated contaminants injected in the City of Marathon shallow effluent disposal wells will continue until alternative treatment and/or disposal methods are implemented. Proposed increases in effluent injection will increase the impacts to surface water.

One alternative, which has been implemented by all other major disposers of wastewater in the Florida Keys, is the construction and use of one or more “deep” injection wells. Deep (greater than 2,000 foot) injection wells were previously recommended for the Marathon treatment systems, but were rejected in lieu of the shallow 60-90 foot wells currently in use. Deep wells protect the near shore and Halo Zone water because they are drilled through multiple layers of low-permeability rock that are tens to hundreds of feet thick. These thick layers do not have the continuous vertical pathways presented in the shallow bedrock and thin Q “duricrust”, and therefore are effective at retarding migration of the effluent to surface water. A deep well is a feasible remedy from a geological point of view and has been implemented by other Keys facilities.

VIII. OPINIONS

In light of the discussion and analyses above, I have reached the following conclusions.

OPINION #1: Marathon's partially treated sewage effluent reaches surface waters within days, or at most within weeks, of injection.

For the vast majority of injected effluent, which moves through preferential pathways, travel-time from Marathon's shallow wells to surface water is a matter of days or, at most, of weeks.

A smaller portion of the injected effluent moves through smaller pores in the rock matrix. For this portion of the effluent, travel-time is slower.

If Marathon increases its injection rate, as it contemplates doing at Area 3, it will further accelerate the flow of effluent to surface water and the mass and rate of nutrients and other chemicals released to surface water.

OPINION #2: Marathon's partially treated sewage effluent travels about 750 feet to reach surface waters.

The straight-line distances traveled by injected effluent to surface waters in Marathon range from 130 to 750 feet. The majority of the effluent follows sub-surface interconnected preferential pathways from the wells and emerges at multiple locations near the edge of the surface waters, and thus are traveling distances approaching these straight-line distances. Some effluent is probably also emerging in discrete areas farther from the shoreline.

OPINION #3: Marathon's partially treated sewage effluent passes through a porous limestone karst containing horizontal and vertical conduits that serve as tunnels or pipes for the effluent.

Effluent passes through limestone karst with lots of preferential pathways – horizontal and vertical conduits that serve as a connected network of tunnels and allow the majority of effluent to move at very high speed.

There is no evidence of a widespread significant Q or duricrust layer that impedes vertical flow from the wells to the groundwater table and surface water. In fact, site-specific evidence from PSU at Area 3 documents migration of the effluent plume up to the water table, and to a distance of more than 400 feet from the injection wells.

Geologic descriptions of the well-known and documented depositional history of the Florida Keys, combined with hydrogeological and dye tracer tests, indicate that the rock underlying Marathon has both primary and secondary natural preferential pathways (tunnels and high permeability zones) that allow rapid (up to 100 feet per hour) lateral and vertical migration of groundwater and any associated contaminants.

OPINION #4: Due to the short travel times, there is minimal, if any, degradation, adsorption, renovation, attenuation or change in the majority of chemical constituents before Marathon's partially treated sewage effluent is discharged into surface water.

Due to the short travel times, there is minimal, if any, degradation, adsorption, renovation, attenuation or change in the majority of effluent chemical constituents before the effluent is discharged into surface water. Estimated denitrification and phosphorous adsorption/ mineralization times from multiple scientific studies of the Key Largo Limestone indicate there is insufficient residence time for the majority of the effluent to be chemically altered in groundwater. Nutrient data collected by PSU from monitoring wells at Area 3 confirm the persistence of injected nutrients in the subsurface. Comparison of monitoring well data with injected concentrations of inorganic parameters confirms that the groundwater contamination plume has the same chemical characteristics as the injectate.

The effects of dilution in the subsurface are on the order of 2-to-50 times depending upon the location, which are insufficient to prevent subsurface discharges from reaching surface water with phosphorous and nitrogen at concentrations in excess of surface water Strategic Targets.

The combination of effluent buoyancy and preferential tunnel pathways in the karst limestone, together with the gradients formed by injection and tidal variation, results in rapid transport and minimal changes to the effluent prior to its discharge to surface water.

The limited days-to-weeks time-of-travel from the injection wells to the surface water results in only minimal attenuation of phosphorous and nitrogen in the majority of the effluent.

A minor portion of the injected effluent is present within a low-permeability or low-porosity zone in the bedrock and has sufficient time to attenuate.

Pharmaceutical and personal care products which pass through the sewage treatment process are likely to migrate through the groundwater and enter surface water with little or no change in their chemical characteristics.

OPINION #5: All of Marathon's injected sewage effluent is released to surface water, with the vast majority of its constituents unchanged.

All of the injected effluent, with the vast majority of its constituents unchanged, is released to surface water. The permitted volume of partially treated sewage effluent, with its various effluent constituents, released from Marathon sewage treatment systems is an average of 1.08 million gallons per day of effluent, with the average value for 2018-2022 being 0.9 MGD. As set forth above, in Table 1, since 2007 Marathon has injected a total of 6.35 tons of phosphorous and 24.71 tons of nitrogen through its shallow wells.

Based upon the 2018-2022 reported injection flows and nutrient concentrations, the time-of-travel of days to weeks indicated by multiple studies in the Keys, the on-site PSU monitoring well water quality data, and minimal denitrification and phosphorous adsorption/mineralization, the estimated flux to surface water is approximately 343 pounds/month total nitrogen and 90 pounds/month total phosphorous, with average concentrations released to surface water on the order of 0.04 mg/L for phosphorous and 0.15 mg/L for nitrogen (using 10 times approximate dilution indicated by the sucralose data).

Because evidence and theory document little attenuation, a very high fraction of the injected effluent with its nutrients, sucralose, pharmaceuticals and the other pollutants is reaching surface water unchanged.

OPINION #6: Most of Marathon's injected sewage effluent emerges as concentrated discharges.

Due to the preferential pathways in the sub-surface, and the short distances and times to surface water, most of the injected effluent emerges as concentrated discharges in multiple specific areas, sometimes in the form of visible plumes.

OPINION #7: The injected effluent maintains its identity as partially treated sewage effluent when it reaches surface waters.

Marathon's effluent maintains its identity as sewage effluent. Nutrient data collected by PSU from monitoring wells at Area 3 confirm the persistence of injected nutrients in the subsurface. Comparison of monitoring well data with injected concentrations of inorganic parameters confirms that the groundwater contamination plume has the same chemical characteristics as the injectate. Groundwater and surface water testing document high concentrations of sucralose (a pollutant characteristic of sewage effluent) in groundwater and the surface waters near the sewage treatment plants.

Literature and geology also lead to an opinion that other chemical pollutants in the sewage that were sufficiently conservative to maintain their chemical identity through wastewater processing (such as pharmaceuticals) will retain that identity to the points of entry into surface waters.

OPINION #8: Marathon's partially treated sewage effluent discharges reach surface water at concentrations above EPA Strategic Targets.

Area 3 on-site data and numerous peer-reviewed scientific studies of effluent transport in the Key Largo Limestone demonstrate that Marathon's discharges cause exceedances of the EPA's Strategic Targets for protection of water quality in the Florida Keys National Marine Sanctuary. Those targets include: for all waters in the FKNMS, dissolved inorganic nitrogen should be less than or equal to 0.010 ppm and total phosphorus should be less than or equal to 0.0077 ppm. Average concentrations in effluent prior to injection from 2018-2022 are 1.5 ppm (mg/L) nitrogen and 0.4 ppm (mg/L) phosphorous (Table 1, above). Using 10 times approximate dilution indicated by the sucralose data, average concentrations of these nutrients released to surface water are on the order of 0.15 mg/L for nitrogen (15 times greater than the Strategic Target of 0.01 ppm) and 0.04 mg/L for phosphorous (5 times greater than the Strategic Target of 0.0077 ppm).

OPINION #9: A deep well is a geologically feasible and improved disposal alternative.

A deep well is a geologically feasible improvement to Marathon's shallow injection wells. Such a well can be drilled, and they have been drilled in other parts of the Keys. Geology suggests it will be effective in eliminating discharge of effluent contamination to near shore waters.

The public wastewater system cannot be shut down. Therefore, until Marathon finally decides or is required to implement a solution, discharges of effluent to surface water will continue, probably for years, until the solution is designed, permitted, built, tested, connected to the system, and finally put in use.

IX. APPENDICES

A. Figures
B. Resume of Donald M. Maynard, Florida Professional Geologist
C. Field Sampling Activities
D. Table of Discharge Monitoring Report Results
E. Other Documents Considered and Relied Upon (Bibliography)

Appendix A: Figures (Separate Electronic File)

Appendix B: Resume of Donald M. Maynard, Florida Professional Geologist (available upon request)

<u>Appendix C:</u> Field Sampling Activities (available upon request)

Appendix D: Table of Discharge Monitoring Reports (available upon request)

<u>Appendix E:</u> Other Documents Considered and Relied Upon (Bibliography)

Applin, E.	1937	Report on Samples from the Florida East Coast RR Weel Drilled at Marathon, Key Vaca, Monroe County Florida Well W-2
Batelle	2007	Evaluation of the Water Quality Protection Program and Science Program for the Florida Keys National Marine Sanctuary
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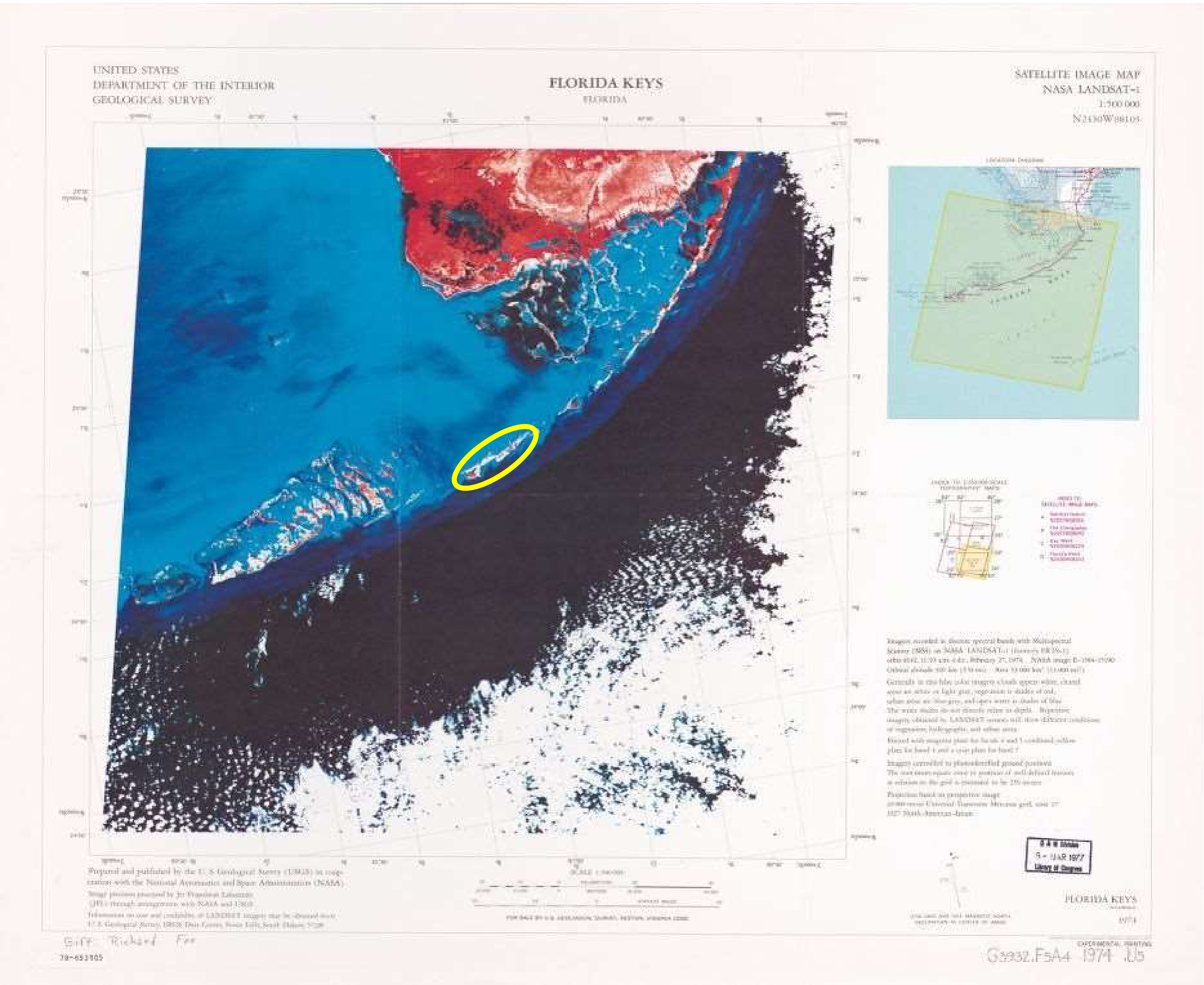


Figure 1: Satellite Map of the Florida Keys

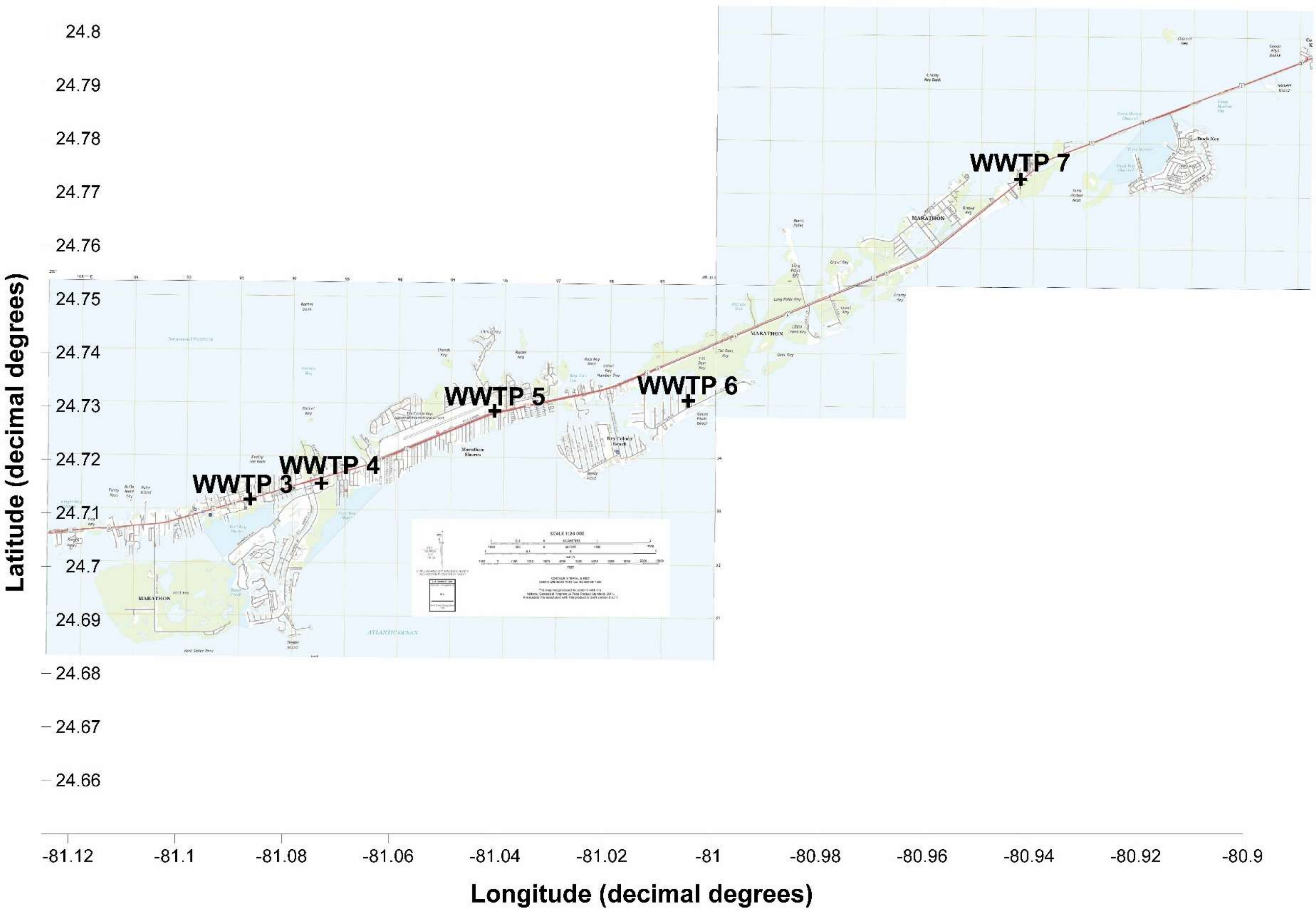


Figure 2: Locations of the City of Marathon Wastewater Treatment Plants

Figure 3: Area 3 Air Photo

Figure 4: Area 4 Air Photo

Figure 5: Area 5 Air Photo

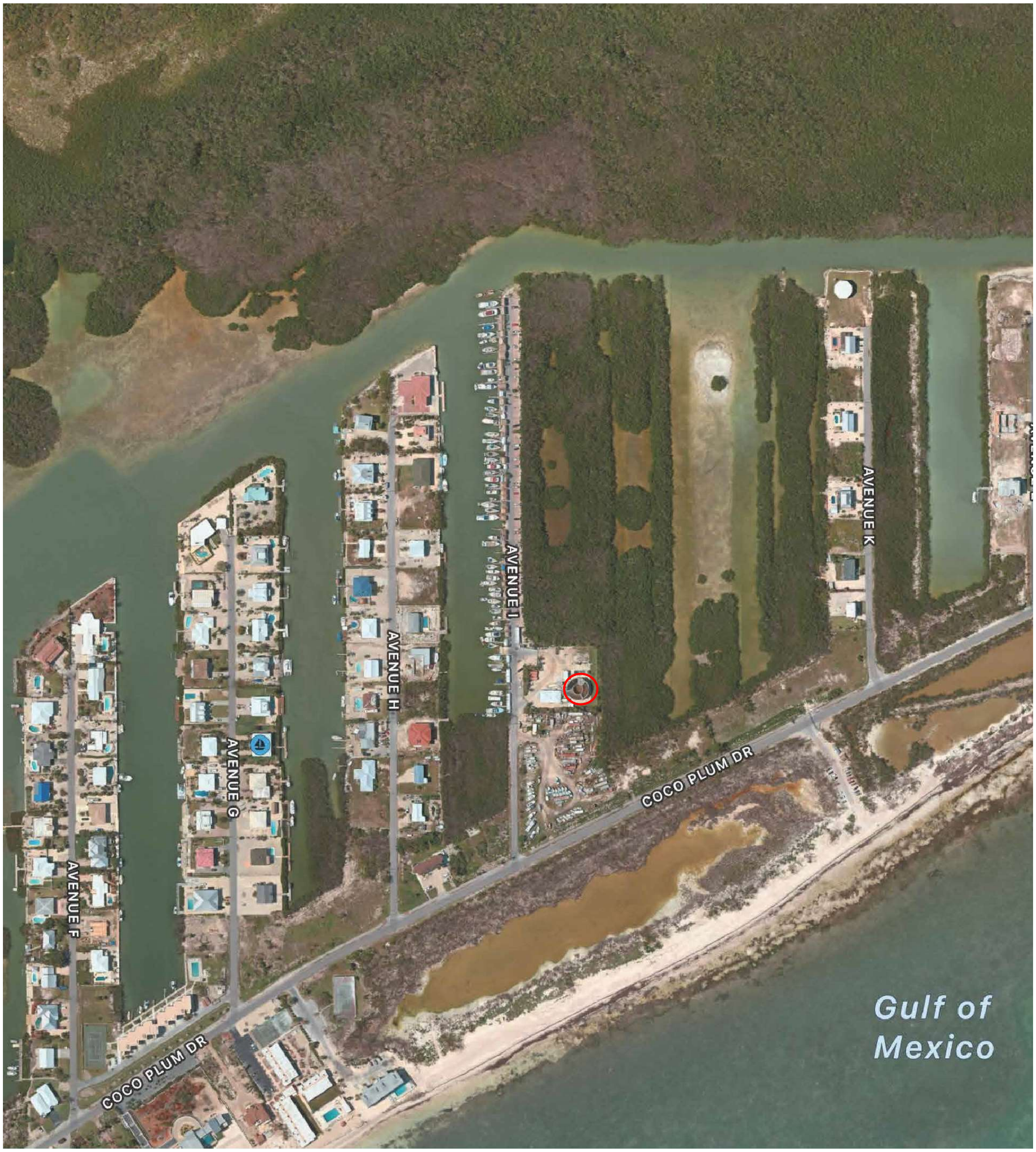


Figure 6: Area 6 Air Photo

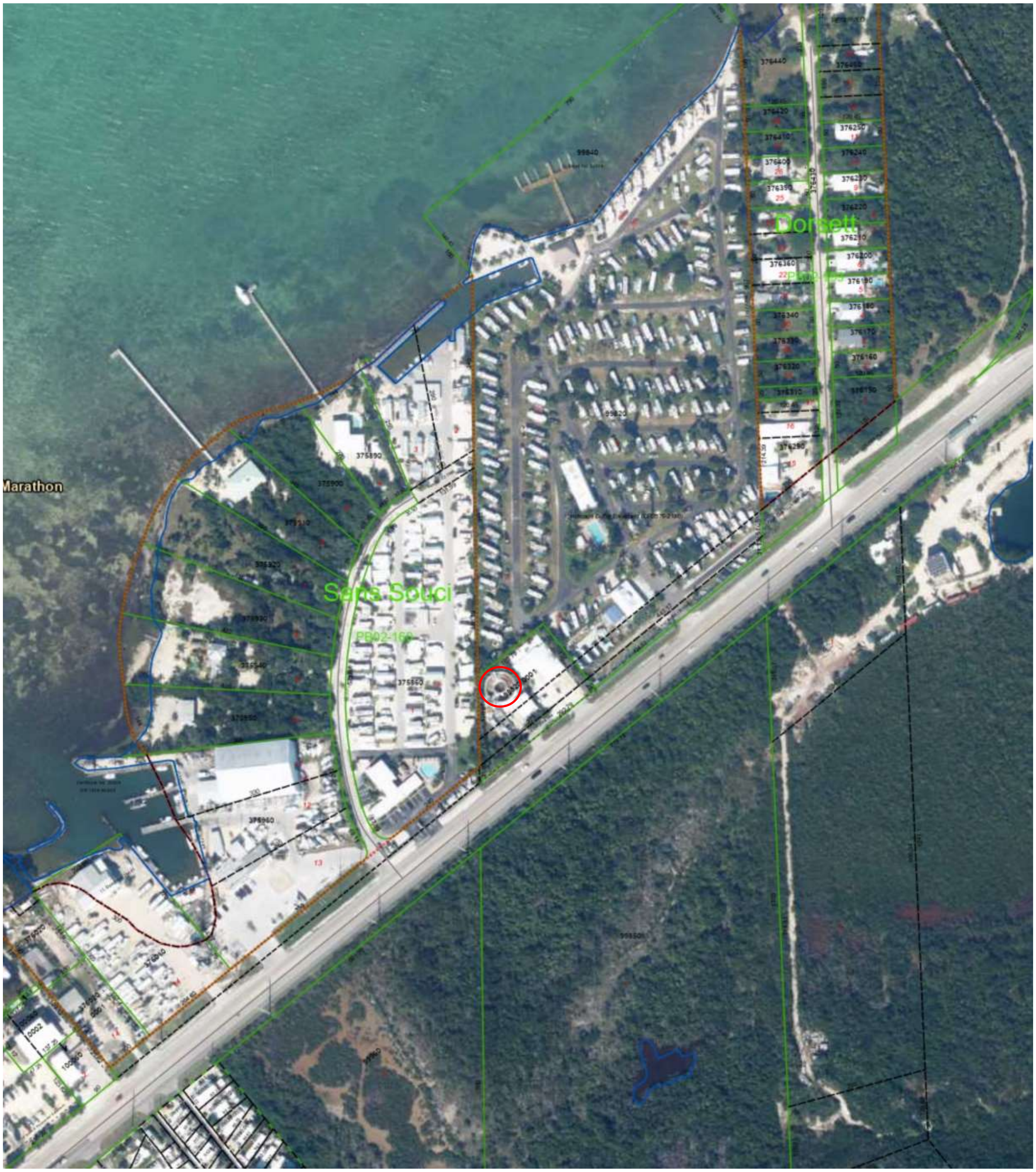
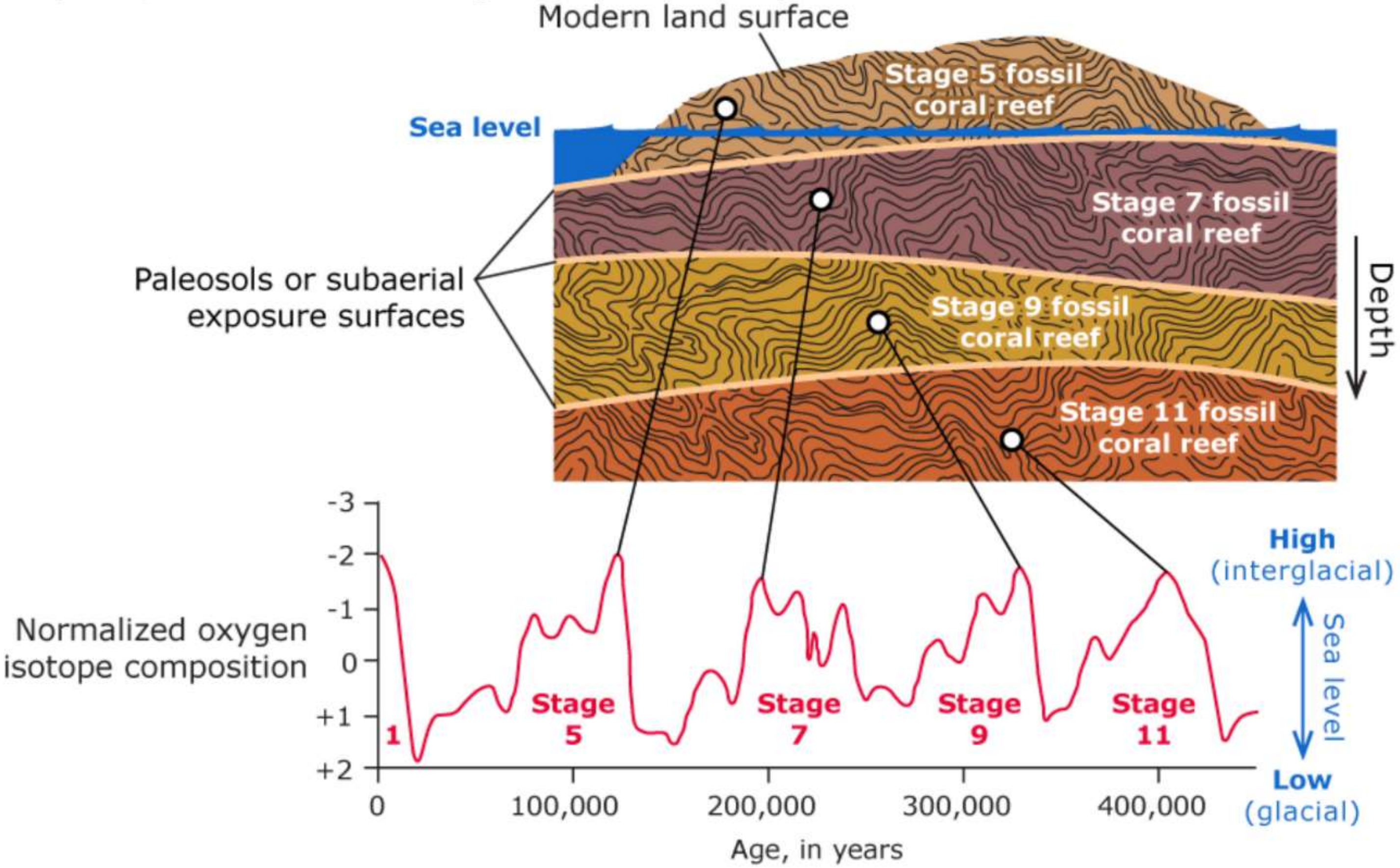


Figure 7: Area 7 Air photo

The geomorphic record of sea level change on a stable or subsiding coastline



Sources/Usage: Public Domain.

Shown here is the same oxygen isotope curve as above, over the past ~400,000 years. On a tectonically stable coast, such as Florida, the land is not uplifting and because the coast is a lower-energy one, wave-cut benches are not as common as in California. However, coral reef growth can take place in favorable locations and the tops of some coral reefs are found just a bit below sea level at the time of growth. Thus, past interglacial high-stands of sea are recorded as coral reef limestones, stacked one on top of the other (see diagram). Deeper limestones are progressively older and each successive reef is marked by a buried soil (paleosol) that formed during the intervening glacial period, when sea level was low.

Figure 8: Relative Sea levels in the Florida Keys Over the past 450,000 Years (USGS, 2017)

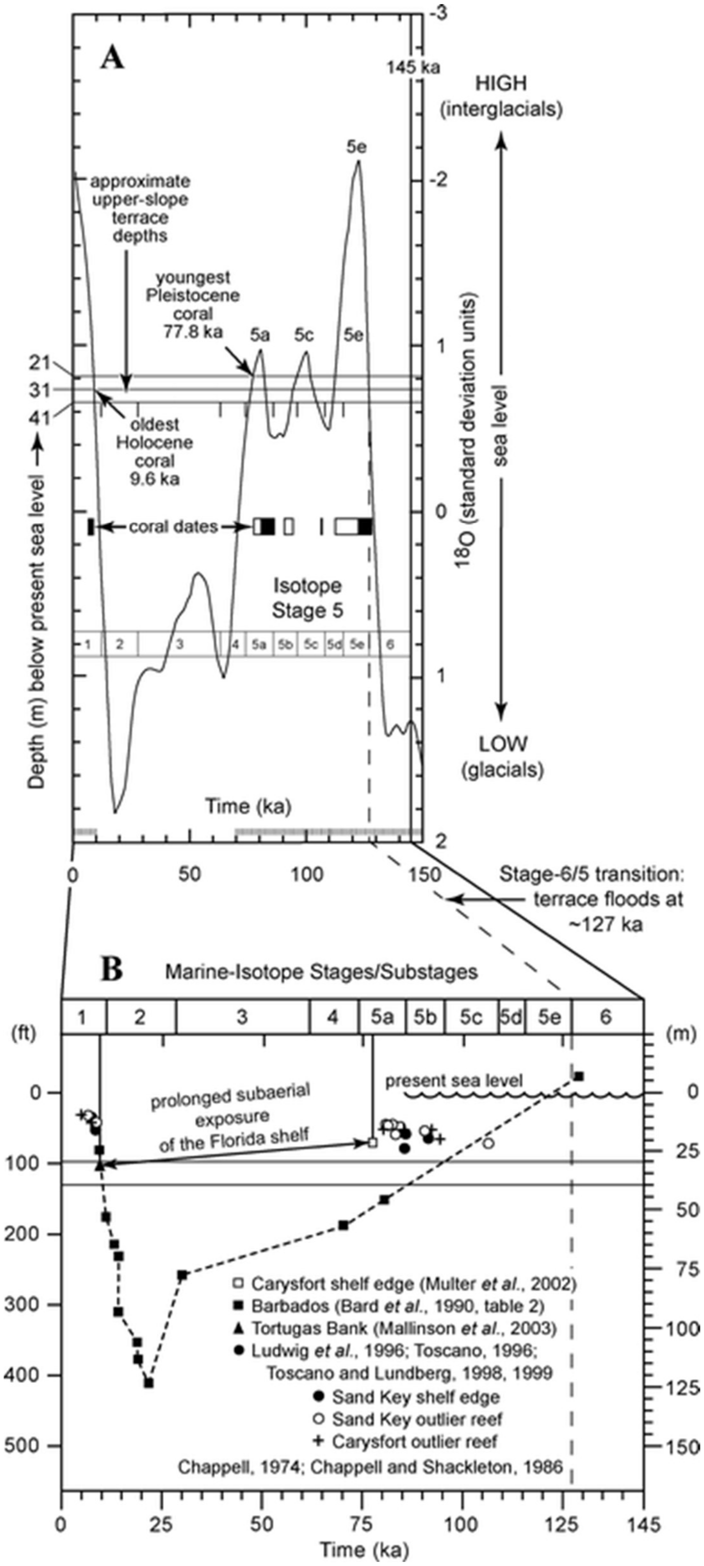


Figure 9: Relative Sea Levels in the Florida Keys Over the Past 145,000 Years (Lidz, 2006)

Figure 10: Windley Key – Key Largo Formation

Figure 11: Eel in Cavern

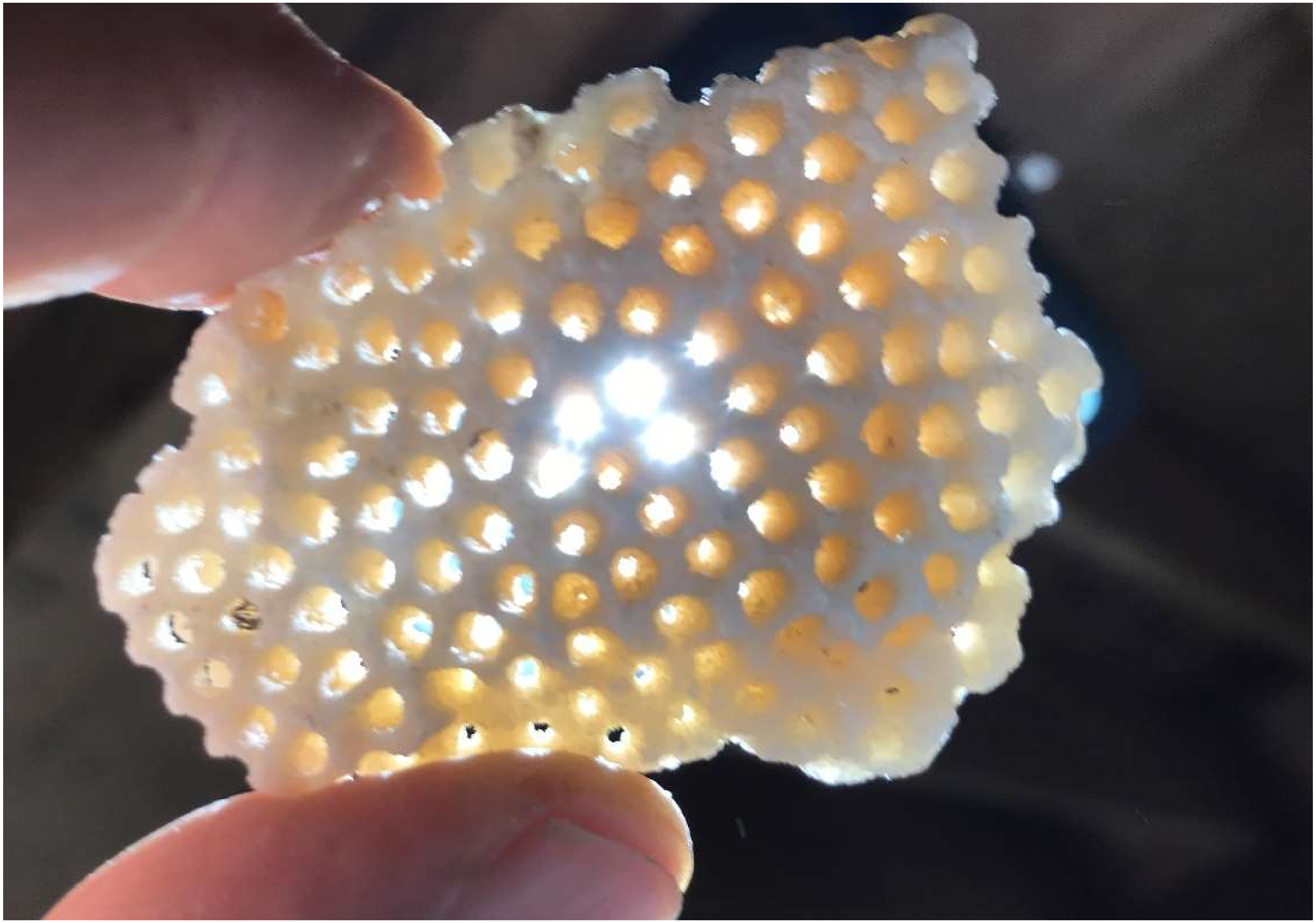


Figure 12: Coral Primary Porosity

Figure 13: Marathon Sombrero Beach Mangrove Roots in Perforated Limestone

Figure14: Marathon Sombrero Beach Key Largo Limestone

Figure 15: Vaca Key Marathon Crane Point Bedrock Solution/Sinkhole

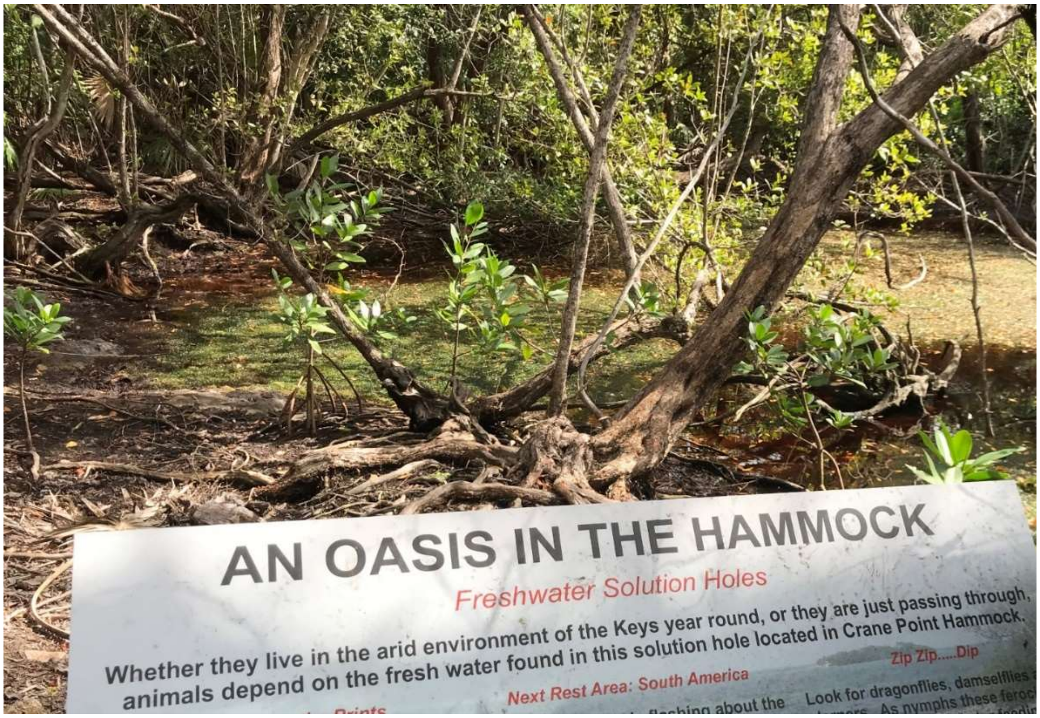


Figure 16: Vaca Key Marathon Crane Point Bedrock Solution/Sinkhole

Figure 17: Vaca Key Marathon Crane Point Bedrock

Figure 18: Bahia Honda Limestone

Figure 19: Mudstone with Secondary Porosity

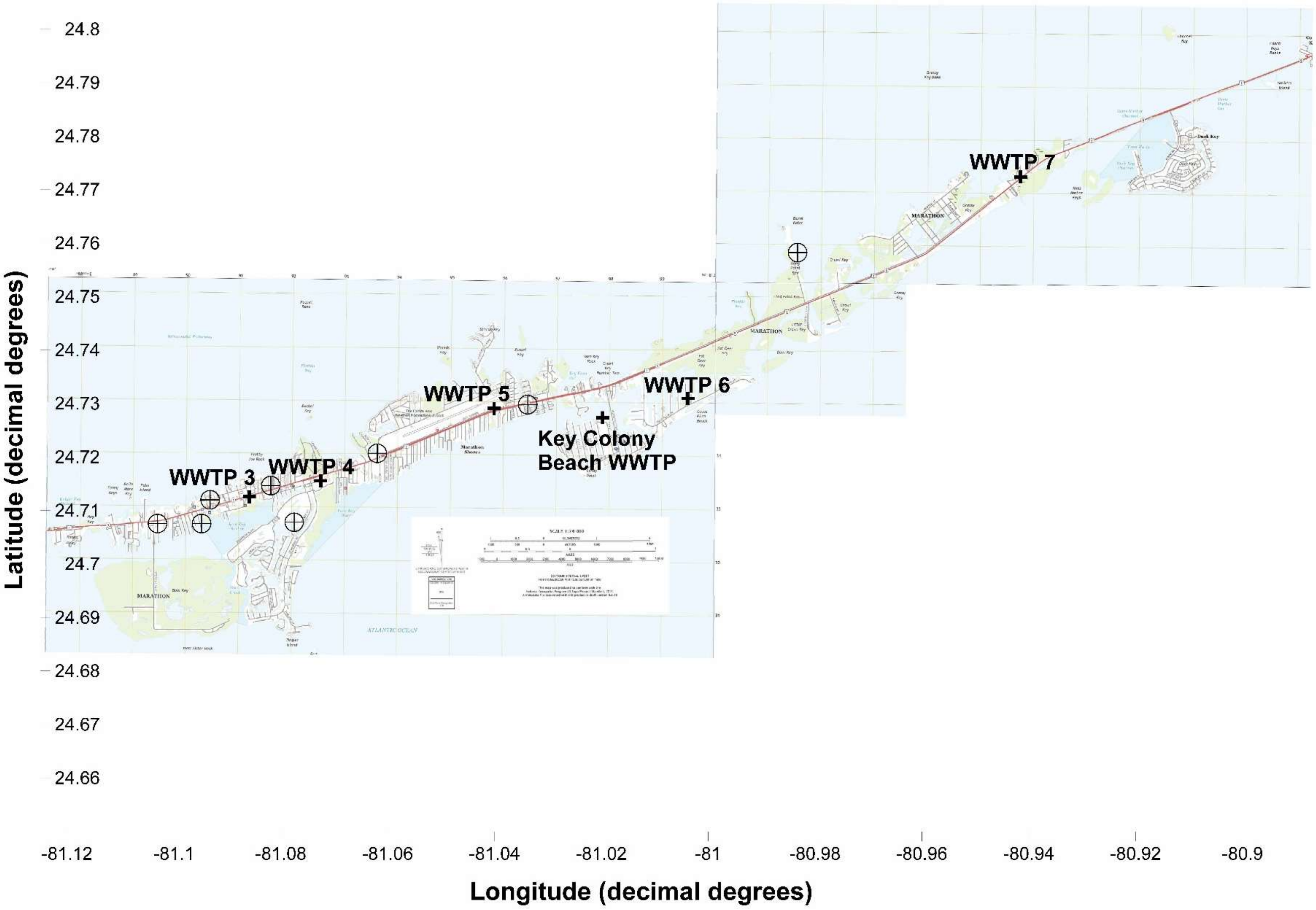


Figure 20: Locations of wells & boreholes in Marathon

Figure 21: Portion of Area 3 Boring B-1 85-90 foot core photo

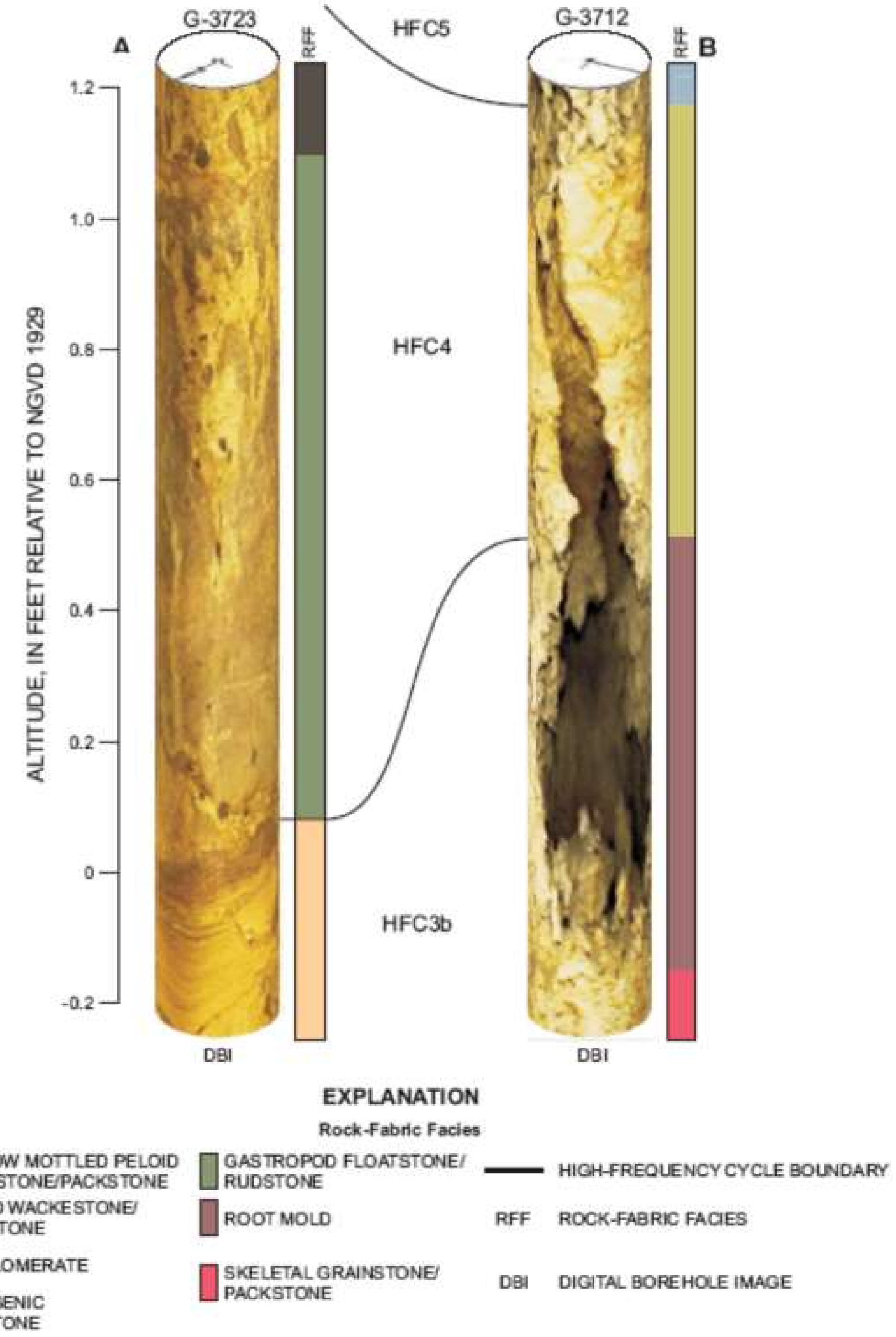
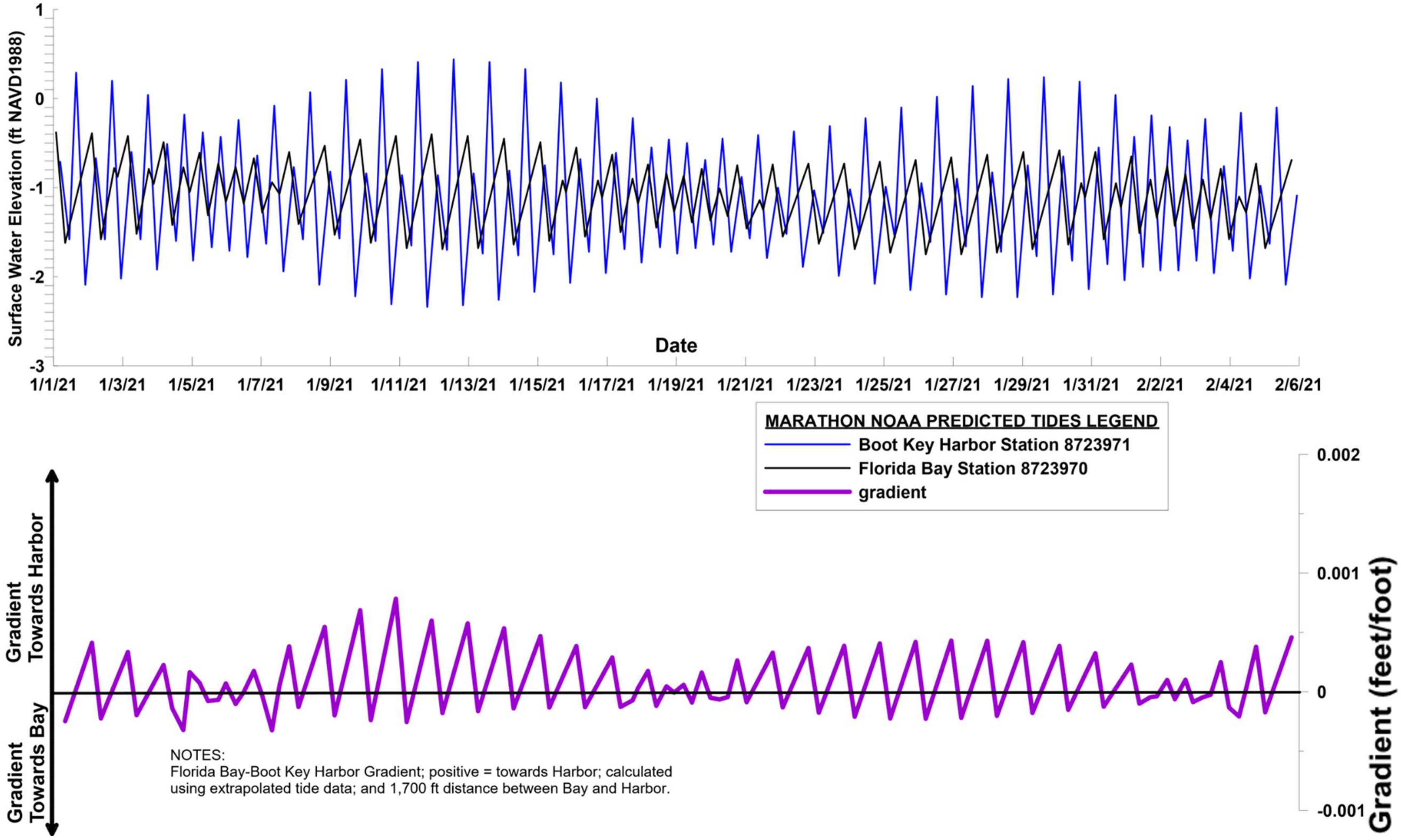


Figure 33. Correlation between rock-fabric facies that span the base of the Miami Limestone and top of the Fort Thompson Formation. The limestone at the base of the Miami Limestone and top of the Fort Thompson Formation in the G-3723 test corehole (A) has high potential to retard vertical seepage, whereas a semi-vertical solution pipe in the G-3712 test corehole (B) allows local vertical conduit flow. This interval of limestone, in approximately two-thirds of the coreholes drilled in the study area, functions as a semiconfining unit.

Figure 22: USGS Q3-Q4 core with vertical conduit from Water Resources Investigations Report 03-4208



NOTES:
Florida Bay-Boot Key Harbor Gradient; positive = towards Harbor; calculated using extrapolated tide data; and 1,700 ft distance between Bay and Harbor.

Figure 23: Vaca Key Tidal Variation and Gradient in 2021

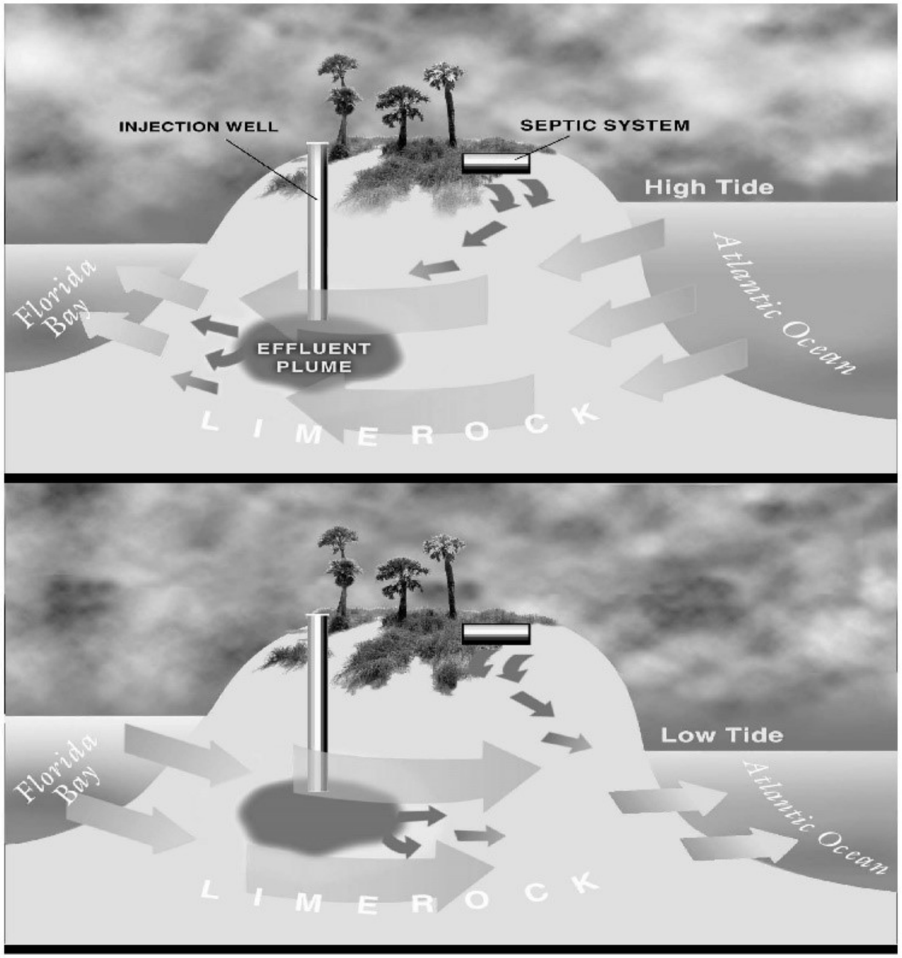


Figure 1. Model of Reich et al. (2002). Variations in Atlantic tide control subsurface head pressures. When Atlantic tide is high, there is a pressure force pushing water towards Florida Bay, which has relatively constant water level. When Atlantic tide is low, there is a pressure force from Florida Bay towards the Atlantic. From FSU Research in Review, Frank Stephenson, ed., used with permission.

Figure 24: Conceptual Model Cross Section of Effluent Migration

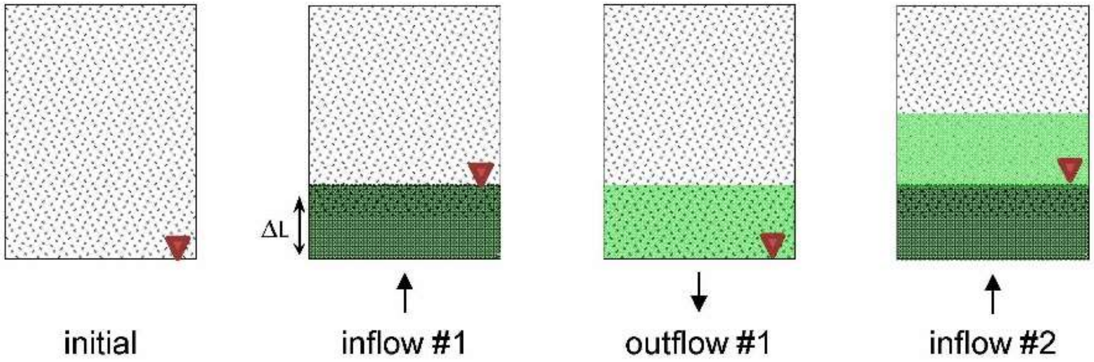
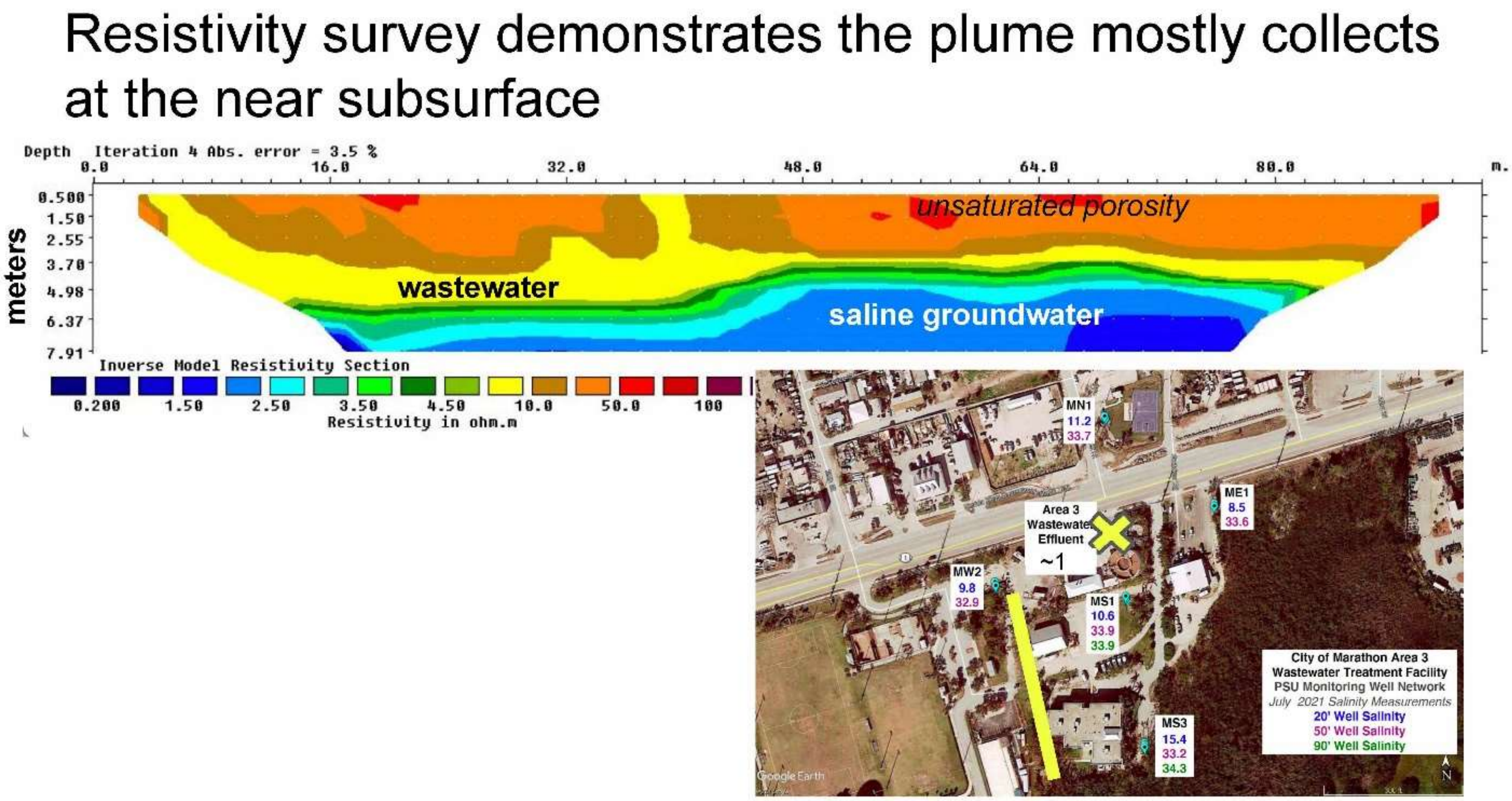


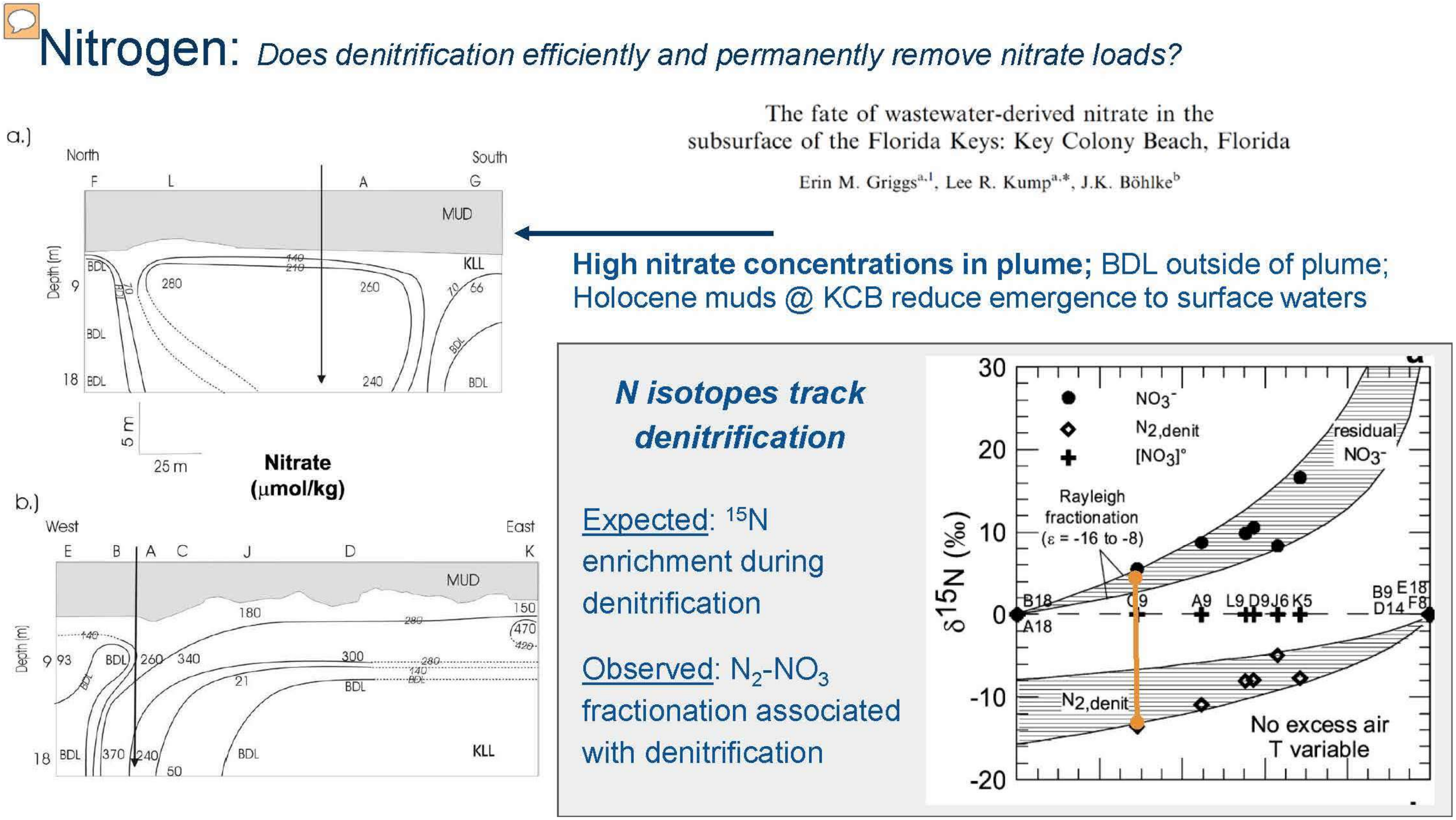
FIGURE 3.2 Accelerated diffusion-like response during inflow-outflow cycles due to mixing and pore-scale hydrodynamic dispersion. Fluid with contaminant invades the water-saturated rock from the bottom and reaches a height, ΔL, shown with the inverted red triangle (inflow #1; dark green); then it recedes, leaving some contaminant behind (outflow #1; remnant contaminant shown as light green). During inflow #2, the high concentration contaminant reaches height ΔL once again (dark green); however, the remnant contaminant from the previous invasion is displaced upward (light green advances to higher position).

Figure 25: Conceptual Model Schematic of Pulsed Effluent Migration



Resistivity survey demonstrates the plume mostly collects at the near subsurface

Figure 26: Area 3 North-South Geophysics Profile from PSU November 2021 Progress Presentation



Nitrogen: *Does denitrification efficiently and permanently remove nitrate loads?*

The fate of wastewater-derived nitrate in the subsurface of the Florida Keys: Key Colony Beach, Florida

Erin M. Griggs[a,1], Lee R. Kump[a,*], J.K. Böhlke[b]

High nitrate concentrations in plume; BDL outside of plume; Holocene muds @ KCB reduce emergence to surface waters

N isotopes track denitrification

Expected: ^{15}N enrichment during denitrification

Observed: N_2-NO_3 fractionation associated with denitrification

Figure 27: Nitrate Fate and Transport Example from PSU November 2021 Progress Presentation

Figure 28: Locations of Monitoring Wells Installed by PSU in 2021

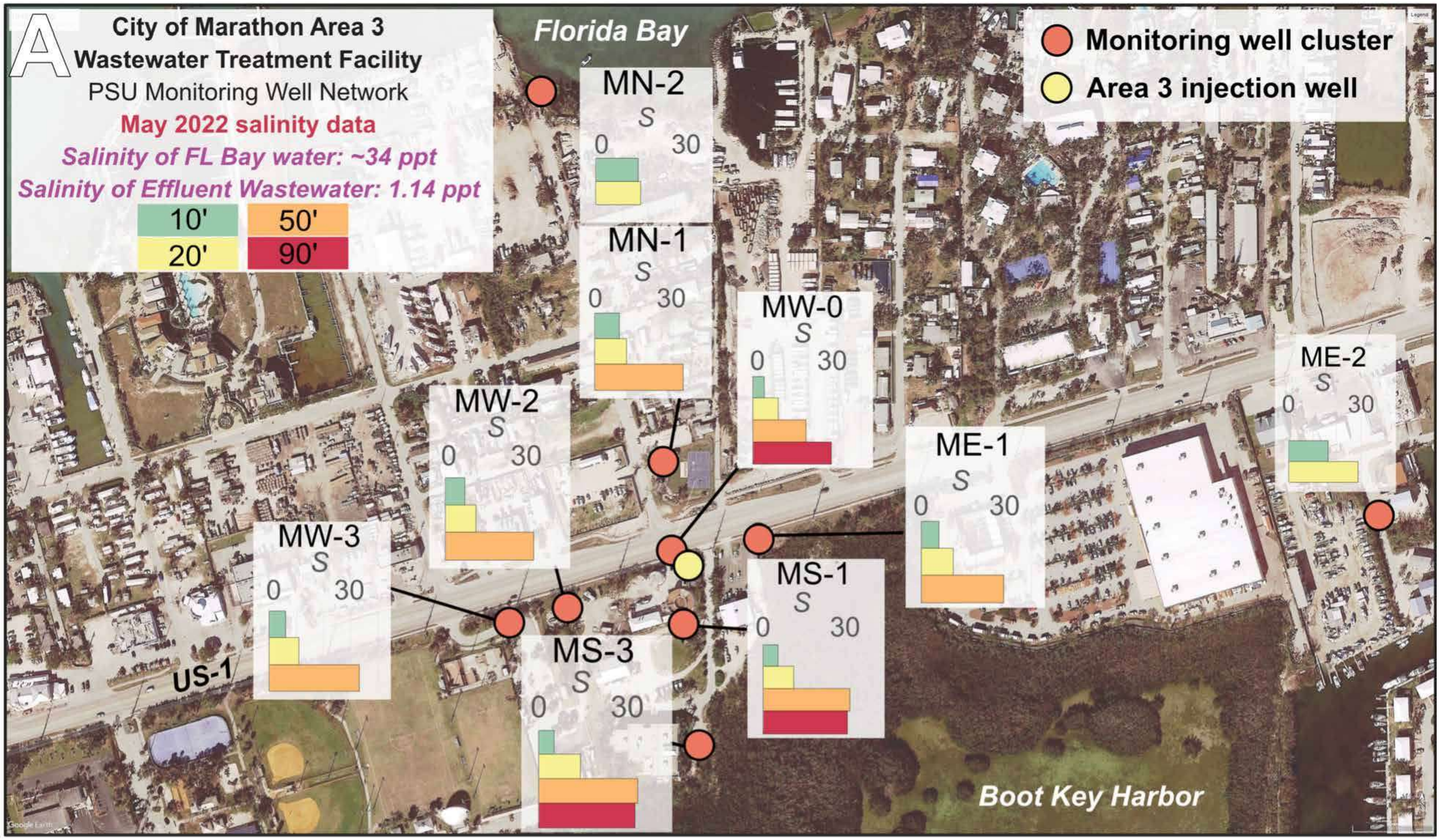
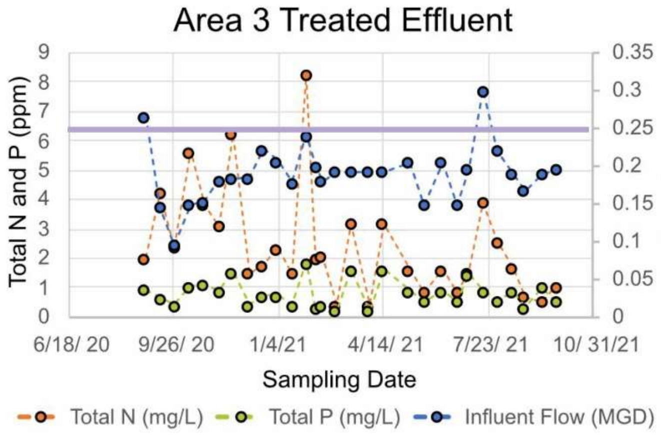


Figure 29: Area 3 Salinity Map from PSU October 2022 Progress Report

Area 3 treated effluent flow and Total N/P compositions 2020-2021

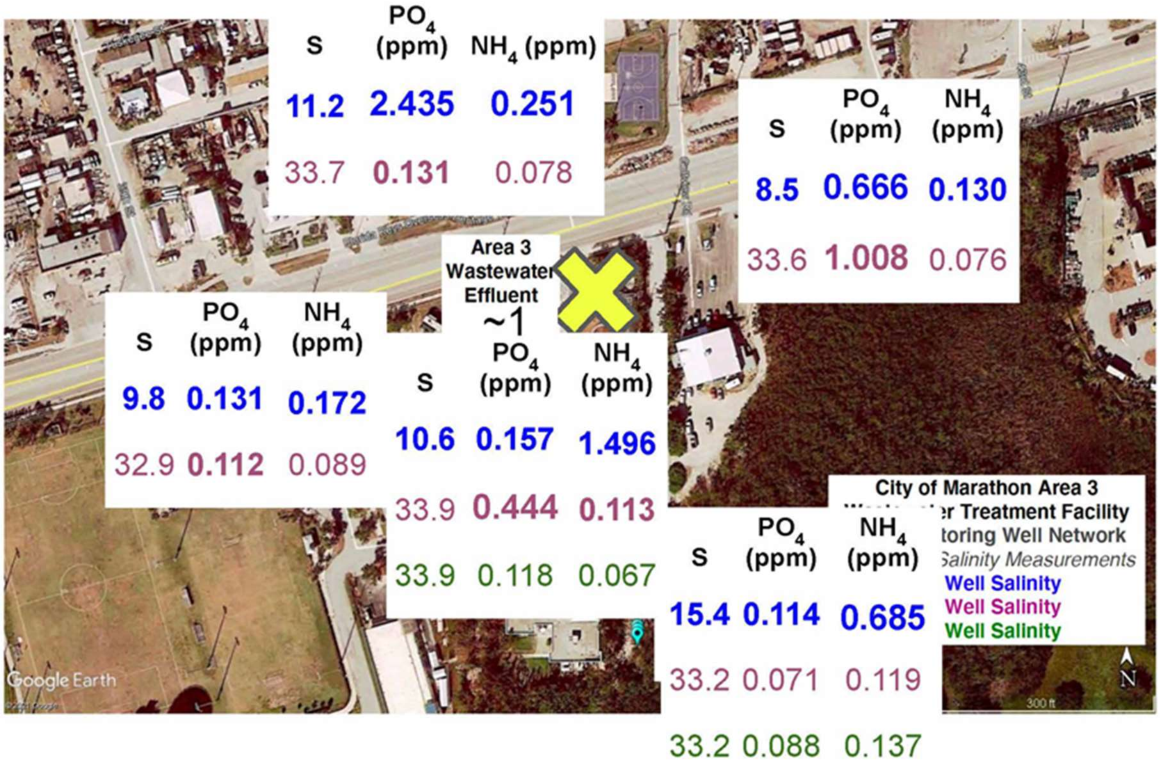


https://depedms.dep.state.fl.us/Oculus/servlet/

Permitted to 0.25 MGD

Average Total P: 0.641±0.456 ppm

Average Total N: 2.280±1.846 ppm



S	PO_4 (ppm)	NH_4 (ppm)
11.2	2.435	0.251
33.7	0.131	0.078

S	PO_4 (ppm)	NH_4 (ppm)
8.5	0.666	0.130
33.6	1.008	0.076

S	PO_4 (ppm)	NH_4 (ppm)
9.8	0.131	0.172
32.9	0.112	0.089

S	PO_4 (ppm)	NH_4 (ppm)
10.6	0.157	1.496
33.9	0.444	0.113
33.9	0.118	0.067

S	PO_4 (ppm)	NH_4 (ppm)
15.4	0.114	0.685
33.2	0.071	0.119
33.2	0.088	0.137

Figure 30: Area 3 N and P Graphs and Map from PSU 2021 Progress Report and Presentation

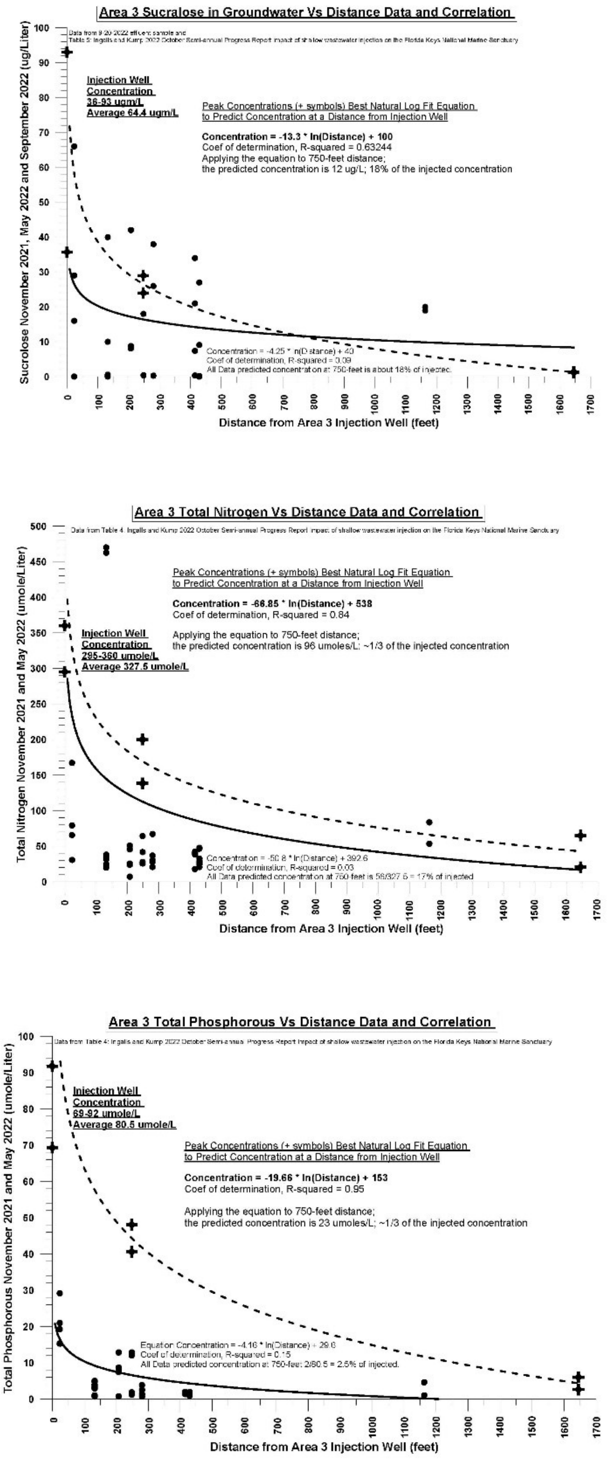


Figure 31: Area 3 Graphs of Concentration Vs Distance from PSU October 2022 Progress Report Data

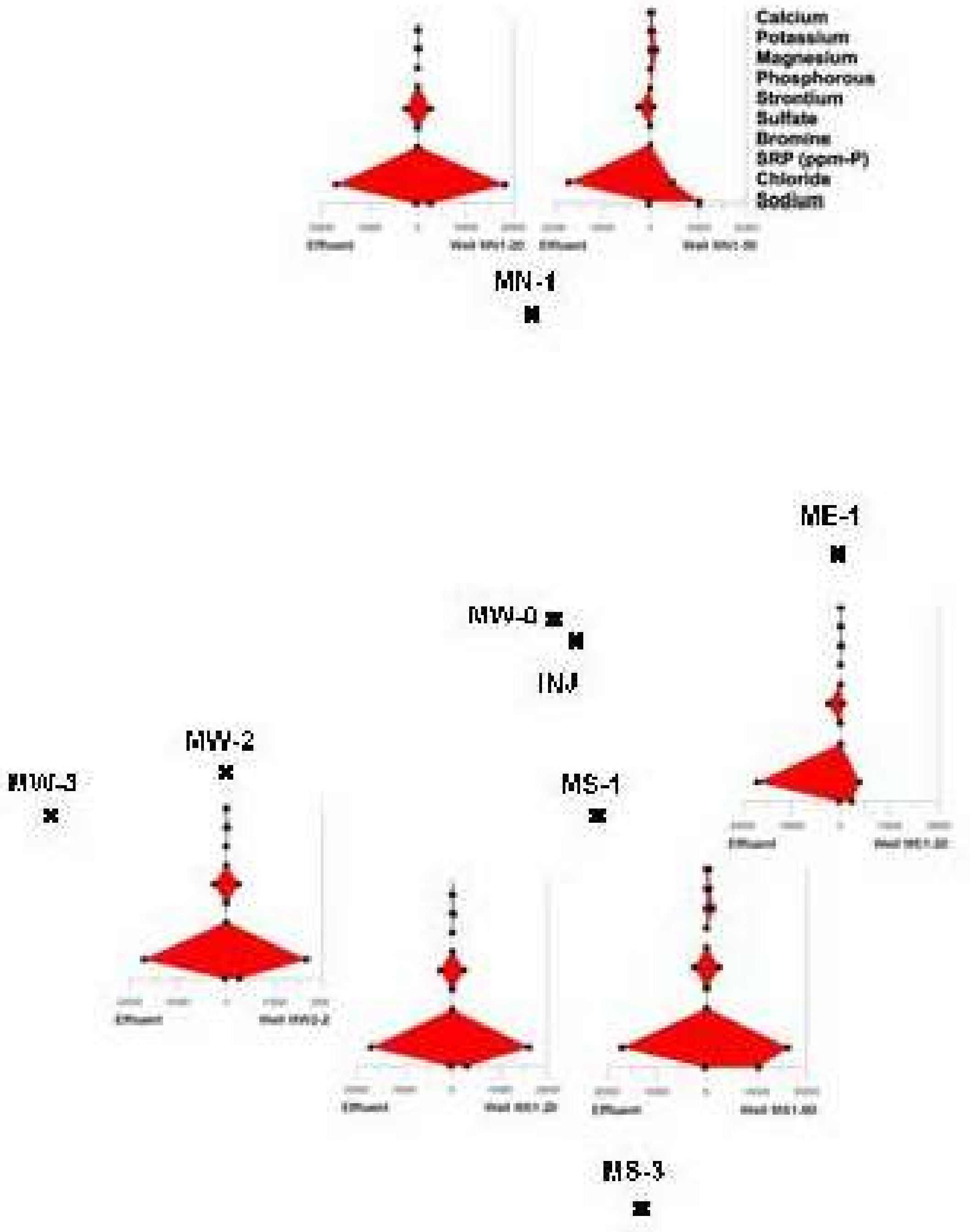


Figure 32: Comparison of Injection Effluent and Monitoring Well Chemistry

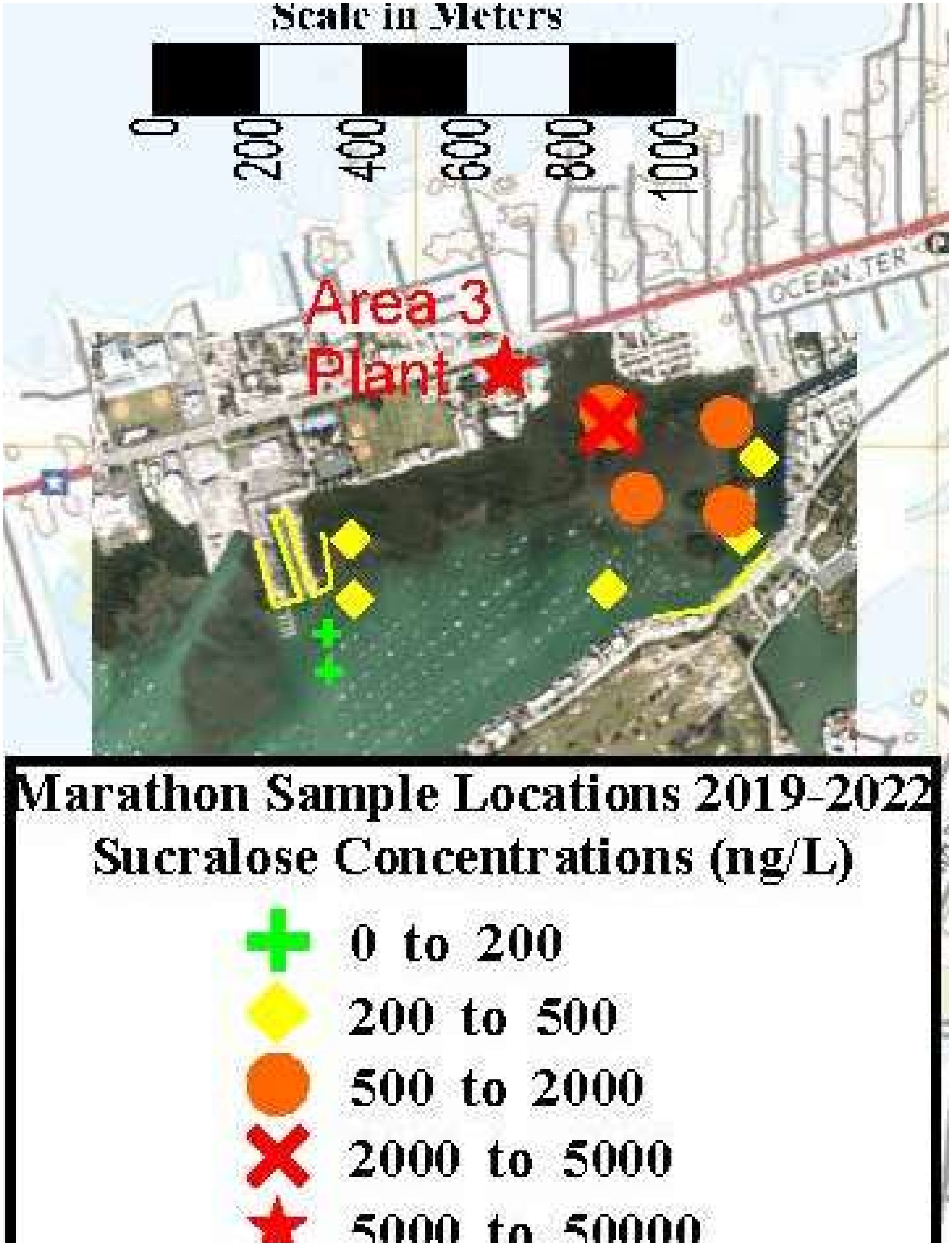


Figure 33: Sucralose Sample Location Map Area 3

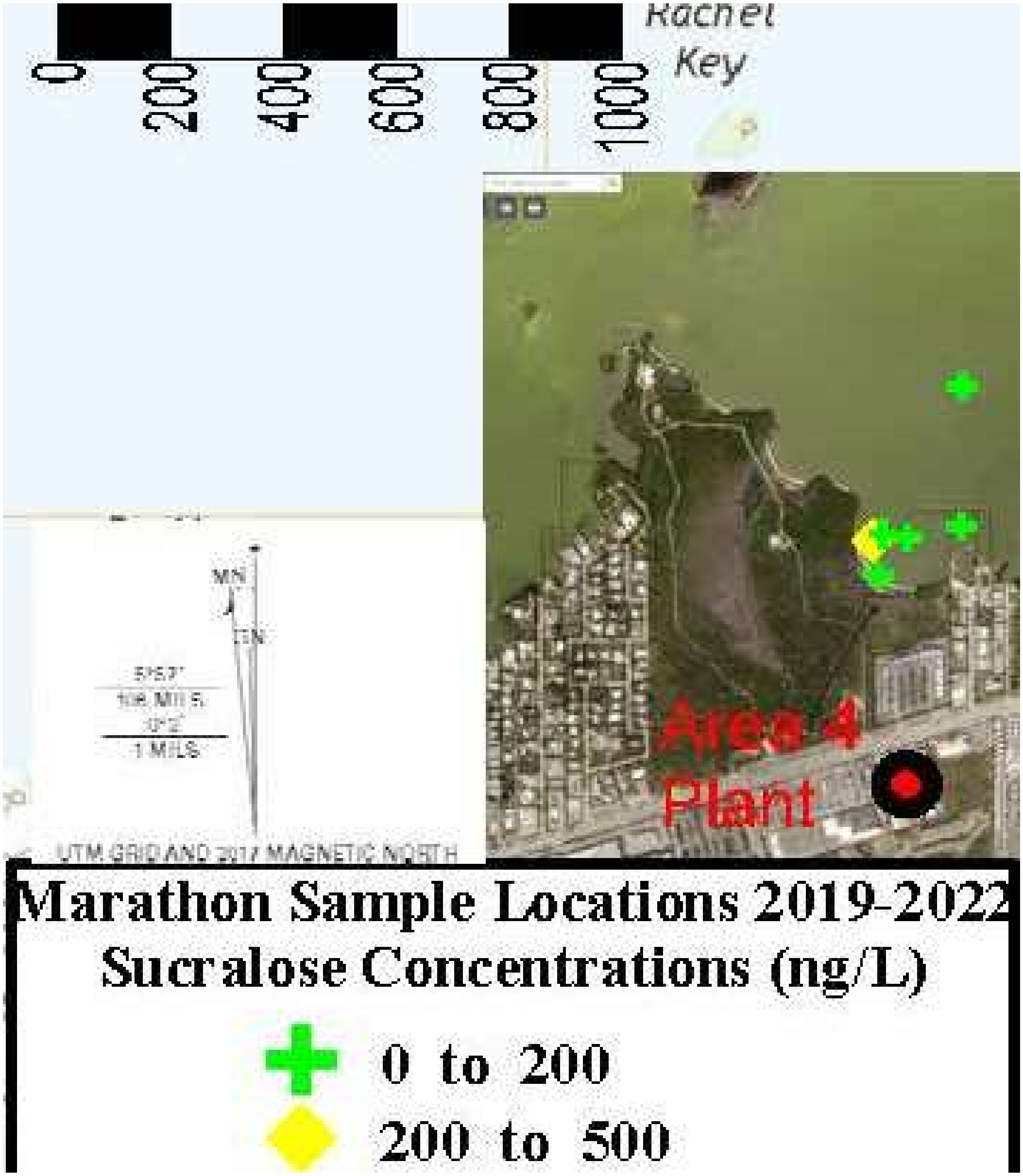


Figure 34: Sucralose Sample Location Map Area 4

Figure 35: Sucralose Sample Location Maps Area 6

boot key harbor
plume photo-movie n

Figure 36: Visible Plume in Boot Key Harbor

Figure 37: Visible Plume in Boot Key Harbor

Figure 38: Visible Plume in Boot Key Harb