Winter Strawberry Production in West Central Florida, at what cost? A GIS Analysis of the relationship between sinkhole development, dry well complaints and groundwater pumping for frost-freeze protection

Mark D. Aurit, GISP
• manages water for SW Florida
• covers 10,000 square miles
• serves > 5 million people.

• 3 cities and 3 counties in the Tampa Bay region.
• provides 186 million gallons drinking water / day

Source: SWFWMD, 2011
http://www.swfwmd.state.fl.us/about/mission/
Strawberries: Dover / Plant City

Florida is the main producer of winter strawberries in the USA.

Approximately 7000 acres are harvested in SW Florida.

Protecting crops from frost-freeze events is important.
Crop protection during frost-frost events

- Passive
  - Site selection
  - Cover

- Active
  - Heaters
  - Wind
  - Water


Table 4. Estimated approximate annual per hectare/hour operating costs (including amortization of investment, but with 0% interest and before taxes) for selected cold temperature (frost) protection systems used 120 hours per year.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated costs/ha/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Stack Oil Heaters (100/ha)*</td>
<td>$ 93.08</td>
</tr>
<tr>
<td>Standard Propane Heaters (154/ha)*</td>
<td>103.98</td>
</tr>
<tr>
<td>Wind Machine (130 BHP propane)</td>
<td>33.36</td>
</tr>
<tr>
<td>Overcrop Sprinkling</td>
<td>4.10</td>
</tr>
<tr>
<td>Under Canopy Sprinkling</td>
<td>4.25</td>
</tr>
<tr>
<td>Frost-free site</td>
<td>0.00</td>
</tr>
</tbody>
</table>

* equal total heat output
Frost-freeze and damage

<table>
<thead>
<tr>
<th>Floral/Fruit Stage Strawberry</th>
<th>Temperature at which 90% Damage Occurs (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight bud</td>
<td>22°F or -5.5°C</td>
</tr>
<tr>
<td>Tight with white petals</td>
<td>28°F or -2.2°C</td>
</tr>
<tr>
<td>Full bloom</td>
<td>32°F or -1.1°C</td>
</tr>
<tr>
<td>Immature fruit</td>
<td>28°F or -2.2°C</td>
</tr>
</tbody>
</table>

Source: OMFRA, 2009
Known effects of water abstraction

Abstraction of water

Rapid reduction in water levels
(940 million gallons water/day vs 37 MGD)

Result

• Dry wells

• Sinkhole development

Source: Bengstonn, 1989
Damage caused during the 2010 frost-freeze

<table>
<thead>
<tr>
<th>Plant City Road Repairs</th>
<th>Trapnell Elementary School</th>
<th>Plant City Water Tower</th>
<th>Hillsborough County</th>
<th>Sinkhole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,600,000</td>
<td>$900,000</td>
<td>$250,000</td>
<td>$4,900,000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>139</td>
<td></td>
</tr>
</tbody>
</table>

Picture illustrating how a 30 yard wide 40-50 foot deep sinkhole destroyed property in Plant City, FL. (Source: Picture by Jay Nolan 2010)

Damage caused by a sinkhole on Highway 27 near Interstate 4 connecting Tampa and Orlando, which resulted in the closure of three of four lanes on January 13, 2010. (Source: Picture by WMG-TV Jacksonville, 2010)
Sinkholes in Florida

Subsidence Incidents Reported to the Florida Geologic Survey

Sinkholes without date information in the FGS database were not counted.

**2010 Sinkhole Data Through February**
Sinkhole is 30 ft x 12 ft
Water levels dropped > 20 ft for 3 days
When temperatures dropped below-normal with freezing temperatures

Damage during 2010 frost-freeze

Repairing Florida sinkholes are EXPENSIVE

By GEORGE H. NEWMAN | The Tampa Tribune Dec 31, 2010
SWFWMD reports costs can range from $1,000-$10,000 per incident

Tampa Bay Waters costs are similar to repair dry wells

<table>
<thead>
<tr>
<th>Process</th>
<th>Detailed Description</th>
<th>Average Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigate Claim</td>
<td>Initial investigation to determine severity of the problem.</td>
<td>$1,000</td>
</tr>
<tr>
<td>Option 1: Repair well OR drill new well using complainant vendor</td>
<td>Repair or drill new well using complainant vendor</td>
<td>Repair Well-$5,000 New Well- $14,000</td>
</tr>
<tr>
<td>Option 2: Repair Well</td>
<td>Water company repairs or drills new well</td>
<td>$9,000</td>
</tr>
<tr>
<td>Well Completion</td>
<td>Final water quality tests to ensure water quality is to federal drinking water standards. Performed by independent consultant</td>
<td>$4,000</td>
</tr>
</tbody>
</table>
Alternative Frost-Freeze Protection

Freeze Cloth

- Estimated Cost for Cloth is $2,000-$2,400 per acre
- Average Labor Cost to apply $300 per acre
- In the Dover/Plant City Area Farmers pay 25% the rest is covered by SWFWMD Facilitating Agricultural Resource Management Systems (FARMS) program
Objectives

1. Analyze how frost-freeze events affected West Central Florida over the past 25 years.

2. Understand the relationship between sinkhole/drywell complaints to a variety of factors (minimum temperatures, ground water level and proximity to strawberry farms).

3. Examine the use of alternative methods through an economic impact analysis.
### Data Sources

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Publisher/Source</th>
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<th>Data Type</th>
<th>Shape</th>
<th>Measure</th>
<th>Time Component</th>
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<tbody>
<tr>
<td>NOAA Temperature Data</td>
<td>National Oceanic and Atmospheric Administration</td>
<td>2010</td>
<td>Vector</td>
<td>Point</td>
<td>F°-Daily Minimum Temperature</td>
<td>Yes</td>
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<tr>
<td>Sinkhole Location</td>
<td>Florida Geologic Survey</td>
<td>2010</td>
<td>Vector</td>
<td>Point</td>
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<td>Yes/No</td>
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<tr>
<td>Strawberry Farms</td>
<td>SWFWMD</td>
<td>2010</td>
<td>Vector</td>
<td>Polygon</td>
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<tr>
<td>Water Use Permits</td>
<td>Southwest Florida Water Management District</td>
<td>2010</td>
<td>Vector</td>
<td>Point</td>
<td>Maximum Daily Permitted Flow Gallons/Day</td>
<td>No</td>
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<tr>
<td>Floridan Aquifer Monitor Sites</td>
<td>Tampa Bay Water</td>
<td>2010</td>
<td>Vector</td>
<td>Point</td>
<td>Daily Average</td>
<td>Yes/No</td>
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<tr>
<td>Well Complaints</td>
<td>Tampa Bay Water</td>
<td>2010</td>
<td>CSV</td>
<td>Table</td>
<td>Daily Average</td>
<td>Yes/No</td>
</tr>
<tr>
<td>SWFWMD 2010 Aerial Photos</td>
<td>Tampa Bay Water</td>
<td>2010</td>
<td>Vector</td>
<td>Point</td>
<td>N/A</td>
<td>Yes</td>
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<tr>
<td></td>
<td>Southwest Florida Water Management District</td>
<td>2010</td>
<td>Raster</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
</tr>
</tbody>
</table>
What Defines a frost freeze event?

Frost freeze event will be defined when temperature < 32 °F (0 °C)

<table>
<thead>
<tr>
<th>Floral/Fruit Stage</th>
<th>Temperature at which Damage Occurs (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight bud</td>
<td>22°F or -5.5°C*</td>
</tr>
<tr>
<td>Tight with white petals</td>
<td>28°F or -2.2°C*</td>
</tr>
<tr>
<td>or immature fruit</td>
<td></td>
</tr>
<tr>
<td>Full bloom</td>
<td>31°F or -0.5°C*</td>
</tr>
<tr>
<td>Strawberry</td>
<td>32°F or 0°C</td>
</tr>
</tbody>
</table>
Analysis

- Spatial and temporal analysis
  - Occurrence of sinkholes and dry well complaints over 25 years
  - Occurrence of sinkholes and dry well complaints during two frost-freeze events (1985 and 2010) and a non frost-freeze year (2007)

- Hot Spot Analysis
- Exploratory Regression Analysis
25 year span

1985

2010

2007

2010
Sinkholes and Dry Well Complaints
1985 - 2010
Sinkholes and Dry Well Complaints
Relationship to Water Level Change
1985 - 2010

Number of Complaints

Change in Water Level

\[ y = 0.0822x^2 - 0.5798x + 4.8983 \]

\[ R^2 = 0.585 \]
Drop in Water Levels during a Frost-Freeze Event, 1985
Statistical Correlation between Minimum Temperature and Water Level Change for Sinkholes & Dry Well Complaints during a frost-freeze event, 1985

No Correlation

Change in Water Level
\[(n=5, r=0.276, P <0.05)\]
Change in Water Level
\( (n=5, r=0.276, P < 0.05) \)

Minimum Temperature
\( (n=45, r=0.110, P < 0.05) \).
Drop in water levels during a frost-freeze event, 2010
Statistical Correlation between Minimum Temperature and Water Level Change for Sinkholes & Dry Well Complaints

Water levels during a frost-freeze event, 2010

Correlation between change in water level

**Change in Water Level**
- **Sinkhole**: \( n=15, r=0.791, P > 0.05 \).
- **Dry Well Complaints**: \( n=22, r=0.783, P > 0.05 \).

\[
y = 0.9032x - 3.6265 \\
R^2 = 0.6279
\]

\[
y = 0.4554x - 1.49 \\
R^2 = 0.6123
\]
Statistical Correlation between Minimum Temperature and Water Level Change for Sinkholes & Dry Well Complaints

Water levels during a frost-freeze event, 2010

Correlation between Minimum Temperature

Minimum Temperature
Sinkhole: \( n=15, r=0.632, P > 0.05 \).
Dry Well Complaints: \( n=22, r=0.625, P > 0.05 \).
Statistical Correlation between Minimum Temperature and Water Level Change for Sinkholes & Dry Well Complaints

Water levels during a frost-freeze event, 2010

Correlation between minimum temperature & change in water level

Minimum Temperature & Water Level Change

Sinkhole: (n=15, r=0.721, P >0.05).
Dry Well Complaints: (n=22, r=0.823, P >0.05).

\[ y = -0.6255x + 54.456 \]

\[ R^2 = 0.5209 \]
Spatial Analysis of the 1985 and 2010 Frost Freeze Events
### Clustering of Sinkholes and Dry Well Complaints 1985, 2007, and 2010?

#### Average Nearest Neighbor

<table>
<thead>
<tr>
<th>Year</th>
<th>Sinkhole</th>
<th>Observed Mean Distance</th>
<th>Expected Mean Distance</th>
<th>Nearest Neighbor Index</th>
<th>Z-Score</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>30</td>
<td>253.875442</td>
<td>2362.907813</td>
<td>0.107442</td>
<td>-9.352506</td>
<td>0.000000</td>
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<tr>
<td>2010</td>
<td>131</td>
<td>391.749768</td>
<td>1126.472101</td>
<td>0.0347767</td>
<td>-14.335758</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Dry Well Complaints</th>
<th>Observed Mean Distance</th>
<th>Expected Mean Distance</th>
<th>Nearest Neighbor Index</th>
<th>Z-Score</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>5</td>
<td>4730.326943</td>
<td>5787.918451</td>
<td>0.817276</td>
<td>-0.781648</td>
<td>0.433550</td>
</tr>
<tr>
<td>2010</td>
<td>812</td>
<td>205.42</td>
<td>1490.73</td>
<td>0.137798</td>
<td>-47</td>
<td>0.000000</td>
</tr>
</tbody>
</table>
Have sinkholes and dry wells occurred in the same areas in both 1985 and 2010?
Dry Well Complaint locations in 2010
Spatial Regression Analysis

Understanding the relationship between sinkhole/drywell complaints to a variety of factors (minimum temperatures, ground water level and proximity to strawberry farms).
Sinkhole and Dry Well Complaints Distance to Strawberry Fields

% Of Incidents

Distance in Miles

- 1985 Sinkholes
- 2007 Dry Well Complaints
- 2010 Sinkholes
- 2010 Dry Well Complaints
Locations of Sinkholes, Dry Well Complaints and Strawberry Fields in 2010
Water Use Permits Greater Than 1 MGPD in 2010
Exploratory Regression
## Exploratory Regression Results

<table>
<thead>
<tr>
<th>Measuring</th>
<th>Passing Models</th>
<th>Table Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Adjusted R-Squared $&gt; 0.50$</td>
<td>$R^2$</td>
<td>Adjusted R-Squared</td>
</tr>
<tr>
<td>Max Coefficient p-value $&lt; 0.05$</td>
<td>$\text{AICc}$</td>
<td>Akaike’s Information Criterion</td>
</tr>
<tr>
<td>Max VIF Value $&lt; 7.50$</td>
<td>$\text{JB}$</td>
<td>Jarque-Bera p-value</td>
</tr>
<tr>
<td>Min Jarque-Bera p-value $&gt; 0.10$</td>
<td>$\text{BP}$</td>
<td>Koenker (BP) Statistic p-value</td>
</tr>
<tr>
<td>Min Moran’s I p-value $&gt; 0.10$</td>
<td>$\text{VIF}$</td>
<td>Max Variance Inflation Factor</td>
</tr>
<tr>
<td></td>
<td>$\text{MI}$</td>
<td>Moran’s I p-value</td>
</tr>
<tr>
<td></td>
<td>Model Variable sign and significance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* = 0.10, ** = 0.05, *** = 0.01</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
<th>$\text{AICc}$</th>
<th>$\text{JB}$</th>
<th>$\text{BP}$</th>
<th>VIF</th>
<th>MI</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinkhole</td>
<td>0.718955</td>
<td>115.0596</td>
<td>0.695553</td>
<td>0.010191</td>
<td>1.849512</td>
<td>0.157826</td>
<td>-SHAVEDISTSF** +SUM_PERM_CROP **</td>
</tr>
<tr>
<td>Dry Well Complaint</td>
<td>0.762637</td>
<td>161.155</td>
<td>0.847513</td>
<td>0.069014</td>
<td>1.53641</td>
<td>0.873654</td>
<td>-DWCAVEDISTSF** +SUM_PERM_CROP **</td>
</tr>
</tbody>
</table>

Indicates Model Significance * = 0.10, ** = 0.05, *** = 0.01

**NOTE:** Adjusted $R^2$ indicates model performance with higher values indicative of better performance, $\text{AICc}$ (Corrected Akaike’s Information Criterion) measures model fit with lower values indicative of better fit, the Koenker BP Statistic measures stationarity with significant p-value indicating non-stationarity, the Jarque-Bera Statistic assess the distribution of the model residuals with significant p-value indicating non-normal distribution, and Moran’s Index measures spatial autocorrelation with significant p-value indicating non-random spatial distribution.
Time Series Animation of the Frost Freeze Event
January 1, 2010 to January 21, 2010
Comparison of frost-freeze events.
Cost of pumping vs cost of using alternative control for 2010

- Cost of investigating and repairing dry wells
  - 2007- total cost was $12,859 (average $2571 per complaint)
  - 2010- total cost was $472,951 (average $2866 per complaint)

- Estimated cost of using the frost freeze cloth
  - Total Cost=$16.5 million ($39,000 per field)
  - FARMS subsides=Farmers pay $4.1 million ($9,750 per field)
  - Farmers pay 25% SWFWMD pays 75%
Conclusion

- **Summary of Findings**
  - A statistically significant correlation between minimum temperatures and change in water level (MinTa < 41°F and WL Change > 20 ft, number of sinkholes increase (N > 10))
  - Sinkhole occurrence are spatially clustered
  - Dry well complaints are spatially clustered
  - Spatial regression analysis found that distance to strawberry fields and water use permits (total volume) influence development of sinkholes and dry well complaints.

- **Comparison to previous studies**
  - 25 year span, plus 3 individual years
  - Bengtsson (1989) study only analyzed single event in 1985
Conclusion

Future/Suggestions

- SWFWMDs Dover/Plant City Freeze Management Plan-2010
- Suggestions and Recommendations from this study
Acknowledgements

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Questions

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