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TO:	Oisin Dolley, P.E.; Scott Krawczuk: City of Sanibel	DATE:	December 18, 2024
FROM:	Jordan L. Varble, P.E.; Gabriella Santucci: Johnson Engineering, Inc.	RE:	Sanibel's Hydrology and Vegetation Before and After Hurricane Ian (2022)

Background

Sanibel is a 12-mile-long barrier island located off the coast of Lee County, near the mouth of the Caloosahatchee River. Sanibel contains two large freshwater basins – the Sanibel River West Basin and the Sanibel River East Basin – which serve as freshwater reservoirs for the island. Together, these basins are 50% freshwater wetlands by area – 1,600 acres. Each basin has a weir which allows freshwater to flow out of the basin and into receiving saltwater bodies. The weirs each have gates which are opened when dictated by the operation schedule and allow flow out of the basins. Its low-lying profile and status as a barrier island make it particularly vulnerable to flooding. Over the course of Sanibel's history, hurricane storm surge has wholly inundated the island with saltwater with some regularity[1], including Hurricane Ian in September of 2022.

Protection of freshwater on the interior of the island is necessary to protect Sanibel's native flora and fauna and conserve freshwater in the surficial aquifer under the island.[1] However, higher baseline freshwater stages increase flood risk, potentially causing the island to flood even during relatively minor rainstorm events. This means that weir operations must strike a balance between protecting upstream resources and preventing flooding. This presents a challenge for current and future stormwater management, particularly when potential future sea level rise is accounted for.

Hurricane Ian

Hurricane Ian made landfall in late September 2022. Ian caused the island to be overtopped with storm surge and led to silt deposits and saltwater contamination of freshwater ponds and wetlands. Since Ian, there have been large amounts of vegetation loss and a general sense amongst residents that the island's hydrology has changed.[2] Interior freshwater stages seem higher during the dry season, and, after large rainfall events, residents report that water levels recede more slowly than they did in the past.

Water Budget and Plant Health

In *The Sanibel Report* (1976), an average annual water budget was created for the interior wetland areas of Sanibel. A water budget essentially details the ways in which water enters and leaves a system, as well as the quantities. Inflows often include precipitation, treated wastewater effluent, surface water inflow, and groundwater inflow. Outflows include open water evaporation, runoff, groundwater outflow (percolation), and evapotranspiration (ET). Outflows equal inflows unless there was a change in storage within the basin. Sanibel generally does not have changes in storage from year to year. Estimates of both evaporation and ET can be difficult to verify, especially for wetlands on barrier islands with shallow aquifers, but approximations were made in the 1976 report using a pan evaporation coefficient of 0.7 for the basin.

The water budget created in *The Sanibel Report*, which may be found in **Table 1**, reports that evaporation and ET are responsible for 24% and 75% of yearly outflow. Given the large share of the water budget that is attributed to ET, any degradation in plant health has the potential to cause significant changes in the island's hydrology. Note that since many of the numbers in **Table 1** are rough estimates, the inflows and outflows are not exactly equivalent.

Table 1. Annual mass balance of the hydrologic budget for the interior wetlands of Sanibel Island in inches[1].

Inflow Factors		Outflow Factors	
Precipitation	43.2	Water Storage	0.0
Surface Water Inflow	0.0	Open Water Evaporation	12.3
Groundwater Inflow	0.0	Evapotranspiration	37.1
Upward Leakage	1.2	Well Pumpage (for Irrigation)	0.0
Artesian Well Discharge	2.5	Surface Water Outflow	0.1
Treated Wastewater Effluent	3.8	Groundwater Outflow	0.3
Total	≈ 50	**Total**	≈ 50

NDVI Analysis

One method of quantifying vegetation greenness and density is the Normalized Difference Vegetation Index (NDVI), which can be calculated using aerial imagery. Comparing NDVI values over time can be useful in assessing changes in plant health. NDVI is a ratio between red and near infrared satellite band values[3] and is calculated as shown in **Equation 1**.

$$NDVI = \frac{NIR - R}{NIR + R} = \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4}$$

Equation 1. Formula for NDVI and corresponding Landsat 8 band values.

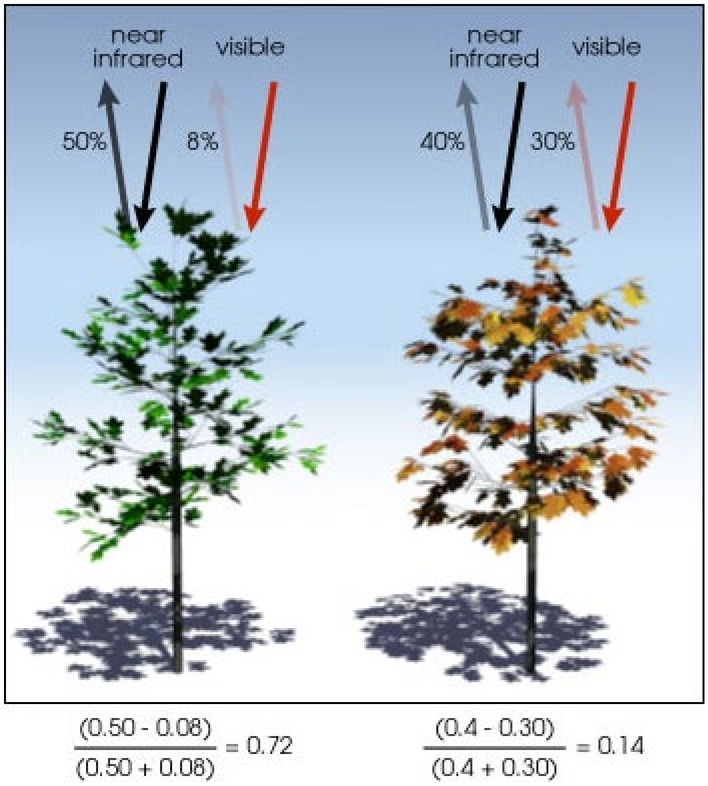

Figure 1. Example NDVI values for healthy and unhealthy vegetation.[4]

Landsat 8 was launched by USGS and NASA in 2013 and records an image of Sanibel every 16 days, with a pixel size of 30 meters. Surface reflectance and top of atmosphere data sets from Landsat 8 were used for NDVI calculations for the period of record. Surface reflectance data is atmospherically corrected and is especially useful when comparing images of a region over time.[5] Top of atmosphere data requires less processing and can be filtered by the amount of cloud cover present.[6]

NDVI values range from -1.0 to +1.0, with more positive numbers indicating more or healthier vegetation (see also **Figure 1**). **Figures 2** and **3** show long-term average NDVI values for images with 1% or less cloud cover and were created using top of atmosphere data. **Figures 2** and **3** are on a scale of green to white to blue, with green being healthy vegetation, white being no or dead vegetation, and blue being open water. **Figure 2** shows the period from November 2013 to September 2022, and **Figure 3** shows the period from November 2022 to May 2023. It can be clearly seen that the hurricane had a devastating impact on plant life.

Figure 4 was created using Landsat 8 surface reflectance data that was then processed to exclude cloudy pixels from the images and shows the average NDVI value over the interior freshwater basins (see **Figure 5**) from 2013 to 2024. **Figure 4** also shows the monthly range of water levels at Beach Road Weir from 2019 to 2024.[7] In the years following Hurricane Ian, there has been a slight increase in the minimum water levels at Beach Road, even as the vegetation has begun to recover, though the increase is not dramatic and shows that the surface water levels indeed recover after rainy months, either due to ET, manual opening of the sluice gates, or both.

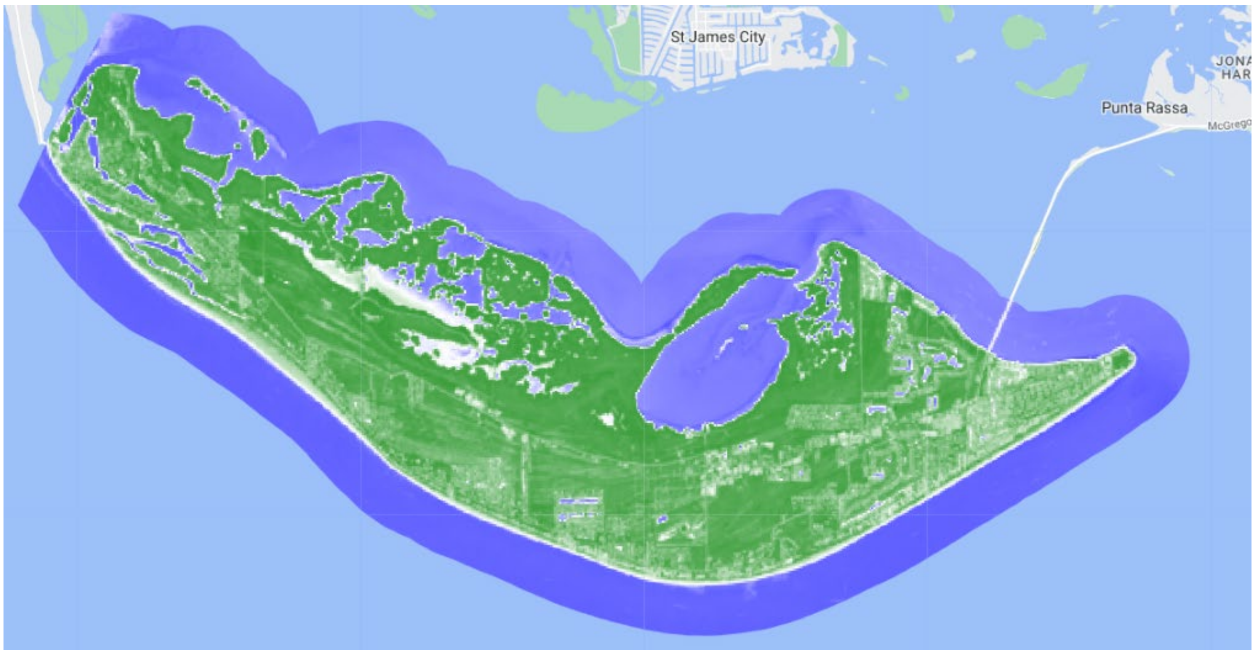

Figure 2. Map showing NDVI values before Hurricane Ian (long-term average November 2013 to September 2022).

Figure 3. Map showing NDVI values after Hurricane Ian (averaged November 2022 to May 2023).

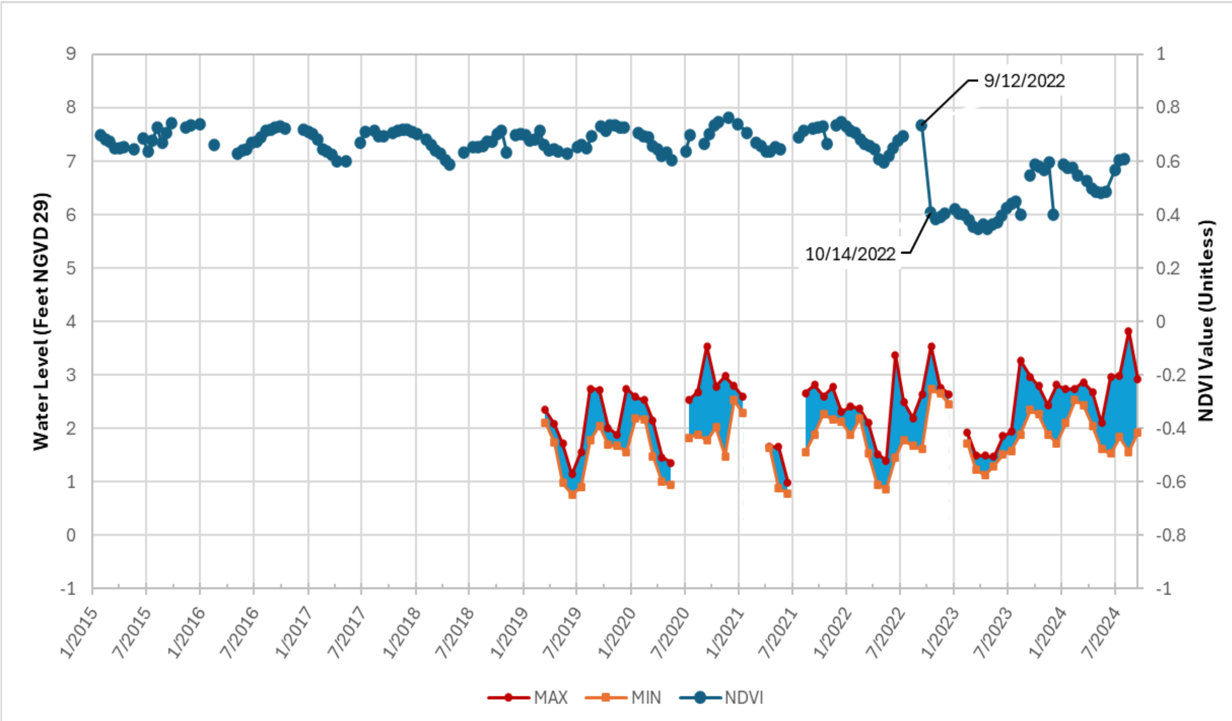

Figure 4. Averaged Landsat 8 NDVI values for the interior freshwater basins and water levels recorded at Beach Road Weir.

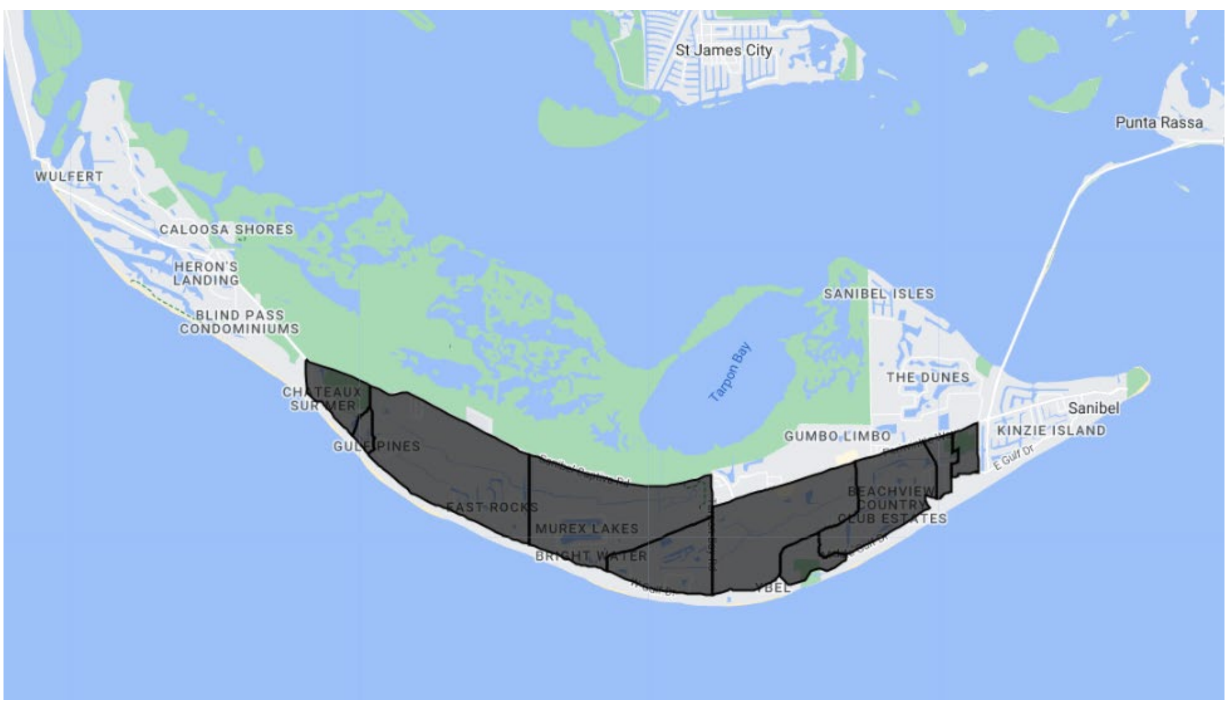

Figure 5. Interior basin area used in creating Figure 4.

Observed Water Level Data

Surface Water

Beach Road Weir water level data obtained from SCCF was analyzed to see if there were any trends in the rate of decline of surface water levels during periods without rainfall and without sluice gate operation. It is assumed that this rate of decline should be roughly equivalent to evapotranspiration (ET). The expectation was that following Hurricane Ian and the associated vegetation changes, water levels would decline more slowly than before the hurricane due to a reduction in ET caused by higher plant stress. However, this did not appear to be the case. If anything, it seems that water levels have been declining more quickly in the final months of the year following the hurricane, particularly in 2023. **Figure 6** shows the water level, weir openings, and the periods of decline analyzed for the period of record. See **Table 2** and **Figure 7** for results of the water level decline analysis. Blue cells in **Table 2** indicate relevant periods of missing data. It is worth noting that the period of record of the surface water level data extends only from 2019 to 2024, with some large data gaps, and some of the periods included have a small amount of rainfall but were included in the interest of having enough data to analyze. No correlation was found between NDVI and water level decline rates. It is unclear what exactly might have caused the increase in water level decline rates in late 2023, but one possibility is vegetative regrowth causing increased water uptake by plants.

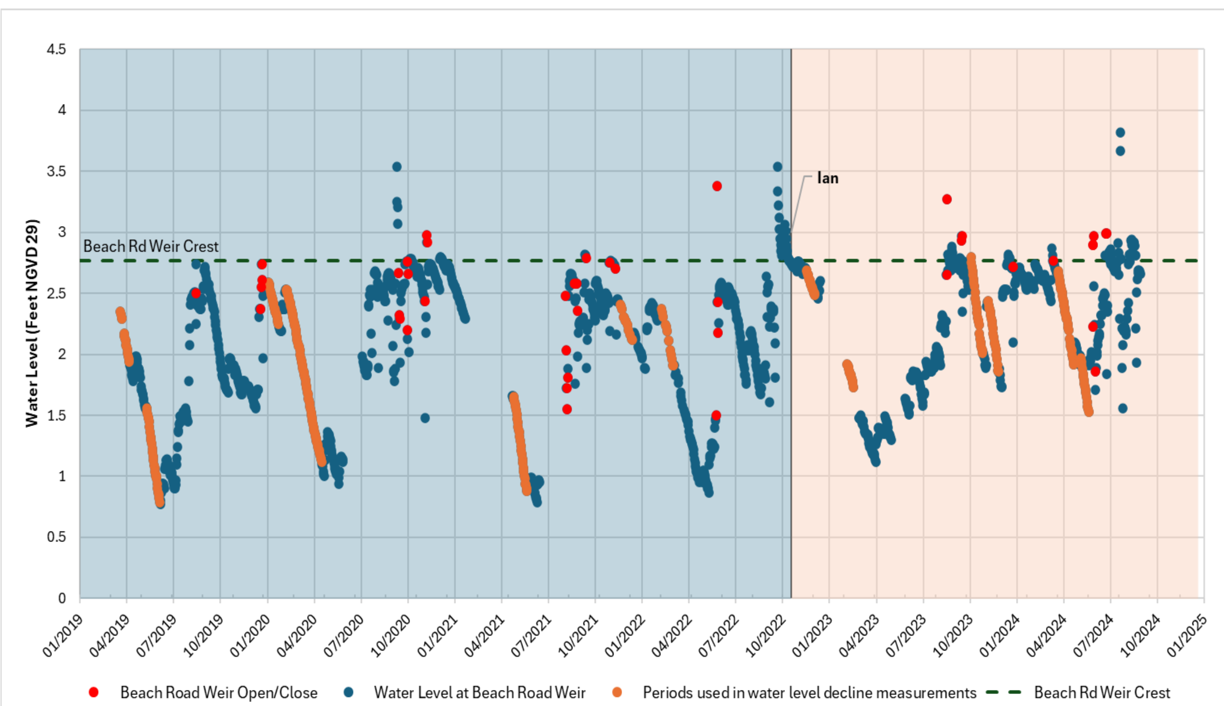

Figure 6. Water level, weir openings, and water level decline periods at Beach Road Weir for period of record.

Table 2. Water level declines at Beach Road Weir in inches per day during periods without precipitation, opening of sluice gates, or discharge of water over the weir.

	2019	2020	2021	2022	2023	2024
JAN		0.2064		0.2412		
FEB		0.2568		0.2412	0.1752	
MAR	0.294	0.2568		0.2412		
APR	0.294	0.2568				0.2928
MAY	0.366		0.3792			0.354
JUN	0.366					
JUL						
AUG						
SEP						
OCT					0.4248	
NOV			0.1452		0.342	
DEC			0.1452	0.1452	0.342	

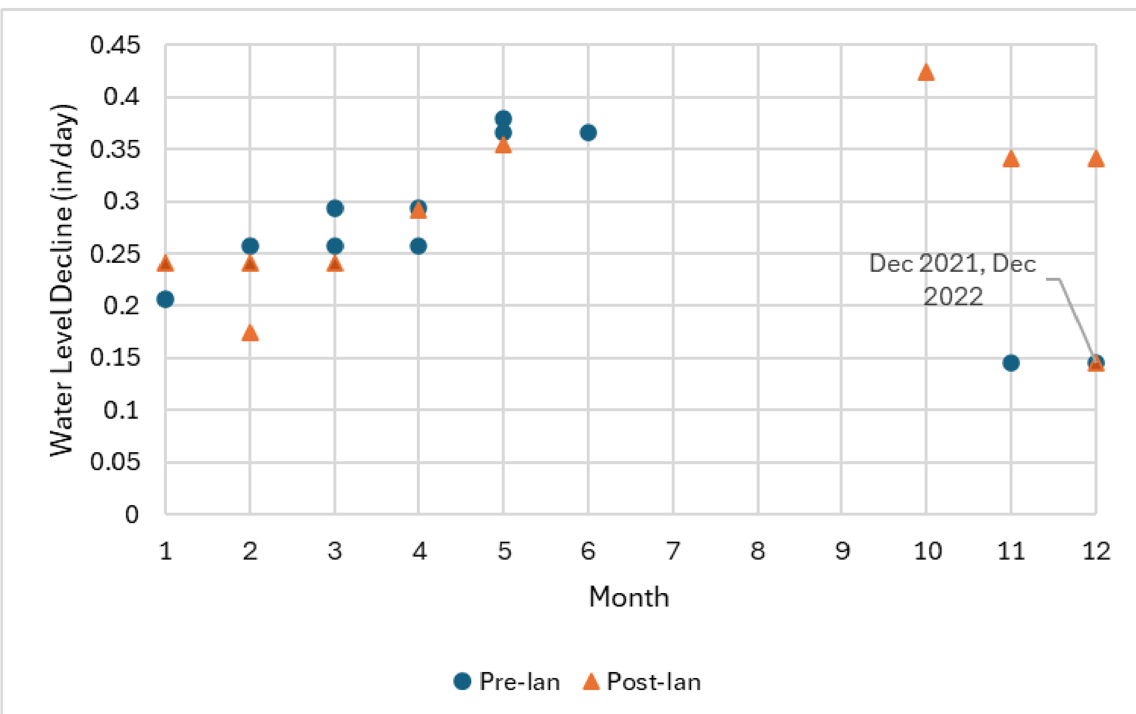

Figure 7. Water level decline at Beach Road Weir in inches per day during periods without precipitation, opening of sluice gates, or discharge over weir.

Groundwater

In addition to water level data collected at Beach Road Weir, data was analyzed at USGS well L-1403, which is located along Casa Ybel Road (see **Figure 8**) and monitors groundwater levels in the surficial aquifer of the east basin.[8] Measurements at this well are taken periodically, typically once or twice each month. **Figure 9** shows the depth of groundwater levels below the surface over time.[9] Although there are no visible changes clearly due to the hurricane, it appears that groundwater levels have been trending upwards since around 2017, though the water levels are within the historical period of record.

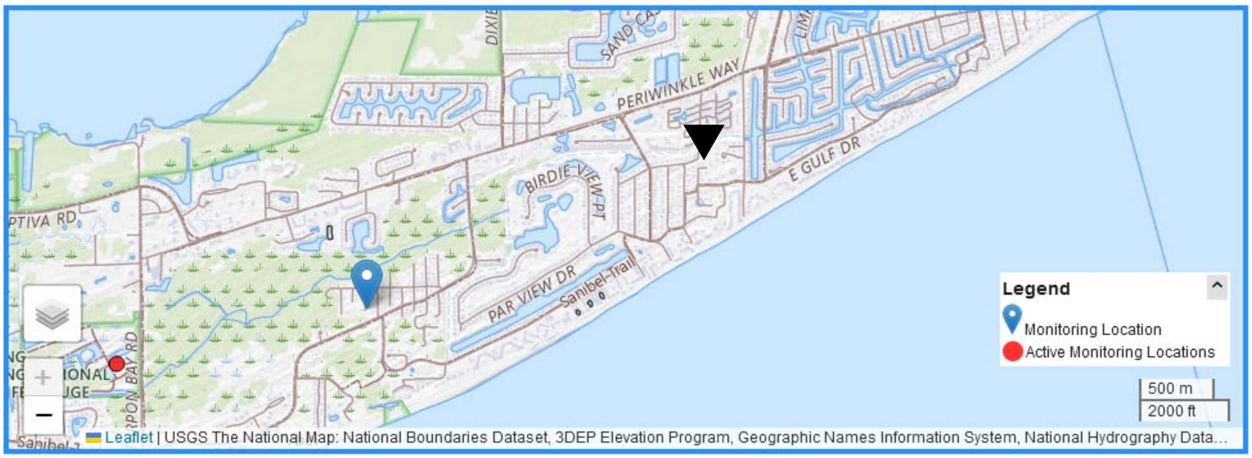

Figure 8. Location of USGS well L-1403 (blue marker) and Beach Road Weir monitoring equipment (black marker).

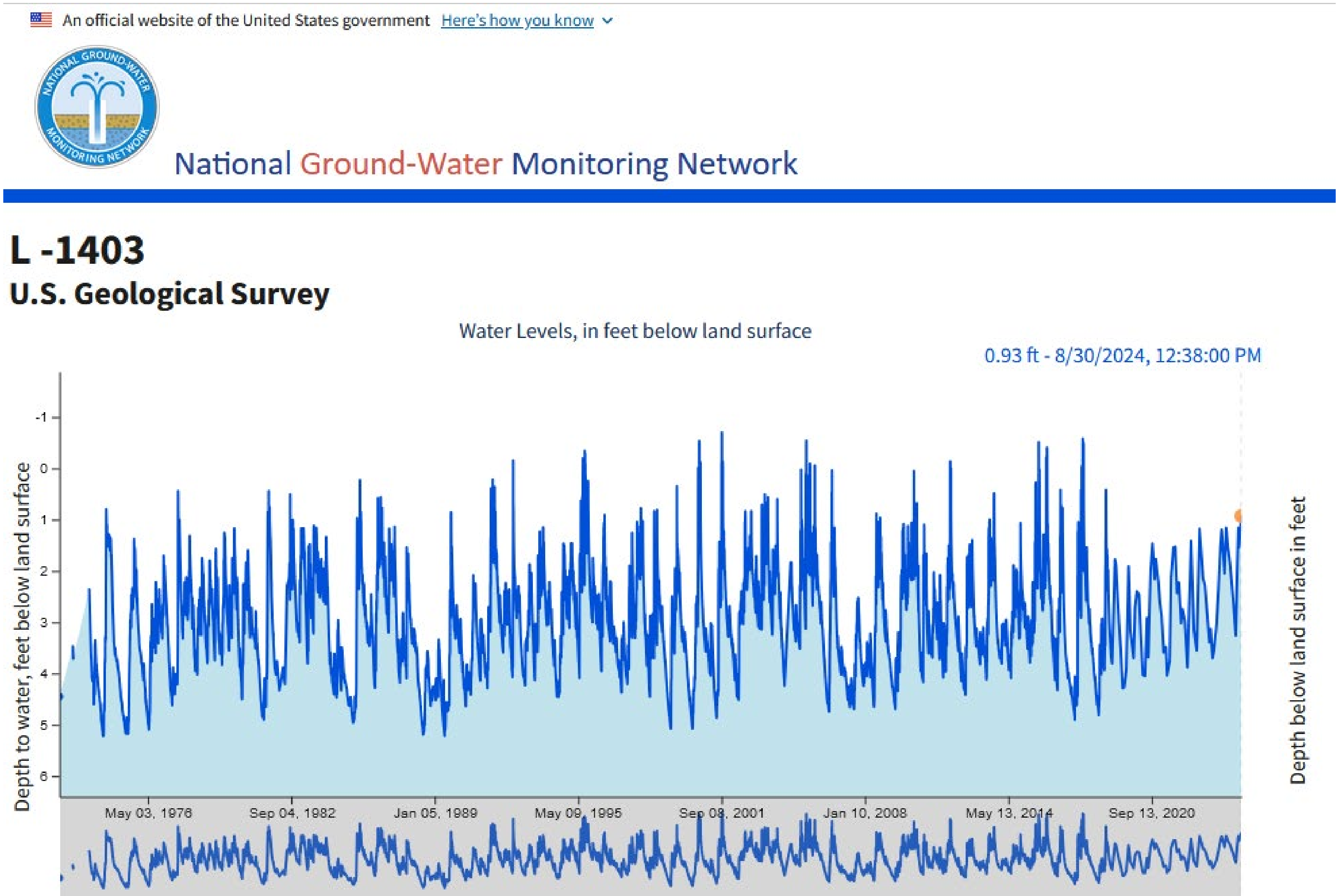

Figure 9. Groundwater depth below surface at USGS well L-1403 for period of record.

To further explore groundwater changes, **Table 3** was created, containing the average, minimum, and maximum, groundwater stage[9] for each year from 2017 to 2024, along with total annual rainfall[10] for each year. The net change in yearly minimum water level from 2017 to present is approximately 1.3 feet, a significant rise for Sanibel, while yearly average and minimum have seen more modest increases.

Table 3. Surficial aquifer water level at L-1403 for years 2017 to 2024, feet NGVD 29.

Year	2017	2018	2019	2020	2021	2022	2023	2024	*Change from 2017 - 2024*
Minimum	0.02	-0.03	0.31	0.55	0.56	0.72	0.90	1.34	***+1.32***
Average	1.75	0.79	1.46	1.90	1.83	1.98	2.08	2.61	***+0.27***
Maximum	3.17	1.58	2.82	3.13	3.07	3.42	3.44	3.44	***+0.86***
Total Rainfall (in.)	54.85	38.28	43.14	66.91	49.81	51.15	37.92	53.08 (as of August 2024)	--

One possibility for the increases in stages since 2017 is that the heavy rainfall Southwest Florida experienced in 2024 has (1) kept groundwater higher than normal and (2) prevented stages from falling as low as they usually do. While the first statement appears to be true, the second seems unlikely when other years of high rainfall are considered. When comparing 2020 (66.91 inches) and 2024, there has been a much greater increase in the annual minimum stage than the annual maximum stage – 0.79 feet versus 0.31 feet. So, while rainfall does play a role in groundwater levels, it does not seem to be the only factor.

Another potential cause of the increase in groundwater levels is the loss of vegetation following Hurricane Ian. **Figure 10** was created to check for a correlation between NDVI (and therefore vegetative health) and groundwater at L-1403 over the period from 2013 to 2024. The average groundwater stage for each water year is included to show the overall trend. Although groundwater levels increased following vegetation loss, water levels have not gone down as the vegetation has recovered. Instead, they continued to trend upward.

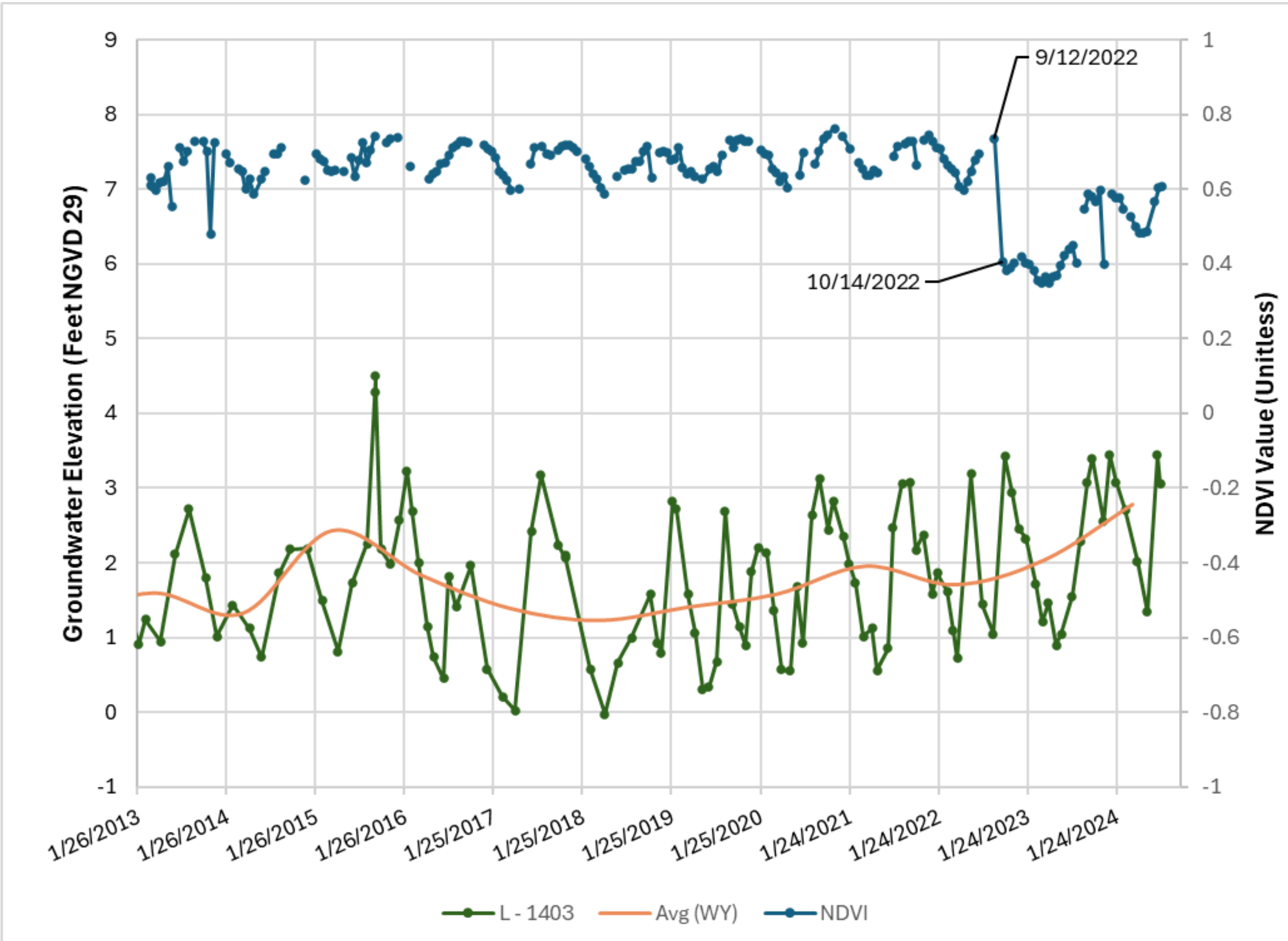

Figure 10. Water level at L-1403 and calculated Landsat 8 NDVI values for the interior basins over time. Orange line indicates average level per water year.

Conclusions

Most of the water leaving the interior basins on Sanibel has historically done so through evapotranspiration, a process inherently tied to plants. Given that plant populations have experienced a significant decline after Hurricane Ian, it would make sense for water levels to recede more slowly following rainfall events. This was generally not found to be the case for measured surface water across the island, but an investigation into minimum groundwater levels exhibits the changes experienced by many residents of the Island. This investigation found a notable increase in the annual minimum groundwater level since 2017 and does not appear to be attributable to Hurricane Ian (2022).

References

1. Clark, John. 1976. *The Sanibel Report*. The Conservation Foundation. Washington, D.C.
2. City of Sanibel staff, personal correspondence. 2024.
3. USGS Landsat NDVI: https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index
4. NASA Earth Observatory: Measuring Vegetation (NDVI & EVI) (nasa.gov)
5. USGS Landsat Science Products Storymap: https://geonarrative.usgs.gov/landsat-science-products/
6. Google Earth Engine Top of Atmosphere data description: https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA
7. Water level data provided by SCCF. 2024.
8. Location of USGS well L-1403: L -1403 - USGS Water Data for the Nation
9. L-1403 Data: L -1403 - U.S. Geological Survey - National Ground Water Monitoring Network (usgs.gov)
10. Manual rain gauge readings, City of Sanibel staff. 2024.