Expansion-Contraction: Spatial and Temporal Variability in Connectivity in a Stream-Wetland Flow Network

Savannah Fransbergen
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Expansion-Contraction: Spatial and Temporal Variability in Connectivity in a Stream-Wetland Flow Network

by

Savannah Fransbergen

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Science and Policy School of Geosciences College of Arts and Sciences University of South Florida

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ABSTRACT

The seasonal expansion and contraction in a stream-wetland flow network is often difficult to characterize due to a lack of accurate mapping products, but proper characterization is important for the management of these resources. A new approach to mapping hydrography, resulting in a Regional Hydrography Dataset (RHD), may offer additional insights not provided by the national standard, the National Hydrography Dataset (NHD). The RHD can be customized to provide seasonal or monthly hydrograph, whereas the NHD is static. We conducted field validation (241 sites) and geospatial analyses to assess the accuracy of these products in the northern Tampa Bay Area. RHD was more accurate, had a lower error of omission rate, and was more representative of our study area conditions than NHD. RHD also had fewer false-negative prediction points, which means it was better at conveying the landscape connectivity we were observing on the ground. RHD is an improvement but does not substitute for wet season fieldwork when accuracy is critical. We conducted a geospatial analysis to characterize the flow network, including connected wetlands, through a year. We found that seasonality affected flowline length, which inherently affected the amount of connected wetland area. Between August and May, 37% of the wetland area connected to the stream network in the wet season is disconnected as the flow network transitions into the dry season. To determine which sections of the flow network were experiencing the most drastic changes, we used the Strahler stream ordering method for May and September hydrography. It was found that 99.7% of first-order streams, 69% of second-order streams, and 18% of third-order stream length were lost due to
seasonal influences. Most seasonal flow is in 1st, 2nd, and 3rd stream order streams, while perennial occurs primarily in higher-order positions (i.e., 4th, 5th, and 6th orders)
INTRODUCTION

Rivers and streams are integral components of the landscape. They transfer water, nutrients, sediments, and organisms via perennial, intermittent, and ephemeral channels to downgradient waters, floodplains, and connected wetlands. Through time, these processes shape the hydrologic landscape (Ward, 1989).

Streams contain many components that experience different biological, chemical, and geological processes at various locations. For example, headwater wetlands typically experience slower flow than their downstream counterparts, affecting biodiversity. Slower flow allows more complex seeded plants to take root, encouraging long-distance dispersal techniques (Cohen, 2016). Additionally, low flow input may make surrounding receiving waters more chemically stable than their downstream counterparts. As chemical stability increases, plants and animals that favor these conditions may colonize these wetlands and increase landscape-level biodiversity, inherently stabilizing populations (Cohen, 2016). Long water residence times also encourage sinking functions (e.g., sediment deposits storing more complex organic compounds) as opposed to sites with the higher flow (Cohen, 2016). Sediments in slow-flowing areas have a higher tendency to precipitate out of the water column, where they may be retained for extended periods.

Stream morphology affects biogeochemical aspects of surrounding wetlands and downstream waters (Fitzpatrick et al., 1998). One way to characterize stream morphology is the Strahler stream ordering method (Strahler, 1957). The Strahler method classifies rivers by the
number of stream connections. By sorting streams in this manner, biodiversity, nutrient cycling, and other geochemical processes become easier to infer based on hydrology (Fitzpatrick, 1998). Although much attention has been on mainstem rivers (higher-order streams), smaller components (lower-order streams) are also important. Lower-order streams often appear as ephemeral or intermittent connections influenced by seasonal changes. These seasonal stream network extensions increase the diversity of biotic and abiotic factors that affects a stream’s biogeochemical makeup and contributing functions. The variability in stream function and contributions through network expansion affects the composition and integrity of downstream waters (US EPA, 2015).

Headwater streams and wetlands comprise 70% of all stream length in the US (Nadeau & Rains, 2007). Headwater streams and wetlands provide essential services such as flood control (Acreman, 2013), habitat, filtration, nutrient cycling, and sediment supply (Cohen et al., 2013). Though most of the stream length in the US consists of smaller connections, many are subject to the protections of the Clean Water Act.

Regulatory decisions and functional assessments of wetlands and streams are often based on the presence and duration of a surface water connection. For example, streams connected to surrounding water bodies and a more permanent groundwater source are usually protected more than their intermittent or ephemeral counterparts (Yeo, 2019). In addition, ephemeral and intermittent wetlands lack accurate location information due to seasonal fluctuations in the stream network, which inhibits proper prioritization and protection of those wetlands. For example, in March 2020, Twin Pines Minerals mine requested a permit to mine near the Okefenokee swamp due to regulatory protections no longer encompassing ephemeral
connections or seasonal streams and wetlands. This permit request has not been denied and is still under review (Dunlap, 2021).

An essential first step to proper management is knowing where streams and connected wetlands occur and for how long they are typically connected by surface water during a typical year. Therefore, it is crucial to map and study the seasonal flow network. In the past, wetland-stream network mapping was attempted through optical and radar remote sensing. However, such models have limitations that are not suited to our study area. For example, optical remote sensing is limited by cloud cover and dense tree canopy coverage. Synthetic aperture radar remote sensing is hindered by its scale, which can detect landmarks at a scale of fewer than 100 meters to kilometers (Moreira et al., 2013).

The dynamic nature of stream networks makes it a challenge to construct a meaningful, comprehensive, and informative map using standard mapping methods. For example, when streams experience seasonal changes, the stream network expands into other bodies of water, such as wetlands. As a result, dry season imagery may not reflect wet season stream size, length, or flow changes. Surrounding vegetation may also interfere with aerial detection of wet season surface water connections. For example, rapidly proliferating vegetation may overhang wetland boundaries and small channels in the wet season, making aerial photo interpretation challenging. New tools and mapping practices can provide more accurate insight into wetland connectivity to streams and rivers, which can help conservation efforts.

Tampa Bay is an example of a location with abundant streams, wetlands, and multiple mapping products available. The national standard is the National Hydrography Dataset (NHD), with NHD Plus in development (U. S. Geological Survey, 2020). However, Tampa has an additional resource, a Regional Hydrography Dataset (RHD), that is not a static product, like
NHD. Instead, data can be characterized annually, seasonally, or by groundwater pumping periods (Lee et al., 2021).

The National Hydrography Dataset is the most complex, up-to-date nationwide hydrography database in the United States publicly available. The NHD dataset utilizes various files for its mapping products, such as US Geological Survey (USGS) hydrologic digital line graph files, US Forest Service cartographic feature files, Environmental Protection Agency reach files, and USGS tagged hydro vector data, and printed maps (National Hydrography Dataset, 2021). The database is updated and maintained by USGS, and local stewards complete additional proofing and data entry from local entities. While the data is not formally ground-truthed by USGS, the public can submit supplemental information to the USGS to be incorporated into map updates. Additionally, USGS works with many state, federal, and local organizations to collaborate on data products, cost-sharing projects, and project support (National Hydrography Dataset, 2021). NHD flowline and waterbody data are mapped at a 1:100,000 to 1:24,000 scale (varies by data source) throughout the US (National Hydrography Dataset, 2021). The scale captures most North American rivers, streams, lakes, glaciers, dams, and similar features. Additionally, flowline data mapping is based on surrounding features and is mapped within 167 feet of their geographic positions as mapped by USGS (National Hydrography Dataset, 2021).

NHDPlus is another product of USGS that consists of streamflow information that is mapped starting at 1:24,000 scale but can reach a higher resolution scale. However, the product is relatively new and has been in a developmental stage for many years. NHDPlus only encompasses about 80% of the United States (National Hydrography Dataset, 2021).

RHD was developed using standard GIS tools and local topography and stream gage information, making the method portable to other locations. An advantage of RHD is that it can
track seasonal changes in the stream network based on runoff data collected by stream gauges (Wieczorek, 2010), whereas NHD is a static product. As a result, the RHD product can be tailored to provide stream networks based on gauged streamflow during certain seasons, months, years, or even sets of years, such as before or after a change in land management policy. The University of South Florida School of Geosciences has developed the RHD for the northern Tampa Bay area with support from Tampa Bay Water, a regional water supply authority (Lee et al., 2021).

In this study I assess the accuracy of stream-mapping products in the Tampa Bay region and use geospatial analysis to characterize seasonal and monthly changes in the wetland-stream network. I describe this study and results in this thesis and have also prepared a companion geodatabase, animation. In 2020, I presented this study orally at the Society of Wetland Scientists National Meeting (Fransbergen et al., 2020). The study is organized around four central objectives:

**Objective 1: Contrast maps generated by current hydrography datasets**

Approach: Geospatial analysis and fieldwork to:

- Determine whether estimates of stream length and connected wetland area differ when different sources are used for hydrography datasets
- Contrast the relative accuracy of hydrography maps provided by NHD, NHDPlus, and RHD
Objective 2: Characterize the Wetland-Stream Network in the Wet Season and in the Dry Season

Approach: Geospatial analysis of seasonal changes to:

- Total length and distribution of the stream network (hydrography)
- Total area and distribution of wetlands with surface water connections to the stream network, i.e., connected wetlands

Objective 3: Characterize the Monthly Expansion and Contraction of the Wetland-Stream Network, Through a Full Annual Cycle

Approach: Geospatial analysis of monthly changes to:

- Total length and distribution of the stream network
- Total area of wetlands with surface water connections to the stream network
- Relative area of connected wetlands each month compared to a wet season standard (September)

Objective 4: Characterize the Stream Network by Stream Order in the Wet Season and In the Dry Season

Approach: Geospatial analysis of the stream network and connected wetlands, in a dry-season month (May) and a wet-season month (September), classified by stream order:

- Total length and distribution of stream segments classified by stream order
- Total area of wetlands connected to stream segments classified by stream order
METHODS

Study Area

The Northern Tampa Bay Area (NTBA) is located in west-central Florida and comprises about 1,800 mi$^2$ (Haag, 2005). This region experiences a humid, subtropical climate characterized by a warm summer and mildly dry winter (Elder, 2017). Typical temperatures vary between 15.7 °C at the beginning of winter to 27.7 °C in summer (NOAA, 2021). Precipitation data were collected from Tampa International airport (Appendix A). The average precipitation is 1,244 millimeters in the Northern Tampa Bay area, with the most significant rainfall occurring during a three-month wet season (Appendix B). The three-month wet season accounts for 47% of all yearly precipitation, with the wettest month being August which accounts for 17% of annual rainfall alone (Appendix B). The month with the least precipitation is May, accounting for 5% of yearly rainfall (NOAA, 2021).

The region sits on the Upper Floridian aquifer, a complex karst system that flows into the Gulf of Mexico and Tampa Bay (Haag, 2012; Elder, 2017). The abundant rivers drain into Tampa Bay and the Gulf of Mexico (e.g., the Hillsborough River, Anclote River, and the Tampa Bypass Canal), with only 20 percent of the area classified as urbanized from FLUCCs data (FDEP, 2017). The geology of Tampa Bay primarily consists of permeable limestone that sits on top of bedrock known as the Florida Platform (Haag, 2012). Soils are generally poorly drained with a sandy subsoil, sand throughout, or have a loam subsoil (Yates, 2011). The topography consists of shallow depressions, drainage ways, and low ridges (Yates, 2011). Additionally, the
terrain is somewhat flat, with a gradual elevation increase northward from south Hillsborough County from 0.1 – 32 meters (Tyler, 2007). Florida’s low-lying landscape and karst geology contribute to the pervasiveness of wetlands.

In the 1780s, The US had a collective 392 million acres of wetlands, which decreased to 104 million acres by the 1980s (Dahl, 1990). Florida alone lost 9.3 million acres of wetland area over the same period. Additionally, from 1985 to 1996, annual wetland loss in Florida has averaged 5,000 acres (Dahl, 1990). However, wetlands are still pervasive in the Tampa Bay area due to precipitation patterns, low-lying topography, and conservation efforts.

The study area (about 150,000 hectares) is located in the Northern Tampa Bay Area region and includes portions of Hillsborough, Pasco, Pinellas, and Hernando Counties (Fig. 1). Groundwater wellfields are maintained in the study area for municipal groundwater extraction. In the late 20th century, average groundwater extraction was approximately 150 million gallons a day which had severe effects on water levels in waterbodies, rivers, and streams. Pumping rates were subsequently reduced to 90 million gallons per day following widespread recognition of the environmental impact of over-extraction (Southwest Florida Water Management District (SWFWMD), 2004).
Development of the Regional Hydrography Dataset

The seasonal expansion and contraction of streams mean that stream networks should be evaluated with a dynamic product that can adapt to seasonal changes. The Regional Hydrography Dataset was developed to map a dynamic stream network using two sources of data: (1) USGS WaterWatch runoff data and (2) LiDAR (light detection and ranging) terrain data. The approach delineates streams based on cubic feet per second (CFS) and monthly or yearly runoff data. Data are averaged over months or multiple years (Wieczorek, 2010). This method focuses on streamflow mapping and estimates where headwaters begin at specific points in the hydrologic landscape (Wieczorek, 2010). First, streamflow data from watershed outlets were converted to runoff per unit area, assuming different watershed parts contributed equally to downstream
waters. This was retrieved from the USGS WaterWatch data. Next, LiDAR terrain data were used to map the upslope area of each 2.5 × 2.5 feet (0.76 × 0.76 meters) grid cell (Lee et al., 2021). Next, the upslope area was multiplied by runoff depth to generate a flow grid (cubic feet per second), which was used to classify tributaries based on flow magnitude (Lee et al., 2021). Finally, the classified tributary grid was used to estimate the locations of streams across the study area. Since RHD is generated from runoff data that varies in time, the RHD maps can be generated for different months, seasons, and periods before and after groundwater pumping at well fields (Lee et al., 2021). All flowline datasets used in the project were post cutback years (2003-2015). “Wet season” hydrography was generated using data from July- September and “dry season” hydrography was generated using data from April- June.

**Modifications to the Wetland/Waterbody Layers**

The NWI (U.S. Fish and Wildlife Service, 2014) and NHD (U.S. Geological Survey, 2020) data products were obtained from online sources. The NHD product came as three separate products (NHD Waterbody 1, 2, and 3) which I merged prior to the analysis. Next, the adjoining boundaries for each product were dissolved so that determinations of average wetland size would not be affected by differences in wetland classification systems used by NWI and NHD. NHD waterbody products were only utilized in one portion of the study “Contrast Wetland Maps Provided by NWI and NHD”, all other references to wetland mapping that occur within this document refer to the NWI map.
Objective 1) Contrast Maps Generated by Current Hydrography Datasets

Determine Whether Estimates of Stream Length and Connected Wetland Area Differ When Different Sources Are Used for Hydrography Datasets

NHD and RHD (0.25 cfs wet, and 0.5 cfs wet) flowlines were buffered 40 meters to account for mapping offsets and the intersections below were performed to determine which wetlands/ waterbodies were connected to the flow network in each dataset. Our source for wetland mapping was the National Wetland Inventory (NWI) map, a nationally available mapping product in common use.

We performed a similar exploratory study on a different map that includes wetlands, the National Hydrography Dataset Waterbody map, but did not further develop that line of inquiry. Those initial results are in Appendix F.

Contrast the Relative Accuracy of Mapping Provided by NHD, NHDPlus, and RHD

The field verification process was conducted primarily during the wet season. In 2019, field review was conducted late August through early October and in 2020, field review was conducted September through mid-October. In addition, preliminary dry season fieldwork (13 site visits) was conducted April 21st, 2021. In 2019, 153 sites were visited, followed by 88 site visits in 2020 (Figure 2). The total number of site visits exceeds the total number of sites because some sites were visited on more than one occasion. (Table 1).
Table 1. Number of field sites established during the wet season. Some sites were visited more than once during this study. For example, dry season observations were made at 13 of these sites in 2021.

<table>
<thead>
<tr>
<th>Year</th>
<th>Season</th>
<th>Sites Established</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Wet</td>
<td>153</td>
</tr>
<tr>
<td>2020</td>
<td>Wet</td>
<td>88</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>241</td>
</tr>
</tbody>
</table>

Figure 2. Distribution of field sites (2019 and 2020) across the study area (northern Tampa Bay, FL).

In 2019, site selection was driven by the need to assess the accuracy of a draft version of RHD that was subsequently updated. We visited locations where larger and smaller flows were predicted (e.g., points verified both mainstream stems and headwater tributaries). In 2020, the
final RHD was available for field verification and the project expanded to include verification of the NHD.

In addition to visiting locations where hydrography datasets predicted flow, we also visited locations near wetlands that were mapped as surface water isolated wetlands, i.e., no mapped inlet or outlet (Figure 3). These locations, i.e., “negative prediction points” are further classified in the confusion matrix are true-negative and false-negative points (Table 3). Negative prediction point target sites were identified using two methods. First, we used the NWI layer to identify wetlands, then we overlaid the RHD layer to determine which wetlands were not predicted to have wet season connections to the stream network. We refined this search by utilizing topography layers and photo interpretation to identify the most likely locations for a surface water inlet or outlet to a specific wetland (Figure 4). The alternative approach we used was to record observations of wet season unmapped surface water connections made opportunistically while on route to other field sites.

In the field, we looked for various flow indicators such as channel morphology, rafted materials, aquatic plants, saturated soils, culvers, bridges, and standing water. Every site was photo documented and included videography of flow if present. Third-person accounts from employees of flow evidence were also considered in parks where RHD was predicted to flow but was not present at the sites. In the office, Microsoft Excel and ESRI GIS products were used to QC and organize the data.
Table 2. Definitions and formulas used in the confusion matrix (Markham, 2020).

<table>
<thead>
<tr>
<th>Confusion Matrix Metric</th>
<th>Formula</th>
<th>Definition</th>
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<tr>
<td>Accuracy</td>
<td>(TP+TN)/total</td>
<td>How often the classifier is correct</td>
</tr>
<tr>
<td>Error of Omission</td>
<td>FN/(TP+FN)</td>
<td>When it predicts yes, how often did the hydrography fail to predict it</td>
</tr>
<tr>
<td>Misclassification Rate</td>
<td>(FP+FN)/total</td>
<td>How often is the classifier wrong</td>
</tr>
<tr>
<td>Precision</td>
<td>TP/(TP+FP)</td>
<td>When it predicts yes, how often is it correct</td>
</tr>
<tr>
<td>True Positive Rate</td>
<td>TP/(TP+FN)</td>
<td>When it’s actually yes, how often does it predict yes</td>
</tr>
<tr>
<td>False Positive Rate</td>
<td>FP/(TN+FP)</td>
<td>When it’s actually no, how often does it predict yes</td>
</tr>
<tr>
<td>True Negative Rate</td>
<td>TN/(TN+FP)</td>
<td>When it actually no, how often does it predict no</td>
</tr>
<tr>
<td>Prevalence</td>
<td>(FN+TP)/total</td>
<td>How often does the yes condition occur in the sample</td>
</tr>
</tbody>
</table>

We assessed the performance of 5 RHD datasets (listed below), as well as NHD and NHDPlus through a confusion matrix based on definitions and formulas provided in Figure 3 and Table 2.

- Annual (0.25 cfs) (Average of annual cfs)
- Wet (0.25) (Average wet season cfs)
- Wet (0.5)
- September (0.25)
- September (0.5)
The most accurate flowline dataset based on confusion matrix results was then compared to photos and field observations to determine if it rightfully reflected what we were observing on the ground.

**Figure 4.** Data point classification based on hydrography and field observations. Legend abbreviations: *FN* False Negative, *FP* False Positive, *TN* True Negative, *TP* True Positive.
Objective 2) Characterize the Expansion and Contraction of the Wetland-Stream Network In the Wet Season and In the Dry Season

The differences in total streamflow length during seasonal changes are difficult to map accurately. Most available mapping products are static and do not reflect seasonal changes. However, the RHD contained wet season (July-Sept) and dry season (April-June) flowlines generated to reflect flow as low as 0.25 cfs.

**Total Length and Distribution of the Stream Network**

The total stream length of both datasets was found using the calculate geometry tool (ArcGIS Pro version 7.2.1).

**Total Area and Distribution of Wetlands Draining Into the Stream Network**

Flowlines in both datasets were buffered (100 meters) and intersected with the NWI map. A 100-meter buffer was chosen because it included wetland features likely to drain into the wetland-stream network. The layer produced contained all wetland areas inside of the buffered flowlines. Next, the total wetland area within the flowline buffer for both seasons was calculated using the Calculate Geometry tool (ArcGIS Pro version 2.7.1).

Objective 3) Characterize the Monthly Expansion and Contraction of the Wetland-Stream Network, Through a Full Annual Cycle

**Total Length and Distribution of the Stream Network**

To compare monthly changes in RHD flowlines, the total stream length needed to be calculated. This was accomplished by using the “calculate geometry” function in the attribute table of all months. The total length of all flowlines was extracted and graphed for each month (Figure 6).
**Total Area of Connected Wetlands**

Next, a comparative analysis for connected wetland areas by month was completed. All monthly flowlines were buffered 100 meters and intersected with the NWI layer. The area inside of the buffer for each month was counted as a hydrologically connected wetland area.

Connected wetland area was defined as “wetland area inside a 100-meter buffer.” The connected wetland area was determined based on monthly flowline data and intersected with the NWI layer. To do this, flowlines for all months at 0.25 cfs were extracted and turned into individual layers and buffered 100 meters (Figure 8). The monthly buffered flowline layers were then sequentially intersected with the NWI layer, and the final products showed the total connected wetland area for all twelve months that fell inside the flowline buffers.

The overall results from the process produced monthly layers that showed wetland area hydrologically connected to flowlines within a 100-meter buffer, wetland area outside of the buffer (as long as some portion of the wetland intersected the buffered flowlines), and tables of monthly connected wetland area.

**Relative Area of Connected Wetlands Compared to September**

To further analyze seasonal effects on the stream network, we calculated the change in connected wetland area by month relative to September. September was chosen because it is a month at the peak of the wet season and used in wet season analyses by Tampa Bay Water. First, NWI wetlands were intersected with buffered (100 m) September hydrography (0.25 cfs) flowlines to create a layer of wetland area hydrologically connected to September flowlines (Figure 5) as described in the previous section. Then, all other 11 monthly buffered flowlines
(0.25 cfs) were intersected with the buffered September flowlines. The products were 11 intersection layers. Next, the total wetland area hydrologically connected by each monthly flowline was subtracted from the connected wetland area in September. Then, the wetland area connected by flowlines was used to calculate the percent change relative to September. The calculation for percent change is:

\[
C = (X^2 - X^1)/X^1
\]  
[1]

Where \(C\) is relative change, \(X^2\) is the initial value (September baseline), and \(X^1\) is the final value (wetland area connected by flowlines of each month).
Figure 5: Connected wetland area inside and outside a 100-meter buffer using September (0.25 cfs) flowlines. The amount of hydrologically connected wetland area to flowlines was found for September and May. This figure shows wetland area (green) hydrologically connected by September flowlines within a 100-meter buffer (blue).
Objective 4) Characterize the Expansion and Contraction of the Stream Network by Stream Order in the Wet Season and the Dry Season

The Total Length of Stream Segments Classified by Stream Order

The Strahler method was used on monthly flowline data to differentiate stream network (i.e., higher, and lower order) streams flowing in different seasons. The method was a way to determine a gain or loss in ephemeral or intermittent connections, particularly in lower-order streams, brought on by the wet and dry seasons. First, all monthly hydrography layers of 0.25 cfs or greater in were utilized with a particular emphasis on September and May, with stream order assigned to each dataset (Strahler, 1957). September was selected because it is traditionally the month in which wet season fieldwork has been conducted in this region and would help tie this study to previous published work. May was selected for dry season, as it was the month that contained the least amount of streamflow channel length. The process set up a framework that distinguished how flowlines were distributed and introduced a ranking system for quantifying parts of the stream network contributing to downstream waters (e.g., more lower-order streams in headwater areas are part of the stream network in the wet season).

Grids of cubic feet per second flow averaged for each month were extracted from the RHD database and separated into twelve individual layers. The raster calculator tool was used in conjunction with the cubic feet per second grid of each month to apply the expression of the form: “cfs of a given month >= 0.25,” which created a grid of 1’s (streams) and 0’s (no streams). The process above was completed for all 12 months using the same parameters. The “stream ordering” tool was then used where the “input stream raster” option was filled with the reclassified raster indicating the presence and absence of streams, and the “input flow direction raster” was the original flow direction grid in the RHD database indicating the downslope grid
cell that would receive flow from a given grid cell. Next, the “stream to feature” tool was used to turn the rasterized flowlines into feature lines.

The stream ordering tool generated grid codes (stream orders) for September and May. However, the stream order for May (which only went up to four) needed to be reworked to make September and May comparable. First, each September grid code (assigned stream order) was separated by order (total of 6 separate layers), and a 3-feet buffer was applied around each grid code layer. The new buffered layers for each order were then intersected and assigned to May flowlines (this way, May and September followed the same order). The reassignment of flowlines was accomplished by using the “clip” tool with the “input features” as the May stream order flowline layer and “clip feature” as buffered September stream orders. This process was completed six times for a final product showing six new stream orders assigned to May instead of four. To avoid any overestimation of distance from the buffer, each line segment of each stream order that was clipped to May was multiplied by 6 feet (total length of buffer extending off each line segment in either direction) or subtracted that number off the entire length of each stream order layer. The stream order distance correction is as follows:

\[
(Total\ stream\ order\ length - (Number\ of\ stream\ order\ segments \times 6)) = Total\ length\ of\ stream\ order\ in\ May
\]

The Total Area of Wetlands Connected to Stream Segments Classified by Stream Order (September vs. May)

First, each stream order layer for September and May were separated into individual layers (the longest stream network extended to the 6th order, so each month had six layers). Next,
flowlines in each stream order layer for both months were buffered by 100 meters. Each stream order buffer was then intersected with the NWI layer to get a connected wetland area per stream order. The tool was used a total of twelve times (six stream orders in September and May) and produced a layer of wetland area connected by flowlines for each stream order. Finally, the “calculate geometry” tool generated hectares' wetland area per stream order per month.
RESULTS

Objective 1) Contrast Maps Generated by Current Hydrography datasets

Determine Whether Estimates of Stream Length and Connected Wetland Area Differ when Different Sources are Used for Hydrography Datasets

The length of the flow network in the study area was 59% greater when mapped using the RHD (0.25 cfs, wet season) than with the NHD. The RHD predicts 2,343 km of stream length occurs in the area during the wet season while the NHD predicts 962 km occur in this same area. The spatial distribution of the stream network also varies between the two sources, only 273 km of streams in the study area appear on both hydrography datasets (Fig 6).

Table 3: NHD and RHD stream length comparison.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Stream Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHD</td>
<td>2,343</td>
</tr>
<tr>
<td>NHD</td>
<td>962</td>
</tr>
</tbody>
</table>
Figure 6: NHD and RHD flowline comparison.

The wetland connectivity study included an additional variant of the RHD that only includes streamflow down to 0.5cfs (RHD, 0.5cfs). The RHD dataset (0.25 cfs) predicted a greater proportion of wetland area was connected to the flow network than did either of the other two hydrography datasets (Table 4). This was true whether the wetland map tested was the NWI map (Table 4) or the NHD waterbody map (Appendix F). The RHD (0.25 cfs) hydrography indicated 82% of the NWI wetland area in the study area was connected to the stream network and that the average size of connected wetlands was 15 hectares. In comparison, the RHD
generated from streamflow up to 0.5 cfs (RHD, 0.5 cfs) indicated 76% of the NWI wetland area was connected to the stream network (average wetland size 20 hectares). Of the three datasets tested, the NHD indicated the least amount of NWI wetland area was hydrologically connected to the stream network and failed to connect smaller wetlands to the stream network. The connectivity estimates generated by NHD flowlines was 54%, i.e., 28% less than predicted by the RHD (0.25 cfs), and the average size of NWI wetlands connected by NHD flowlines was 34 hectares (Table 4). In the next section, we determine which hydrography dataset best describes actual field conditions.

Table 4: Wetland connectivity estimates based on the NWI wetland map. RHD (wet season) and NHD flowlines were intersected with NWI mapped wetlands to compare the amount of connected wetland area and the average size of connected wetlands.

<table>
<thead>
<tr>
<th>Flowlines</th>
<th>Percent of NWI wetland area connected by flowlines (ha)</th>
<th>Percent of total study area</th>
<th>Average size (ha) of connected wetlands/waterbodies (Standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHD (0.25 cfs)</td>
<td>82%</td>
<td>24%</td>
<td>15 (+/-206)</td>
</tr>
<tr>
<td>RHD (0.5 cfs)</td>
<td>76%</td>
<td>22%</td>
<td>20 (+/-251)</td>
</tr>
<tr>
<td>NHD</td>
<td>54%</td>
<td>16%</td>
<td>34 (+/-390)</td>
</tr>
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</table>

Contrast the Relative Accuracy of Mapping Provided by NHD, NHDPlus, and RHD

The confusion matrix metrics used to evaluate flowline performance are shown in Table 5. All the models were evaluated using their field point classifications which is shown in column 2. The RHD datasets collectively were more accurate and had a lower error of omission than NHD. This means that RHD did a better job of predicting flow that was observed in the field, and wetlands shown in the NWI dataset (Appendix F). The RHD datasets also had a lower misclassification rate and higher true positive rate, which means the model was wrong less times.
when flow was observed in the field. NHD had a higher precision rate, lower false positive rate, and higher true negative rate that indicates when the NHD predicts a flow occurrence, it will be there. Overall though the accuracy was not high for either dataset (explained more in the discussion section) the RHD better reflected wet season field conditions that we were observing in the study area.

The wet season and September flowlines performed very similarly during the field verification process. However, September had a lower false-positive rate which means it was a little more accurate in terms of what was supposed to be predicted was true. The same can be said for the true negative rate, which was better predicted by September flowlines. September hydrography best- reflected field conditions and predicted more seasonal stream segments than NHD flowlines.
Table 5. Confusion matrix and performance results. Confusion matrix data (first column) and performance metrics for the National Hydrography Dataset (NHD), NHDPlus, and, for RHD only: models generated from annual, wet season, or Sept streamflow. Performance metrics are presented for wet season and Sept RHD models generated from runoff data down to 0.5 cfs and down to 0.25 cfs.

<table>
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<tr>
<th>Flowlines</th>
<th>Field Point Classification</th>
<th>Accuracy</th>
<th>Error of Omission</th>
<th>Precision</th>
<th>Misclassification Rate</th>
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<th>False Positive Rate</th>
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Table 5 (Continued). Confusion matrix and performance results. Confusion matrix data (first column) and performance metrics for the National Hydrography Dataset (NHD), NHDPlus, and, for RHD only: models generated from annual, wet season, or Sept streamflow. Performance metrics are presented for wet season and Sept RHD models generated from runoff data down to 0.5 cfs and down to 0.25 cfs.

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<th>Flowlines</th>
<th>Field Point Classification</th>
<th>Accuracy</th>
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<td>45%</td>
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</table>
Objective 2) Characterize the Expansion and Contraction of the Wetland-Stream Network in the Wet Season and the Dry Season

**Total Length and Distribution of the Stream Network**

Seasonal changes have historically been difficult to assess because of the expansion and contraction of the stream network. NHD is a static product, and the flowlines do not reflect any changes pertinent to changing precipitation conditions in different areas. In contrast, the RHD methodology facilitates a seasonal analysis. Wet season total flowlines of the RHD extended 2,343 km while dry season extended less than half of wet season at 1,161 km. The seasonal difference in stream length of the two datasets is 1,182 km (Table 6).

**Total Area and Distribution of Wetlands with a Hydrological Connection to the Stream Network**

Seasonal stream length distribution directly affected connected wetland areas with wet season flowlines connected to 36,586 ha, and dry season flowlines connected to 14,617 ha of wetland area. The seasonal variation is reflected in the connected wetland area with a difference of 21,969 ha. The stream length and hydrologically connected wetland area are 2 and 2.5 times greater, respectively, in the wet season. Seasonal changes are significant when considering which mapping method to use, and a static product may not accurately represent regional differences in wet and dry seasons.
Table 6. Wet season and dry season stream length and connected wetland area. Both RHD datasets were compared and the seasonal differences between nearly doubled from dry to wet.

<table>
<thead>
<tr>
<th>Season</th>
<th>Stream Length (km)</th>
<th>Connected Wetland Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet (0.25 cfs)</td>
<td>2,343</td>
<td>36,586</td>
</tr>
<tr>
<td>Dry (0.25 cfs)</td>
<td>1,161</td>
<td>14,617</td>
</tr>
<tr>
<td>Seasonal Difference</td>
<td>1,182</td>
<td>21,969</td>
</tr>
</tbody>
</table>

Objective 3) Characterize the Monthly Expansion and Contraction of the Wetland-Stream Network, Through a Full Annual Cycle

Total Stream Length and Distribution of the Stream Network

For the first RHD analysis, all monthly data were analyzed by total stream length to detect seasonal changes. We found a peak occurred from July-Sept where flowline length increased, which is the historically wet season (Figure 7). We also found that March and April experiences a smaller wet season before May, which contains the least flowline length as it is the dry season. September has 1626 kilometers more stream length than May, illustrating the difference between wet and dry season months. Finally, 73% of stream length goes dry between August and May.
Figure 7. Monthly stream length distribution for a full annual cycle. All monthly stream lengths from the 0.25 cfs dataset were found.

**Total Area of Connected Wetlands by Month**

The amount of connected wetland area to the flow network was calculated for all months. We found that the amount of connected wetland area by month mirrors the stream length by month in the previous approach (Figure 7). September had 10,894 hectares more of wetland area in 100-meter buffered flowlines compared to May. Additionally, September has 12,505 hectares more of the total connected wetland area than May (Figure 8). August had the longest flowline length compared to all months, corresponding with the wetland area result. The extent of wetlands draining to streams varies between the wet and dry seasons based on these results (Table 7). Using September as a baseline allows one to see the advantages or disadvantages of conducting fieldwork during seasonal changes by using percent change.
Figure 8. Monthly distribution of connected wetland area for a full annual cycle. All 0.25 cfs flowlines were intersected with the NWI waterbody layer that resulted in connected wetland area.

Relative Area of Connected Wetlands Compared to September

The seasonal fluctuations of the stream network were observed by using the connected wetland area in September as a baseline value (Figure 9). The data exhibits the same seasonal changes as previous results when using September as the baseline to compare with other months (Table 8). There is a minor wet season in March and April, followed by a contraction of the stream network in May. August’s percent change is a positive number because it had more connected wetland areas than September. We found that as the months progressed to September starting in January, the percent change increased except for May. October through December decreased relative to September, which means connected wetland areas decreased progressively in these months. May experienced a 33 percent change which means it is the farthest away from September in terms of the related area of all months due to a smaller stream network in the dry
season (Table 8). August had an increase of 2 percent, which means it exceeded September’s baseline by 773 hectares of connected wetland area relative to September.

Table 7. Total connected wetland area as the flow network expands and contacts monthly.

<table>
<thead>
<tr>
<th>Month (2003-2015)</th>
<th>Wetland Area within buffer (hectares)</th>
<th>Hydrologically connected Wetland Area outside of buffer (hectares)</th>
<th>Total Connected Wetland Area (hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>9,506</td>
<td>21,039</td>
<td>30,545</td>
</tr>
<tr>
<td>February</td>
<td>9,550</td>
<td>21,266</td>
<td>30,816</td>
</tr>
<tr>
<td>March</td>
<td>10,469</td>
<td>21,481</td>
<td>31,950</td>
</tr>
<tr>
<td>April</td>
<td>10,008</td>
<td>21,273</td>
<td>31,281</td>
</tr>
<tr>
<td>May</td>
<td><strong>6,526</strong></td>
<td><strong>19,110</strong></td>
<td><strong>25,636</strong></td>
</tr>
<tr>
<td>June</td>
<td>12,166</td>
<td>21,844</td>
<td>34,010</td>
</tr>
<tr>
<td>July</td>
<td>16,583</td>
<td>20,983</td>
<td>37,566</td>
</tr>
<tr>
<td>August</td>
<td>18,710</td>
<td>20,204</td>
<td>38,914</td>
</tr>
<tr>
<td>September</td>
<td><strong>17,420</strong></td>
<td><strong>20,721</strong></td>
<td><strong>38,141</strong></td>
</tr>
<tr>
<td>October</td>
<td>12,056</td>
<td>21,675</td>
<td>33,731</td>
</tr>
<tr>
<td>November</td>
<td>7,800</td>
<td>19,973</td>
<td>27,773</td>
</tr>
<tr>
<td>December</td>
<td>7,574</td>
<td>19,884</td>
<td>27,458</td>
</tr>
</tbody>
</table>
Figure 9. The amount of connected wetland area inside and outside a 100-meter buffer in September (0.25 cfs) flowlines.
Table 8. Percent change of connected wetland area by month using September as a baseline.

<table>
<thead>
<tr>
<th>Month</th>
<th>Percent change in connected wetland area relative to Sept (ha)</th>
<th>Change in connected wetland area (ha) relative to Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-20% (30,545)</td>
<td>-7,596</td>
</tr>
<tr>
<td>February</td>
<td>-19% (30,816)</td>
<td>-7,325</td>
</tr>
<tr>
<td>March</td>
<td>-16% (31,950)</td>
<td>-6,191</td>
</tr>
<tr>
<td>April</td>
<td>-18% (31,281)</td>
<td>-6,860</td>
</tr>
<tr>
<td>May</td>
<td>-33% (25,636)</td>
<td>-12,505</td>
</tr>
<tr>
<td>June</td>
<td>-11% (34,010)</td>
<td>-4,131</td>
</tr>
<tr>
<td>July</td>
<td>-1.5% (37,566)</td>
<td>-565</td>
</tr>
<tr>
<td>August</td>
<td>2% (38,914)</td>
<td>+773</td>
</tr>
<tr>
<td>September</td>
<td><strong>Baseline (38,141)</strong></td>
<td><strong>Baseline</strong></td>
</tr>
<tr>
<td>October</td>
<td>-12% (33,731)</td>
<td>-4,410</td>
</tr>
<tr>
<td>November</td>
<td>-27% (27,773)</td>
<td>-10,368</td>
</tr>
<tr>
<td>December</td>
<td>-28% (27,458)</td>
<td>-10,683</td>
</tr>
</tbody>
</table>

Objective 4) Characterize the Expansion and Contraction of the Stream Network by Stream Order in the Wet Season and the Dry Season

Total Length and Distribution of Stream Segments Classified by Stream Order

Now that all stream lengths were calculated and assessed for connected wetland area, the next step was assigning stream order by month. The highest assigned stream order value using the Strahler stream ordering tool was 6, determined by the number of tributaries draining to a particular stream segment. For example, May stream order only goes to stream order four because there are fewer seasonal upstream tributaries in the dry season (data not shown).

As the months progressed from the wet season into the dry season, fewer tributaries were connected, reducing the number of stream segments generated for all stream order values. (Figure 10). Next, the results from when September stream order was clipped to May to generate six stream orders will be discussed (Figure 10).
Figure 10. Length and distribution of stream segments classified by stream order for Sept (top) and May (bottom). Each stream segment stream order classification was assigned in September.
After determining the amount of September flowlines left in May, it is apparent the flow length lost seasonally by lower-order streams is drastic (Table 9). First-order streams in September were almost absent in May, with a 99.7% decrease. Virtually all seasonal flowlines that were present in September dried up and disappeared in May. In May, a reduction of second-order streams also occurred, where 69% of the September flowlines were lost.

The larger stream orders are similar between May and September, which is evident in stream order four, where the May and September stream length difference was 0.5%, and the 5th and 6th orders experienced no change (Table 9). In May 71% of the stream network was lost compared to September. The total length of May flowlines totaled 670.291 kilometers, where September totaled 2,275.670 kilometers where the difference is 1,605.477 kilometers in total length. Most of the stream length changes occurred in the first three stream orders while the 4th, 5th, and 6th orders stay relatively the same as the main stems of perennial streams.

Table 9. September stream order length and distribution in September (wet season) and May (dry season).

<table>
<thead>
<tr>
<th>Stream Order</th>
<th>Stream Length in September (km)</th>
<th>Stream length (Sept) remaining in May (km)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,139.457</td>
<td>3.133</td>
<td>-99.7%</td>
</tr>
<tr>
<td>2</td>
<td>601.453</td>
<td>185.642</td>
<td>-69%</td>
</tr>
<tr>
<td>3</td>
<td>290.398</td>
<td>237.969</td>
<td>-18%</td>
</tr>
<tr>
<td>4</td>
<td>161.214</td>
<td>160.309</td>
<td>-0.5%</td>
</tr>
<tr>
<td>5</td>
<td>72.822</td>
<td>72.815</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>10.326</td>
<td>10.325</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>2,275.670</td>
<td>670.193</td>
<td>-71%</td>
</tr>
</tbody>
</table>

Total Area of Wetlands Connected to Stream Segments Classified by Stream Order

Next, the total wetland area connected was calculated. It was found that the most significant change of connected wetland areas can be seen in the first three-stream orders for May and September (Table 10). The greatest difference of wetland area connected to
flowlines is seen in first-order streams at a 91% decrease from September to May. Since most of the flowline length is gone (Table 10), May has a smaller network of first-order streams that connect to wetlands. Second-order streams in May connected to 59% less wetland area than in September. Third-order streams in May lost 15% of the connected wetland area compared to September. Like the stream network results (Table 10), the 4th, 5th, and 6th order streams did not drastically change when comparing May and September.

Table 10. Connected wetland area by stream length classified by stream order.

<table>
<thead>
<tr>
<th>Stream Order</th>
<th>September (hectares)</th>
<th>May (hectares)</th>
<th>Total Difference (hectares)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9,924</td>
<td>881</td>
<td>9,043</td>
<td>-91%</td>
</tr>
<tr>
<td>2</td>
<td>5,259</td>
<td>2,143</td>
<td>3,116</td>
<td>-59%</td>
</tr>
<tr>
<td>3</td>
<td>2,494</td>
<td>2,125</td>
<td>369</td>
<td>-15%</td>
</tr>
<tr>
<td>4</td>
<td>1,771</td>
<td>1,763</td>
<td>8</td>
<td>-0.5%</td>
</tr>
<tr>
<td>5</td>
<td>886</td>
<td>886</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>118</td>
<td>118</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>20,452</td>
<td>7,916</td>
<td>12,536</td>
<td>-61%</td>
</tr>
</tbody>
</table>
DISCUSSION

Objective 1) Assess the Performance of Current Mapping Tools

**Contrast the Relative Accuracy of Mapping Provided by NHD, NHDPlus, and RHD**

Many studies have addressed the topic of eliminating fieldwork by using remote sensing such as optical remote sensing and synthetic aperture radar (SAR). However, obstacles such as cloudy conditions, weather conditions, and nighttime inhibits optical remote sensing while SAR is limited by its range which at most, can only scale down to kilometers (Moreira et al., 2013). Therefore, due to the SAR’s larger scale, the model would not apply to the tributaries upstream that are either A) have a width less than several feet, or B) only have a shallow sheet of water flowing beneath thick palmetto vegetation (Adeli, 2020). SAR is a method that should be evaluated for its applicability in this study area, since to the best of our knowledge has not been applied in the central Florida region to map wetland-stream channels. Another study with a similar approach to this project used the Strahler method to study the order of headwater streams and their downstream links in relation to a flow network’s water quality (Fitzpatrick, 1998). Our study adds to previous studies by studying the expansion and contraction of the flow network and connected wetland area by verifying small-scale regional prediction models and using geospatial analyses to study wetland connectivity.

NHD underpredicts upstream channels between wetlands meaning when we saw water, most times, NHD did not predict flow indicators to be present. NHD had the highest precision,
true negative rate, and lower false positive rate which can be attributed to its development procedures. For example, NHD flowlines are generated based on proximity to landmarks (National Hydrography Dataset, 2021). Therefore, when a channel is predicted to occur in a specific place, it will be there. However, when looking outside the NHD prediction framework to areas such as wellfields or more rural areas, NHD had the highest error of omission rate.

The wet-season dataset appeared to have a high false positive rate compared to NHD but only 12 out of 241 points were false positives which was 5 percent of the dataset. Additionally, the low number of true negative sites led the false positive rate to appear very high at 29%. Most of those points were also in an area surveyed called Cross Bar, where recent land changes were not reflected in LiDAR. Additionally, some of the false-positive points also occurred at Morris Bridge, which seemed to be experiencing flooding issues, which means more flood prevention infrastructure, and new development along the northern border.

Based on our field review, September RHD overall was more accurate, and had a lower error of omission rate than NHD flowlines (Table 7). Initially, when we selected field sites in ArcGIS, it was expected that a high number of sites would not have evidence of streamflow. However, when field verified, 31 sites were true negatives meaning the landscape has more wetland-stream channels than we thought. The low denominator in the false-positive formula caused the September dataset to have a high false-positive rate. The dataset did not predict false positives very often (11/241) which was 5% of the sites. Again, most of those points were also in areas where recent land changes were not reflected in LiDAR.

We realized that many smaller ephemeral and intermittent streams are very time-sensitive during the field verification process. For example, we would go to a site where RHD predicts water, and only damp ground was present. In cases like this, we relied on third-party accounts.
from park employees. We would also find standing water with little or no flow evidence during the end of the wet season. For instance, some small ephemeral connections were documented under litter or in a dense patch of saw palmettos. If we missed the timing on those smaller flowlines, it would be extremely challenging to find again in the dry season.

There was some debate as to whether we should count standing water as evidence of flow. However, there was a chance that vegetation obscured noticeable evidence, the flow was occurring at the subsurface level, or the flow was so slow we couldn’t discern movement, particularly where high-water levels throughout the region were likely to halt wet season flow. Therefore, any points that had water or had other evidence of flow were counted as positive sites. A complete geodatabase with site classification for the confusion matrix based on field observations and flowline distance is available (Appendix C).

When field verifying models and predicted seasonal connections, we needed a way to check if our wet and dry season data were collected in normal precipitation conditions. The Annual Precipitation Tool (APT) utilized our field point’s locations, and dates to average 30 years of precipitation data at that location to differentiate precipitation conditions. We analyzed two points from 2020, two points from 2019, and a dry season point.

As the months progress, the precipitation input goes from normal conditions to wetter than normal in 2020 (Appendix B). This is consistent with the trends observed in stream length and connected wetland area during an annual cycle. However, in 2019 August and September started off wetter and progressively leveled out to normal conditions. We accommodated the variable precipitation conditions by sampling in a variety of areas that were located upland, downstream, in forested areas, or depressions. We also lengthened our sample window by field verifying sites throughout the whole month of September which allowed us to collect data in all
conditions in that month. These conditions are extremely important to consider as many protections, such as the Navigable Waters Protection Rule only encompasses hydrology that occurs under a “normal” season condition (EPA, 2021).

The error of omission was critical when contrasting models and determining if they could replace field visits because it told us about the presence of wetland-stream channels in headwater areas. The higher the error of omission, the more the model is going to underestimate the extent of wetland-stream channels. The NHD and RHD model's errors of omissions resulted from different problems. We realized that NHD had a high error of omission (76%) because it was missing a lot of the streams that we verified. RHD’s error of omission (34%) resulted from land use changes. Some false predictions stemmed from old information such as outdated levees, dams, retention areas or outdated imagery. There were some instances in the field where NHD and RHD flowlines were regularly offset from existing stream channels, indicating that a new drainage system was incorporated recently, and the mapping had not been updated yet. Many factors affect prediction outcomes for both models, and neither can be used to eliminate field verification (supplementary information can be found in Appendix E).

**Objective 2) Characterize the Expansion and Contraction of the Wetland-Stream Network in the Wet Season and the Dry Season**

**Total Length and Distribution of the Stream Network**

Wet-season stream-channel length was double the stream-channel length of May which was evident in the field, as many of the small seasonal streams started to dry up and disappear by October. When precipitation patterns of a pronounced wet and dry season heavily influence a study area, the timing of fieldwork is imperative.
**Total Area and Distribution of Wetlands on the Stream Network**

When the total connected wetland area was calculated for the wet season and dry season RHD datasets, the difference was around 22,000 hectares. The amount of connected wetland area directly correlates to the differences in stream length. When current policies do not protect seasonal connections, the expanded wet season wetland area is left vulnerable in return. For example, development in or around headwater wetlands can affect water quality, wetland production, and sediment compositions. From the 1970’s to 2010 rangeland that previously surrounded wetlands were converted to developmental land use that resulted in the loss of surrounding land cover categories such as rangeland, and water (McCarthy, 2018). Development in the Tampa Bay area is common, and it is important to examine land use changes and the effects on surrounding wet season stream channels for the integrity of downstream waters.

**Objective 3) Characterize the Monthly Expansion and Contraction of the Wetland-stream Network, Through a Full Annual Cycle**

**Total Length and Distribution of the Stream Network**

Seasonal fluctuations and the changes in connected wetland area are important to consider when conducting fieldwork or proposing protections. We analyzed the total length of all months to visually display seasonal changes (Appendix D). The first noticeable characteristic between May and September is the lack of smaller seasonal stream channels in May. Second, May’s stream order only goes up to four, while September goes up to six, implying a longer stream network with more tributaries. Part of the reason that May only goes to stream order four is that it is missing many of the headwater tributaries that exist in September. However, the main issue was that the same stream classified as stream order six in September was classified as a
fourth-order stream in May. More significant streams with a flow greater than 20 cfs did not change seasonally, just the number of upstream tributaries. The stream ordering tool worked how it was supposed to, but the results needed to be reorganized to make wet and dry seasons comparable. The model at this point showed how many fewer tributaries existed in the dry season, which was already reflected in the total stream length of the wet and dry seasons. At this point, we realized that what we truly wanted was to reconfigure the stream ordering results of other months to that of September (completed at a later step in the study) because it had the most tributaries (with the exception of August).

**Total Area of Connected Wetlands by Month**

The hydrologically connected wetland area was calculated for all months instead of only May and September. It was found that the wetland area on stream channels changed seasonally and exhibited a similar pattern as the RHD monthly stream length data. For example, if fieldwork is performed in August, there is an 2% increase of connected wetland area, equating to 773 more hectares of wetlands intersecting stream channels. Conversely, when fieldwork is conducted in May, there is a 33% loss of connected wetland area, equating to 12,505 hectares less coverage than September. Additionally, there is a “mini” wet season in March and April, followed by a dry season-low in May. Wetland area on stream channels peaks at the official wet season period (July- Sept) and decreases as the wet season concludes (Appendix B). The stream-channel length follows this same trend as the connected wetland area. The takeaway from these results is that the input of nearby streams to wetlands greatly expands and contracts depending on the season.
Relative Area of Connected Wetlands Compared to September

The area of connected wetlands was analyzed in relation to September for every month, but we wanted a more specific estimate within a 100-meter buffer around stream channels. The 100-meter buffered stream channel was proposed to quantify smaller seasonal wetlands influenced by ephemeral connections that may not have been included in a smaller buffer, such as the forty-meter buffer created in the initial wetland analysis between NHD and NWI. Additionally, the buffer was designed to encompass upland wetlands that may not have been directly located next to stream channels. The smaller seasonal stream channels in September directly drained to and from an abundance of smaller seasonal wetlands that dotted the landscape. When looking at May, most of those seasonal connections did not exist.

Objective 4) Characterize the Expansion and Contraction of the Stream Network by Stream Order in the Wet Season and the Dry Season

Total Length and Distribution of Stream Segments Classified by Stream Order

Almost 100% of first order stream length, and 91% of hydrologically connected wetland area goes dry from the wettest month (August) to the month with the least amount of streamflow channel length (May). The more minor intermittent and ephemeral streams were lost or ordered differently in dryer months than wet-season months. Stream order was generated to display seasonal differences in stream length for all months. The more significant perennial streams did not change in order when using the stream ordering tool. Wet-season months were ordered up to six grid codes (stream order), while dry season (May) only had four grid codes assigned. We had the idea to work around the initial stream order set by the tool to make May comparable to September by giving it six grid codes. We chose the smallest buffer possible to cover the
flowlines during the process of changing May grid codes. The buffer used had a rounded edge, and while we did try to minimize overestimating, there was some extra length in May. However, this allowed us to see which order seasonal flowlines fell under and the length distribution in each grid code by season. Seasonal connections in the flow network that increase or decrease hydrologically connected wetland areas to surrounding headwater wetlands are constantly changing. By using the Strahler stream ordering method and documenting where most seasonal changes occur in the flow network, one could prioritize hydrologically connected wetlands for future protections based on where they are in the flow network.

The Total Area of Wetlands Connected to Stream Segments Classified by Stream Order

Seasonally influenced stream lengths start at stream order one and progress to order three, gaining in streamflow and permanence. Stream orders 4, 5, and 6 are perennial streams where seasonal influence doesn’t necessarily affect their ordering. In the previous objective, the most significant loss of stream length occurred in the first three stream orders in the reassigned May dataset, with 99.7% of first-order streams lost, 69% of second-order streams, and 18% of third-order streams lost compared to the wet-season month of September. This same pattern is reflected in the connected wetland area; as stream length decreases, so does the amount of hydrologically connected wetland area in lower stream orders from first to third order streams. One of the main issues with the current wetland legislature is that often seasonal influences are not accounted for in regulations. Because of the nature of how isolated wetlands, and ephemeral or intermittent streams are defined by the Clean Water Act, they are often afforded less protections that waterbodies that have surface water connections year-round (US EPA, 2015). Our results indicated that the most drastic changes occur in the first three stream orders, which
are those that are most affected by seasonality (Meyer, 2007). Additionally, stream length and the hydrologically connected wetland area drastically increase when the flow network expands during the wet season. Therefore, it is essential to consider the ecological, biological, and chemical contributions of seasonally isolated headwater wetlands, and hydrologically connected wetland area as the flow network expands and contracts.
CONCLUSIONS

We found that when the flow network expands and contacts it connects and disconnects the surrounding landscape in the process. The standard, the National Hydrography Dataset severely undermaps the hydrography we were seeing across the landscape, leading to underestimates of total stream length and of the landscape (e.g., wetland) connectivity to rivers and oceans. Newer products (RHD) are a significant improvement but do not replace the need for wet season field verification when accuracy is essential. Additionally, we found that the stream network expands seasonally, vastly increasing landscape connectivity during the wet season (73% of the stream length is seasonal). Seasonal connections are common between headwater (lower order) streams and associated wetlands during the wet season. By the dry season 99.7% of lower order streams have disappeared with a loss of connection to 91% of the headwater wetland area. What we do (e.g., development, stormwater management) in parts of the landscape currently considered hydrologically isolated may have the potential to impact rivers and oceans, particularly during the wet season. For this reason, regulatory decisions should be made based on a dynamic model that reflects annual changes as opposed to a static product such as NHD.
REFERENCES


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U. S. Geological Survey, 2020, NHD_H_Florida_State_Shape (published 20201217), accessed January 8th, 2021 at URL https://www.sciencebase.gov/catalog/item/5a96cdc1e4b06990606c4d58


APPENDICES
Figure A1: Weather station locations used for precipitation analyses. To gather precipitation data for the wet season (July-September), the average precipitation values for all months needed to be collected. Three stations located west (Tarpon Springs), south (Tampa International Airport), and Northeast (St. Leo) were selected for a comparative analysis of monthly and annual precipitation values from 1991–2020 (NOAA, 2021).
Appendix B: Antecedent Precipitation

Figure B1. Antecedent Precipitation Tool results for Starkey wellfield ending Sept 15, 2020. The figure displays the antecedent precipitation results for the wet season (July-Sept) using site SK_33 (28. 25083, 82.63012) visited in 2020. The coordinates reference Starkey wellfield, a location within the study area. August and September experience wetter than normal conditions, while July is drier (EPA, 2021).
Appendix B (Continued):

Figure B2. Antecedent Precipitation Tool results for Starkey wellfield ending Oct 06, 2020. The figure displays the antecedent precipitation results for the wet season (July-Sept) using site SK_73 (28.2369, -82.5865) visited in 2020. The coordinates reference Starkey wellfield, a location within the study area. August, September, and October experience normal conditions (EPA, 2021).
Figure B3. Antecedent Precipitation Tool results for Starkey wellfield ending May 10, 2021. The figure displays the antecedent precipitation results for the wet season (July-Sept) using site SK_33 (28.25083, -82.63012) visited in 2021. The coordinates reference Starkey wellfield, a location within the study area. March experienced wetter than normal conditions, while April and May experienced normal conditions (EPA, 2021).
Figure B4. Antecedent Precipitation Tool results for Starkey wellfield ending Oct 01, 2019. The figure displays the antecedent precipitation results for the wet season (July-Sept) using site SK_29 (28.2357, -82.5799) visited in 2019. The coordinates reference Starkey wellfield, a location within the study area. August and September were wetter than normal, while October experienced dry conditions (EPA, 2021).
Appendix B (Continued):

Figure B5. Antecedent Precipitation Tool results for a dispersed location ending Sept 09, 2019. The figure displays the antecedent precipitation results for the wet season using site DW_01 (28.0422, -82.5399) visited in September of 2019. July experienced wetter than normal conditions, while August and September experienced normal conditions (EPA, 2021).
Appendix B (Continued):

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tampa Airport</strong></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>2.65</td>
</tr>
<tr>
<td>Feb</td>
<td>2.62</td>
</tr>
<tr>
<td>Mar</td>
<td>2.52</td>
</tr>
<tr>
<td>Apr</td>
<td>2.55</td>
</tr>
<tr>
<td>May</td>
<td>2.40</td>
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<tr>
<td>Jun</td>
<td>7.37</td>
</tr>
<tr>
<td>Jul</td>
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<tr>
<td>Aug</td>
<td>9.03</td>
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<tr>
<td>Sep</td>
<td>6.09</td>
</tr>
<tr>
<td>Oct</td>
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</tr>
<tr>
<td>Dec</td>
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<tr>
<td>Annual</td>
<td>49.48</td>
</tr>
</tbody>
</table>

| **Tarpon Springs**                |                          |
| Jan                               | 3.03                     |
| Feb                               | 2.51                     |
| Mar                               | 3.08                     |
| Apr                               | 2.69                     |
| May                               | 2.35                     |
| Jun                               | 7.06                     |
| Jul                               | 9.05                     |
| Aug                               | 9.66                     |
| Sep                               | 7.03                     |
| Oct                               | 3.19                     |
| Nov                               | 1.90                     |
| Dec                               | 2.74                     |
| Annual                            | 54.29                    |

| **St. Leo**                       |                          |
| Jan                               | 3.06                     |
| Feb                               | 2.38                     |
| Mar                               | 3.18                     |
| Apr                               | 3.06                     |
| May                               | 2.98                     |
| Jun                               | 8.34                     |
| Jul                               | 8.10                     |
| Aug                               | 8.28                     |
| Sep                               | 6.63                     |
| Oct                               | 3.06                     |
| Nov                               | 1.86                     |
| Dec                               | 2.53                     |
| Annual                            | 53.46                    |

**Figure B6.** Comparative analysis of monthly and annual precipitation from all weather stations. Monthly and annual precipitation data were collected and compared to determine which weather station to use when compiling wet season data. All data were collected from the National Weather Service (NOAA, 2021). The names of the weather stations are in bold (Tampa International Airport, Tarpon Springs, and St. Leo), and highlighted data under each location are the wet season data. The total wet season precipitation was found for all sites by summing the highlighted rows. The annual precipitation wet season percentage is the total percentage of wet season precipitation that fell annually. Lastly, the yearly rainfall of May is the total percentage of rainfall in May that fell annually. The wet season was defined as July-September to maintain consistency with the hydrography product produced by Fouad et al. 2021.
Figure B7: Precipitation comparison between weather stations. Monthly and annual precipitation data were collected and compared to determine which weather station to use when compiling wet season data. All data were collected from the National Weather Service (NOAA, 2021). The names of the weather stations are in bold (Tampa International Airport, Tarpon Springs, and St. Leo), and highlighted data under each location are the wet season data. In addition, precipitation averages from 1991-2020 were collected for each month for each station location and compared.
Appendix B (Continued):

Table B1: A summary of annual and monthly precipitation results. This table summarizes the monthly and annual precipitation data collected and compared against each other to determine which weather station to use when compiling precipitation conditions. All data were collected from the National Weather Service.

<table>
<thead>
<tr>
<th>Precipitation Calculation Results</th>
<th>Percent of Precipitation in Wet Season</th>
<th>Percent of Precipitation in May</th>
<th>Sum of Precipitation in Wet Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa International</td>
<td>46.22</td>
<td>5.25</td>
<td>22.87</td>
</tr>
<tr>
<td>Tarpon Springs</td>
<td>47.41</td>
<td>4.33</td>
<td>25.74</td>
</tr>
<tr>
<td>St. Leo</td>
<td>43.04</td>
<td>5.57</td>
<td>23.01</td>
</tr>
</tbody>
</table>
Appendix C: Geodatabase

A description of the layers used in the thesis graduate project (Fransbergen et al., 2021) can be found in a geodatabase electronically submitted to the committee in support of this work. This file contains data separated into the following categories: RHD, NHD, Wetland Analyses, Stream Order, NHD/RHD Overlay, Field Sites, and a study area. In addition, all data generated for this project can be found in the geodatabase of “ThesisV04_Complete.”
Appendix C (Continued):

Savannah Fransbergen, Dr. Kai Rains, Dr. Mark Rains, Dr. Geoff Fouad


Geodatabase, Readme File

The following is a description of the layers used in the thesis graduate project (Fransbergen et al., 2021). This file contains data separated into the following categories: RHD, NHD, Wetland Analyses, Stream Order, NHD RHD Overlay, Field Sites, and a study area. All data generated for this project can be found in the catalog, as shown below (Figure 1).

![Drawing Order in the catalog containing all contents of the project.](image)

**Figure 1:** Drawing order in the catalog containing all contents of the project.
Appendix C (Continued):

Savannah Fransbergen, Dr. Kai Rains, Dr. Mark Rains, Dr. Geoff Fouad

Descriptions of the project products for the thesis project follow the catalog drawing order. The contents of the project are:

1) **RHD**- Layer contains all original unedited RHD data used for project analyses developed by Dr. Geoff Fouad (Morman, 2019). Included are monthly, annual, and seasonal flowline data from post-cutback files at 0.25 CFS (2003-2015). This layer is split into two subgroups.
   - **Fouad RHD Months**- Each month's post cutback 0.25 CFS flowline data.
   - **Fouad RHD Seasonal/Annual**- Includes post cutback 0.25 flowline data for the wet season and annual datasets.

2) **NHD 2020**- This layer contains two subgroups: "NHDPlus (NHDPLUS_H_0310_HU4_GDB, accessed 1/08/21)," and 'NHD (NHD_H_Florida_State_Shape, accessed 1/08/21)."
   - **NHDPlus** consists of all original data from USGS in the form of flowlines. I clipped and merged all flowline data to the study area. This layer contains the original flowline data that has been clipped to the study area, as well as the original unclipped data. The data folder for NHDPlus as labeled by USGS as "NHDPLUS_H_0310_HU4_GDB."
   - **NHD** contains the original flowline data that I clipped to the study area, and well as the original unclipped data. Data were taken from the USGS website. The data folder for NHD was labeled by USGS as "NHD_H_Florida_State_Shape."
     - **NHD Prep**- NHD Prep consists of two subgroups "NHDFlowlines" and "NHD_Waterbodies where NHD flowline and waterbody data were merged and clipped to fit the study area.
       - **NHD Waterbodies Merged**- This layer consists of all original NHD waterbody data collected from the USGS website. The waterbody data came in the form of separate layers that I merged and clipped to the study area (NHDWaterbody1.sph, NHDWaterbody2.sph, NHDWaterbody3.sph).
       - **NHD Flowlines**- This layer contains all the original flowline data from USGS. The flowline data was available for download as separate layers that I merged and clipped to fit the study area (NHDFlowline1.sph, NHDFlowline2.sph, NHDFlowline3.sph).

3) **Wetland Analyses**- This layer consists of wetland analyses conducted using NHD (USGS) and NWI (US Fish and Wildlife) waterbody data. I merged both datasets clipped them to fit the study area. I then intersected the NHD and NWI waterbody layers with flowlines to determine the connected wetland area. The flowlines used for the intersections were *WetPost 0.25, WetPost 0.5, and NHD*. I buffered by 40 meters (cutoff
value decided when constructing database based off field observations) and intersected with NWI and NHD polygon layers, resulting in a wetland area intersected by the target flowline. Original flowline data collected from deliverable 04 file developed by Dr. Fouad.

- **Connectivity_SeptAsBaseline**
  - This layer was generated to determine the amount of wetland area each month had in relation to September. Each month’s flowlines were buffered by 100 meters. They were then intersected with the NWI layer. The same process was conducted for September. Next, each monthly flowlines was intersected with September to get shared wetland area.

- **Seasonal_WetlandAnalysis**
  - This layer displayed the differences of connected wetland area between Wet 0.25 cfs flowlines (2003–2015) and Dry 0.25 cfs flowlines (2003–2015). Each month was buffered 100 meters. They were then intersected with the NWI wetland dataset. The length of flowlines was also found for each dataset.

- **NHD_WetlandAnalysises**
  - **NHD_WetPost_0Pat25.** This layer was generated to determine the amount of wetland area (from NHD waterbodies merged) that was intersected by 0.25 cfs WetPost flowlines. I intersected the NHD_Waterbody_Dissolve with the WetPost 0.25 flowlines that I buffered 40 meters. Once the intersected layer was produced, a field was created to calculate geometry of wetland area in hectares.

  - **NHD_WetPost_0Pat5.** This layer was generated to determine the amount of wetland area, from NHD_Waterbody_Dissolve, intersects 0.5 cfs WetPost flowlines. I intersected the NHD_Waterbody_Dissolve layer with the WetPost 0.5 flowlines that I buffered at 40 meters. Once the intersected layer was produced, a field was created to calculate geometry of wetland area in hectares.

  - **NHD_WaterBody_NoFlowType436.** Layer formed from a preliminary analysis that was aimed at eliminating all “non-natural” waterbodies such as reservoirs. First, I intersected reservoirs (coded as 436 under FType column in NHD dataset) and intersected the dataset with the flowlines listed above. All reservoirs were selected and removed from the dataset and the same analyses using the flowlines listed above was conducted.

  - **NHD_SelectByLocation.** This layer was generated to determine the amount of wetland area (from NHD_Waterbody_Merged) intersected by NHD flowlines. I intersected the NHD_Waterbodies_Merged layer with NHDFlowline_Merge buffered at 40 meters, then used the “Select By Location” tool. The results showed all NHD wetlands that touched the buffered flowlines.

- **NWI_WetlandAnalyses.** I intersected wetlands from the National Wetland Inventory dataset by different flowlines (0.25 cfs WetPost, 0.5 cfs WetPost, NHD).
to determine amount of connected wetland area by each flowline. I buffered each
flowline by 40 meters and used the tool "select by location" to intersect flowlines
with FL_Wetlands_DissolveBoundaries layer.

- **WetPost_0Pnt25_SelectByLocation**- This layer was generated to
determine the amount of wetland area is intersected by NWI flowlines. I
intersected the FL_Wetlands_DissolveBoundaries with NWI
flowlines (0.25 CFS 2003-2015) that I buffered 40 meters. This produced
a layer of NWI wetlands that touched the buffered flowlines.

- **WetPost_0Pnt5_SelectByLocation**- This layer was generated to
determine the amount of wetland area (from
FL_Wetlands_DissolveBoundaries ) that is intersected by NWI flowlines.
I intersected the FL_Wetlands_DissolveBoundaries layer with NWI
flowlines (0.5 CFS WetPost 2003-2015) that I buffered 40 meters.

- **NHD_SelectByLocation**- This layer was generated to determine the
amount of wetland area (from FL_Wetlands_DissolveBoundaries ) that is intersected by NHDFlowline_Merge. I intersected
FL_Wetlands_DissolveBoundaries with NHD flowlines that I buffered 40
meters.

- **FL_Wetlands_DissolveBoundaries**- This layer consists of all data from
the NWI file from US Fish and Wildlife (titled FL_shapefile_wetlands).
The waterbody layer was selected, and I dissolved all polygon boundaries.

- **FL_Wetlands_Clip**- This layer consists of all data from the NWI file
from US Fish and Wildlife (titled FL_shapefile_wetlands). I clipped the
waterbody layer to the study area.

- **FL_Wetlands**- This layer consists of all wetland polygon data from the
NWI file (titled FL_shapefile_wetlands) from US Fish and Wildlife.

- **Flowline/Wetland Intersection**- Wetlands from the National Wetland Inventory
dataset were intersected by different flowlines (0.25 WetPost, 0.25 MayPost, NHD)
to determine amount of connected wetland area by flowlines. I buffered
each flowline set by 100m and then used the "select by location" tool to intersect flowlines with FL_Wetlands_DissolveBoundaries layer.

- **Wetlands_Int_May_0Pnt25**- I intersected the
FL_Wetlands_DissolveBoundaries with 0.25 CFS May flowlines (2003-
2015) to produce this layer of wetlands intersected by flowlines.

- **Wetlands_Int_NHD**- I intersected the FL_Wetlands_DissolveBoundaries
with NHD flowlines to produce this layer of wetlands intersected by
flowlines.

- **Wetlands_Int_Wet_0Pnt25**- I intersected the
FL_Wetlands_DissolveBoundaries with 0.25 CFS Wet flowlines (2003-
2015) to produce this layer of wetlands intersected by flowlines.
Appendix C (Continued):

- **Wetland Area Sept May**: This layer displays the amount of wetland area within a 100m buffer for 0.25 CFS September and 0.25 CFS May (2003-2015), as well as wetland area outside of the buffer of wetland polygons that touch the buffered flowlines.
  - **May_0Pnt25_WetArea_InBuff100m**: I buffered the flowlines for 0.25 CFS May (2003-2015) 100 meters. Next, the select by location tool was implemented to isolate wetland polygons that were only connected by flowlines. I then intersected these flowlines with the selected wetlands from FL_Wetlands_DissolveBoundaries layer to get an estimate of how much wetland area fell inside of the flowlines.
  - **May_0Pnt25_WetArea_OutBuff100m**: I clipped the FL_Wetlands_DissolveBoundaries with the 0.25 CFS May (2003-2015) flowlines to get wetland area inside the buffer. I then used the erase tool to get the area outside of the buffer, resulting in this layer that consists of wetland area outside of the buffer in connected wetlands.
  - **Sept_0Pnt25_WetArea_InBuff100m**: I buffered the flowlines for 0.25 CFS Sept (2003-2015) 100 meters. Next, the select by location tool was implemented to isolate wetland polygons that were only connected by flowlines. I then intersected these flowlines with the selected wetlands from FL_Wetlands_DissolveBoundaries layer to get an estimate of how much wetland area fell inside of the flowlines.
  - **Sept_0Pnt25_WetArea_OutBuff100m**: I clipped the FL_Wetlands_DissolveBoundaries with the 0.25 CFS Sept (2003-2015) flowlines to get wetland area inside the buffer. I then used the erase tool to get the area outside of the buffer, resulting in this layer that consists of wetland area outside of the buffer in connected wetlands.

4) **Stream Order**: The stream ordering tool requires multiple steps of preparation before it can be utilized. The steps are arranged in order as subgroups under this layer. The steps in order are flow direction grid, DEM.tif data (in folders attached to project labeled “CFS Grids 2003_2015 Post_Cutback-selected”), raster calculator, stream order tool, and feature tool.
- **Flow direction grid.tif**: DEM data of flow direction generated for study area produced by Dr. Geoff Fouad.
- **RasterCalculator_AllMonths**: Layer produced includes all stream raster data generated from the raster calculator from the expression “CFS_AnyMonth.tif >= 0.25” that produced a grid of 1’s (flow) and 0’s (no flow).
- **Stream_Order_As_Raster**: This layer utilized the stream ordering tool and generated stream order for each month in raster format. The “input stream raster” was the grid of 1’s and 0’s from RasterCalculator_AllMonths and “input flow direction raster” was the “Flow_Direction_Grid.tif” file.
Appendix C (Continued):

- **StreamOrderAsFeat** - I used the “stream to feature” tool which converted the rasterized stream order data to polyline data to generate this layer.
- **Sept_Reassigned_May** - May and September stream order was not comparable by grid number assigned by stream ordering tool. I generated this layer by using September stream order grid codes (six generated) to reconfigure May (four generated) grid code to grid code six. I separated, dissolved, and clipped the September grid codes to May flowlines which is shown in this layer. Additionally, I buffered each grid code for September and May (reconfigured) and intersected them with the *FL_Wetlands_DissolveBoundaries* layer to determine the difference of connected wetland area experienced through seasonal changes.

5) **NHD/RHD Overlay** - This layer was created to display the sections of flowlines that RHD and NHD had in common. I used NHD flowlines (*NHDFlowline_Merge*) and *SeptPost 0.25 CPS* (2003-2015) flowlines. I intersected the two flowlines after buffering the *SeptPost 0.25 fifty meters*, and the final product showed where NHD and RHD overlap. I selected fifty meters because it encompassed the NHD flowlines that were slightly off but otherwise similar to RHD. The final intersected layer created from the intersection was all flowline length RHD and NHD had in common.
  - **SeptPost_0Pt25** - Original RHD flowline produced by Dr. Fouad (2003-2015).
  - **NHDFlowline_Merge** - This layer contains all the original flowline data from USGS. The flowline data was presented as separate layers that were merged and clipped to fit the study area.
  - **SeptPost_0Pt25_Buffer** - Original RHD flowline buffered 50 meters.
  - **NHD/RHD_CommonFlow** - Intersection of all flowline length that RHD and NHD shared.

6) **FieldSites 2021** - All field points visited in 2019-2021 are in this layer. Field points in 2019 were primarily collected along RHD lines, as ground-truthing was the priority at the time for the Tampa Bay Water project (Mcrmon, 2019). The 2020 field collection shifted from only RHD to include NHD and points away from predicted flow lines for a more robust study. 2021 included points only revisited in the dry season in Starkey. In total, there are 241 sites with associated data. Total visits exceed 241 because some points that were in a similar location revisited or had similar characteristics were merged. All field data can be found in the excel file at the bottom of the project. The excel file includes confusion matrix data for all field points for different seasons and months.
Appendix D: Streams GIF

The goal of this GIF was to visually display the seasonal changes in wetlands connected to flow networks. RHD 0.25 CFS flowlines were used and played in short intervals to contrast the effects of seasons on the expansion and contraction of the flow network. GIF was produced for SWS presentation and submitted electronically to the committee in support of this work.

Field validation and GIS analyses were used to compare NHD and RHD metrics. RHD predicted more connected wetland area than NHD, and levels of landscape connectivity between wetlands differ between models. As a result, fieldwork and seasonal timing are still more accurate than solely relying on GIS or aerial imagery.
Appendix F: Determine whether estimates of stream length and connected wetland area differ when different sources are used for hydrography datasets

The use of the NWI wetland map is common practice but we compared the wetland mapping in this product against the equivalent NHD product (NHD waterbodies). Although all other portions of the study utilize the NWI layer, which is an industry standard, this initial analysis was informative and included in the study.

Initially we tried to conduct the wetland map analysis of NWI and NHD products by separating artificial wetlands and waterbodies (reservoirs) from natural wetlands. However, while reservoirs were differentiated in the NHD products (coded as F-Type 436) they are not as readily distinguished from natural features in the NWI dataset. For this reason, all artificial and natural wetlands mapped by NWI were included in the wetland map analysis.

NHD and RHD wet season flowlines (0.25 cfs wet, and 0.5 cfs wet) were buffered by 40 meters to account for mapping offsets and the intersections below were performed to identify wetlands/waterbodies connected by these flowlines to the flow network. The wetland maps tested were:

- NHD wetland/waterbody intersections (no reservoirs)
- NHD wetland/waterbody intersections (including reservoirs)
- NWI wetland/waterbody intersections (including reservoirs)

For each intersection for the NHD and NWI mapping products, I summed the total area of wetlands/waterbodies in the study area that were connected to the flow network.
Appendix F (Continued):

The average size of wetlands connected to the flow network appeared to be lowest for all three hydrography datasets when intersected with the NHD waterbody map (F Type 436) that included reservoirs, but the standard deviations associated with these measurements are large (Tables F1 and F2). There were only minimal differences in the total wetland area intersected by the three hydrography datasets regardless of whether the target wetland dataset was the NHD waterbody maps (with or without reservoirs) or the NWI wetland map.

The most striking difference detected during this analysis was that the RHD dataset predicted a greater proportion of wetland area that was connected to the flow network for both the NWI wetland map and the NHD waterbody map (Tables F1 and F2). These differences are explored in greater detail in other sections of this thesis.

When we evaluated the amount of connected wetland area to seasonal flowlines, it was initially thought to exclude reservoirs to target natural wetlands better. In the NHD dataset, reservoirs were coded as F-Type 436 and were easy to pick out using the select-by attribute tool to create a new layer without any reservoirs. However, it became difficult to discern reservoirs or other heavily influenced water sources in the NWI database because different attributes sorted them. While NHD sources were labeled broadly, NWI was labeled very precisely, and there were many categories. Therefore, it was determined that the better approach was to include the artificial waterbodies that are in NWI as they still contributed to the flow network influencing down gradient waters and surrounding wetlands. When conducting a study heavily influenced by precipitation, more specific datasets in tune with the region are better. NWI has a longer history as a wetland mapping product and is more widely recognized, which is why we went with it.
Appendix F (Continued):

Table F1: Wetland connectivity estimates based on the NHD waterbody map. NHD data were separated into waterbodies with no reservoirs (column 1), and waterbodies with reservoirs (column 5) and intersected with buffered (40 m) flowlines derived from the NHD and from the RHD (0.25 cfs, 0.5 cfs, wet season).

<table>
<thead>
<tr>
<th>Flowlines</th>
<th>Percent of NHD wetland area in study area connected by flowlines (no reservoirs) (hectares)</th>
<th>Percent of total study area (no reservoirs)</th>
<th>Average size (ha) of connected wetlands/water bodies (no reservoirs) (standard deviation)</th>
<th>Percent of NHD wetland area connected by flowlines (all waterbodies)</th>
<th>Percent of total study area (all waterbodies)</th>
<th>Average size (ha) of wetlands/water bodies (including reservoirs) (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHD (0.25 cfs)</td>
<td>85%</td>
<td>23%</td>
<td>16 (+/-74)</td>
<td>81%</td>
<td>24%</td>
<td>11 (+/-61)</td>
</tr>
<tr>
<td>RHD (0.5 cfs)</td>
<td>77%</td>
<td>21%</td>
<td>21 (+/-90)</td>
<td>73%</td>
<td>22%</td>
<td>15 (+/-73)</td>
</tr>
<tr>
<td>NHD</td>
<td>54%</td>
<td>14%</td>
<td>25 (+/-114)</td>
<td>51%</td>
<td>15%</td>
<td>16 (+/-90)</td>
</tr>
</tbody>
</table>
Appendix F (Continued):

Table F2: Wetland connectivity estimates based on the NWI wetland map. RHD and NHD flowlines were intersected with NWI mapped wetlands to compare the amount of connected wetland area and the average size of connected wetlands.

<table>
<thead>
<tr>
<th>Flowlines</th>
<th>Percent of NWI wetland area connected by flowlines (ha)</th>
<th>Percent of total study area</th>
<th>Average size (ha) of connected wetlands/waterbodies (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHD (0.25 cfs)</td>
<td>82%</td>
<td>24%</td>
<td>15 (+/-206)</td>
</tr>
<tr>
<td>RHD (0.5 cfs)</td>
<td>76%</td>
<td>22%</td>
<td>20 (+/-251)</td>
</tr>
<tr>
<td>NHD</td>
<td>54%</td>
<td>16%</td>
<td>34 (+/-390)</td>
</tr>
</tbody>
</table>