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Determining Tidal Elevations in Dry Elements within a Coastal Salt Marsh Model

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ABSTRACT: An integrated hydrodynamic/marsh biomass model is a useful tool for analyzing multiple hydrologic activities on a shoreline. A key component of this type of model is the location of local tidal elevations. During astronomic tide simulations, nodes in the finite element mesh are either wet or dry. At nodes that are continuously wet during the simulation, tidal elevations are computed from ADCIRC-2DDI (ADvanced CIRCulation) output. In areas that are intermittently wetted, tidal constituents cannot be determined using ADCIRC because the drying of nodes leaves a gap in the water-level time series. The Inverse Distance Weighting (IDW) interpolation method can be used to interpolate unknown groundwater elevations over dried areas that are then used to calculate tidal elevations. The Dupuit equation is examined as a method to simplify and/or replace the interpolation method. Dry nodes in the ADCIRC output are post-processed using the Dupuit equation to calculate groundwater elevation. The author completed a field study on Apalachicola Bay to compare the interpolation method to the Dupuit method. A transect between two known water surface elevations was selected as a test site. The mean high water (MHW) and mean low water (MLW) tidal elevations were calculated by averaging the local high tide and low tide water surface elevations, respectively, throughout the time-series output. Nodes that were dry at some point in the simulation were treated using the IDW and Dupuit to fill in water surface elevations during those dry periods. After finding the unknown water surface elevations using the Dupuit and interpolation method, the Dupuit estimation was on average 3.4% higher for MHW and 52% lower for MLW. This indicates that this process is sensitive to both the method and parameters used.

KEYWORDS: tidal elevations, datums, coastal salt marsh model, Dupuit, ADCIRC, Inverse Distance Weighting, interpolation

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INTRODUCTION

Marshes serve many useful functions. In addition to protecting the coast from storm surge and erosion caused by wave activity, marshes also provide a vital habitat for aquatic and terrestrial organisms (FDEP 2013). An integrated hydrodynamic/marsh biomass model is a useful tool for analyzing multiple mechanisms on a shoreline (e.g., accretion/erosion of the marsh platform) that are vital to its function. Tidal hydroperiods, corresponding to local fluctuating tides, should be represented accurately when modeling hydrologic activities in close proximity to shorelines. To simplify the tidal hydroperiods, the fluctuating tides are averaged in various ways. Two of the most important averages are the mean high water (MHW) and mean low water (MLW) elevations with respect to a known datum. Tidal elevations are also the basis for establishing privately owned land, state owned land, territorial sea, exclusive economic zone, and high seas boundaries (NOAA 2014).

When tidal elevation data are sparse, such as over patches of salt marsh that are not consistently wet, techniques to fill in the data gaps are necessary. Interpolation methods such as Inverse Distance Weighting (IDW) can be used to compute the elevations at periodically dry locations based on the water surface elevations of surrounding wet areas. IDW assumes that the influence of the known wet node diminishes as a function of distance. Such interpolation methods, however, are based solely on mathematical assumptions and don't account for soil or water characteristics. In an effort to improve the estimation of tidal datums over periodically dry areas, I completed a preliminary case study using the Dupuit equation. This method utilizes a classic groundwater equation named after Jules Dupuit. The Dupuit equation is physically-based and acknowledges several soil characteristics into its calculations. It uses end-point wet node locations and elevations, as well as the horizontal distance between them to approximate the location of the groundwater surface. At transects where limited data are available, the direct application of the Dupuit equation allows users to define tidal elevations that occur below ground and implement their values in future models.

My case study was completed in Apalachicola Bay, located in the Florida panhandle (Figure 1 in Appendix A). The Apalachicola River has the highest volumetric discharge in Florida and is formed by the confluence of the Chattahoochee and Flint Rivers (Iseri 1974). This river provides habitat for a variety of ecologically and economically significant species. Studying Apalachicola Bay can help coastal managers protect the future of this estuary (FDEP 2013). The motivation of this study was to improve the procedure for determining tidal elevations across areas that are not continuously wet. The Dupuit equation is examined as a method to simplify and/or replace interpolation methods.

BACKGROUND

Fluctuating tides create pressure zones that cause groundwater elevation to change in roughly sinusoidal patterns. Tidal variations become of greater importance when modeling hydrologic activities in close proximity to shorelines. Soil composition has the potential to change tidal influence on groundwater. For example, soils with high porosity and permeability will more efficiently conduct water—both vertically and horizontally—through the soil profile, leading to a more responsive ground water surface compared to soils with low porosity and permeability (Schanz 2002). These factors are important to consider when parameterizing a hydrodynamic model.

Groundwater elevation is one variable that controls the rate erosion or accretion of the shoreline, and thus can change the defined shoreline location within a salt marsh model. As described by Li et al. (1997), when the groundwater level is high relative to mean sea level, sediment will be removed and the shoreline will erode. On the other hand, when the groundwater elevation is below mean sea level, the shoreline will advance in the seaward direction in a process called accretion. The defined shoreline location is vital for accuracy and precision of the groundwater elevation. Once the shoreline location has been established for a specific time frame, tidal fluctuations are included within the model to calculate the groundwater elevation. Changes in water surface elevations are proportional to those of fluctuating tides. The one-dimensional Boussinesq equation (1) is often used in modeling shallow groundwater elevation changes:

$$\frac{\partial h(x,t)}{\partial t} = \frac{K}{n_e}\frac{\partial}{\partial x}\left\{h(x,t)\frac{\partial}{\partial t}\ h(x,t)\right\} \qquad (1)$$

where K is the hydraulic conductivity, n_e is the effective porosity, and $h(x,t)$ is the height of the water elevation as a function of distance and time (Gu et al. 2013). This equation utilizes the theory of shallow free surface flow.

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Ondovčin et al. (2012) use the Biot theory of poroelasticity to describe changes in groundwater elevation. This theory states that low porosity leads to a high sensitivity on areal strains and that high porosity leads to a high sensitivity to barometric loading. Ondovčin et al. (2012) conducted experiments to test these theories. These experiments identified high storage capacity, hydraulic conductivity, and low specific yield as the key conditions for an unconfined aquifer to be affected by the tidal variations and reflect measurable change in the groundwater elevation. One test showed that fluctuations of the groundwater elevation had no correlation with barometric pressure changes. This result initiated the idea that the fluctuations in the groundwater elevation were of tidal origin. With this understanding, the authors applied the ideas of Henry Darcy, who proved that the discharge per unit width through permeable soils is a function of the hydraulic gradient. Darcy's Law is often stated in terms of the following equation:

$$q = -Kh\left(\frac{\Delta h}{\Delta x}\right) \qquad (2)$$

where K is the hydraulic conductivity, q is Darcy velocity, h is height of water table, and x is the length in the direction of flow (Bedient 2013). Ondovčin's model found that areas with a weaker solid-phase body will allow the liquid pressure to overcome the stress from the solid-phase material. This intrusion will raise the water table with the flood tide. As explained earlier, groundwater changes with respect to tides. This fact confirms that computing groundwater elevation based on the water level of adjacent wet areas is appropriate in this context.

The Dupuit equation is used to approximate the elevation of the groundwater surface in an unconfined aquifer with respect to a datum. To apply the Dupuit equation, we must make several assumptions. Specifically, we must assume that the water table is only slightly inclined at any point, the streamlines are horizontal and equipotential lines are vertical, and the change in the free surface and change in hydraulic gradient are the same. To formulate the Dupuit equation, I applied these assumptions to equation (2) and the governing one-dimensional Boussinesq equation (1) (Bedient 2013). Figure 2 in Appendix A illustrates the variables that construct steady flow in an unconfined aquifer between two water bodies. The Dupuit equation (3) is stated as follows:

$$h^2 = {h_0}^2 - \frac{x}{L}\left({h_0}^2 - {h_L}^2\right) \qquad (3)$$

where h represents the groundwater elevation above the datum, h_0 is the water surface elevation of the last wet node before dry nodes on the transect, h_L is the elevation of the wet node following the last dry node on the transect, L represents the total horizontal distance between stationary wet nodes, and x is the horizontal distance between the stationary initial wet node and variable dry node (Bedient 2013).

Previous studies, such as Anderson (2004), examine the errors associated with the Dupuit approximations in specific regions. When examining equation (3), it is clear that the error is not mathematically dependent on the length parameter L. However, the error will increase as L increases due to uncertainties in soil composition that increase in probability as the domain expands. In other words, as L increases, soil homogeneity decreases and the Dupuit assumptions become less applicable. The goal of this study is not to change the current equation to make it applicable to several more complex circumstances, but rather to illustrate a simple application on an unconfined aquifer system such as dry areas between creeks in an estuary. The Dupuit method is applied as a post-processing technique on ADCIRC-2DDI (ADvanced CIRCulation) results, and therefore will not slow down simulation time. To my knowledge, application of the Dupuit equation has not been previously analyzed as a tool to interpolate tidal water surface elevations at points that were dried during a simulation. Mean high water (MHW) and mean low water (MLW) elevations calculated using the Dupuit equation are directly compared with an interpolation method.

METHODS

An unstructured finite element mesh, constructed in a Surface Water Modeling System (SMS), was used to create and discretize the study area. In this study, triangular elements were selected with each vertex of the triangle forming a node. At nodes that are continuously wetted during the simulation (e.g., tidal creeks, open water areas), tidal elevations such as MHW and MLW can be computed from ADCIRC output. ADCIRC-2DDI is a two-dimensional numerical model that solves the depth-integrated shallow water equations for water surface elevations and currents (Luettich et al., 1992). I calculated the MHW and MLW tidal elevations by averaging the local maximum and minimum water

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surface elevations, respectively, throughout the simulation results from a 14-day tidal cycle. I used the ADCIRC output directly for nodes that remained wet during the entire simulation. In areas that are intermittently wetted or have dry pockets (e.g., marshes), tidal constituents cannot be determined using this method because the drying of nodes leaves a gap in the water-level time series. Nodes that are dry at some point in the simulation need further calculations in order to compute the tidal elevation. Currently, the Inverse Distance Weighting (IDW) method can be used to interpolate known tidal elevations from wetted areas (such as marsh tidal creek) over dry areas (such as the marsh platform). As stated earlier, IDW assumes that each unknown node has diminishing influence as the distance from the known wet node increases. Recall that the interpolation method is based solely on mathematical assumptions and does not account for soil or water characteristics.

I simulated astronomic tides for 45 days beginning from a cold start with a water level of zero, then applying a 10-day hyperbolic tangent ramp function followed by 5 days of dynamic steady state. During the simulation, I administered an elemental drying check to determine if nodes within each element were wet or dry (Medeiros & Hagen 2013, Dietrich et al. 2006). At continuously wet nodes, MHW and MLW tidal elevations were calculated using the water surface elevation output. In previous methodologies, MHW and MLW tidal elevations at nodes not continuously wet were estimated by interpolating the ADCIRC output tidal elevation data from wetted nodes across the dried areas using the IDW method. In this study, I applied the Dupuit equation to a test transect of the marsh platform, with MHW and MLW elevation values in the creeks provided using an in-house tool within ArcGIS.

In addition, I measured global water surface elevations every hour for 30 days. The elevation output at all nodes from the model was loaded into SMS 11.1 (Surface-water Modeling System). A 500 meter linear transect was established across a peninsula located near the Apalachicola Bay. Twenty nodes closest to the transect line were chosen to supply the data set. Since the nodes do not lie exactly on the transect line due to the unstructured nature of the mesh, the 20 local nodes were projected onto the linear transect and were analyzed in one-dimension (see Figure 3 in Appendix A for linear transect).

Once the linear transect was established, I extracted the water surface elevations at each node for each output time step and saved as a tabular text document. In areas that are intermittently wetted, tidal constituents cannot be determined using ADCIRC because the drying of nodes leaves a gap in the water-level time series. A node was considered dry at individual time steps if the water surface elevation output was -99999, the built-in flag value within ADCIRC to acknowledge the gap in water level time series. These values were all replaced with new water surface elevations computed using the Dupuit equation. If a node was labeled dry during any time step, it was treated as dry throughout the study. Figure 4 in Appendix A illustrates the “island” effect for the first time step. The missing groundwater elevations, graphed with respect to the distance between each node on the transect, create this “island.”

Once water surface elevations at each time step in the dry nodes have been computed and integrated with the remainder of the ADCIRC output, I then used the Dupuit equation to estimate MHW and MLW at nodes that were intermittently wetted or constantly dry.

RESULTS AND DISCUSSION

Of the 20 nodes on the experimental linear transect, nine nodes were considered dry. These nine nodes were expected to be dry due to the peninsula crossed by the transect (“island” effect). Figure 4 in Appendix A illustrates the dry area were the nine nodes are missing a ground water elevation. Nodes that were dry at some point in the simulation were treated using the IDW and Dupuit to fill in water surface elevations during dry periods. An example of MHW, with Dupuit estimation, is presented in Table 1 in Appendix B. After computing estimated MHW and MLW elevations, the values were plotted and compared with results of both Dupuit and IDW methods graphically (Figure 5 in Appendix A).

One key difference between methodologies is how the interpolation method directly computes the tidal elevation (MHW and MLW) without considering physical characteristics of the soil. The Dupuit method computes elevations at each time step according to the Dupuit assumptions, which account for the physical characteristics of the soil. These elevations at each time step were then used to compute tidal datums (MHW and MLW) with respect to the continuously wet nodes water surface elevations and the distance between the continuously wet nodes and variable dry nodes.

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While the results of this study show that the computation of tidal datums is sensitive to the method used, the Dupuit equation does have some limitations. For example, the interpolation method is not limited to regions that follow the Dupuit assumptions. Again, these assumptions are as follows: the water table is only slightly inclined at any point, the streamlines are horizontal and equipotential lines vertical, and the change in the free surface and change in hydraulic gradient are the same (Bedient 2013). The use of the Dupuit equation is contingent on all assumptions being met. Without the assumptions accurately portraying the test area, the Dupuit equation's measurement error will increase.

The output of the Dupuit equation is always a positive number because of the square root function applied in the final step of the calculations. To evaluate using the Dupuit equation, the initial values need to be either all positive or all negative. Modeled water levels near the coast are often near the established vertical datum which is generally related to mean sea level. Therefore, some elevations are positive while others are negative. To apply the Dupuit equation in such a situation, we set a temporary datum such that all water elevations were positive. The distance from the true datum and the temporary datum was coined the "datum factor." After the temporary datum was established, I applied the Dupuit equation and then I mapped the results from the Dupuit equation back to the prior datum by subtracting the datum factor. In our case study, water surface elevations returned by the Dupuit and IDW methods were generally similar, though the Dupuit method consistently predicted lower MLW levels (Figure 5, Table 2). This result is consistent with theory in that the lower water surface elevations are influenced by the geologic and soil conditions within the intermittently wet regions of the marsh.

CONCLUSION

This study used the one-dimensional Dupuit equation to find the unknown water surface elevation between two known water surface elevations. To apply this equation, the Dupuit assumptions must be applicable on a test site. In this study, a transect was established across a peninsula in Apalachicola Bay in order to demonstrate the applicability of this method. The results indicate that the computation of MLW is more sensitive to the computation method (Dupuit or interpolation) than MHW.

Future work on the application of the Dupuit equation includes expanding the analysis into two-dimensions. Once the Dupuit equation has been derived into two-dimensions, projecting node locations onto a linear transect will be unnecessary. The 2D Dupuit equation can then be coupled with an existing physically-based model to improve accuracy. One model in particular that will be examined for application in future studies is the Marsh Equilibrium Model (MEM). The MEM uses long term measurements of shoreline accretion/erosion from sediment and sea level rise to predict biological productivity of marshland (Morris 2002). Tidal elevations are extremely important in this type of ecological model. Tidal elevations at dry nodes will be solved for using 2D Dupuit methodology.

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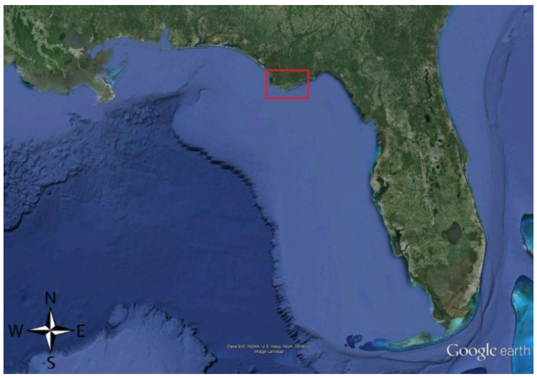
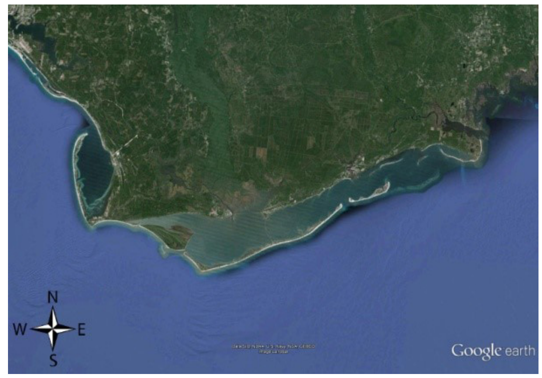
APPENDIX A

Figure 1: (a) Regional study area; (b) Apalachicola Bay.



(a)



(b)

Figure 2: Steady flow in an unconfined acquifer [sic] between two bodies of water with vertical boundaries (Bedient 2013).

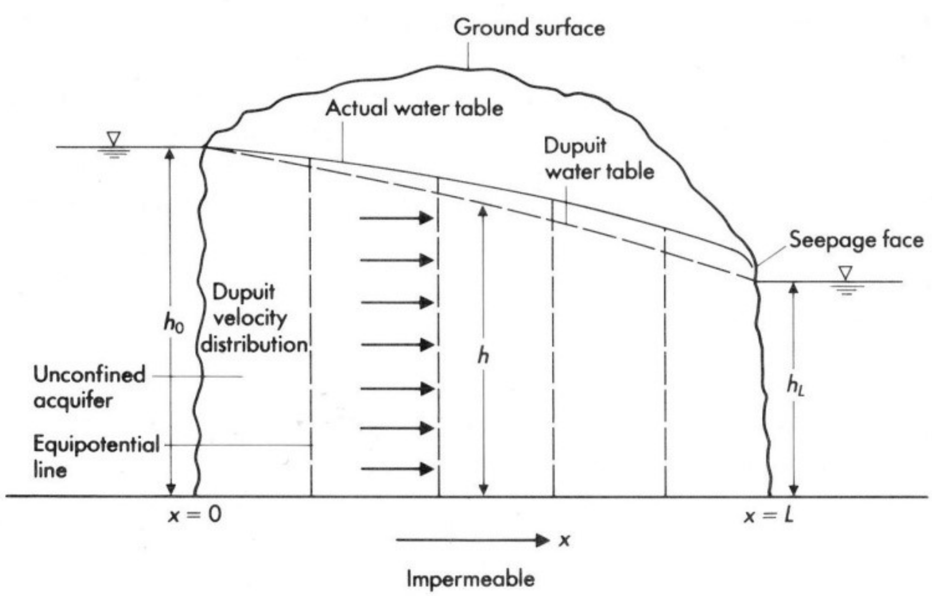


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Figure 3: Regional maps to reference location of transect.

Figure 4: After calculating the distance between nodes on the transect, the ground and water surface elevations were graphed. This figure also illustrates the missing groundwater elevations between the wet nodes creating the "island" effect.

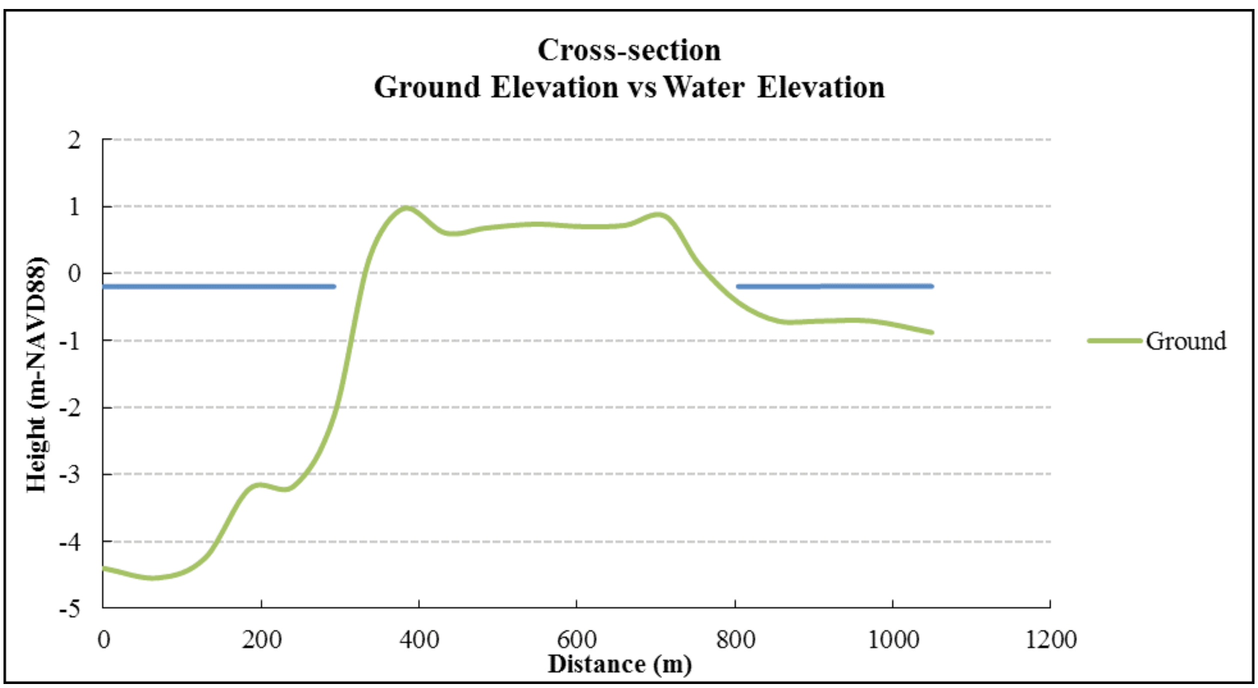

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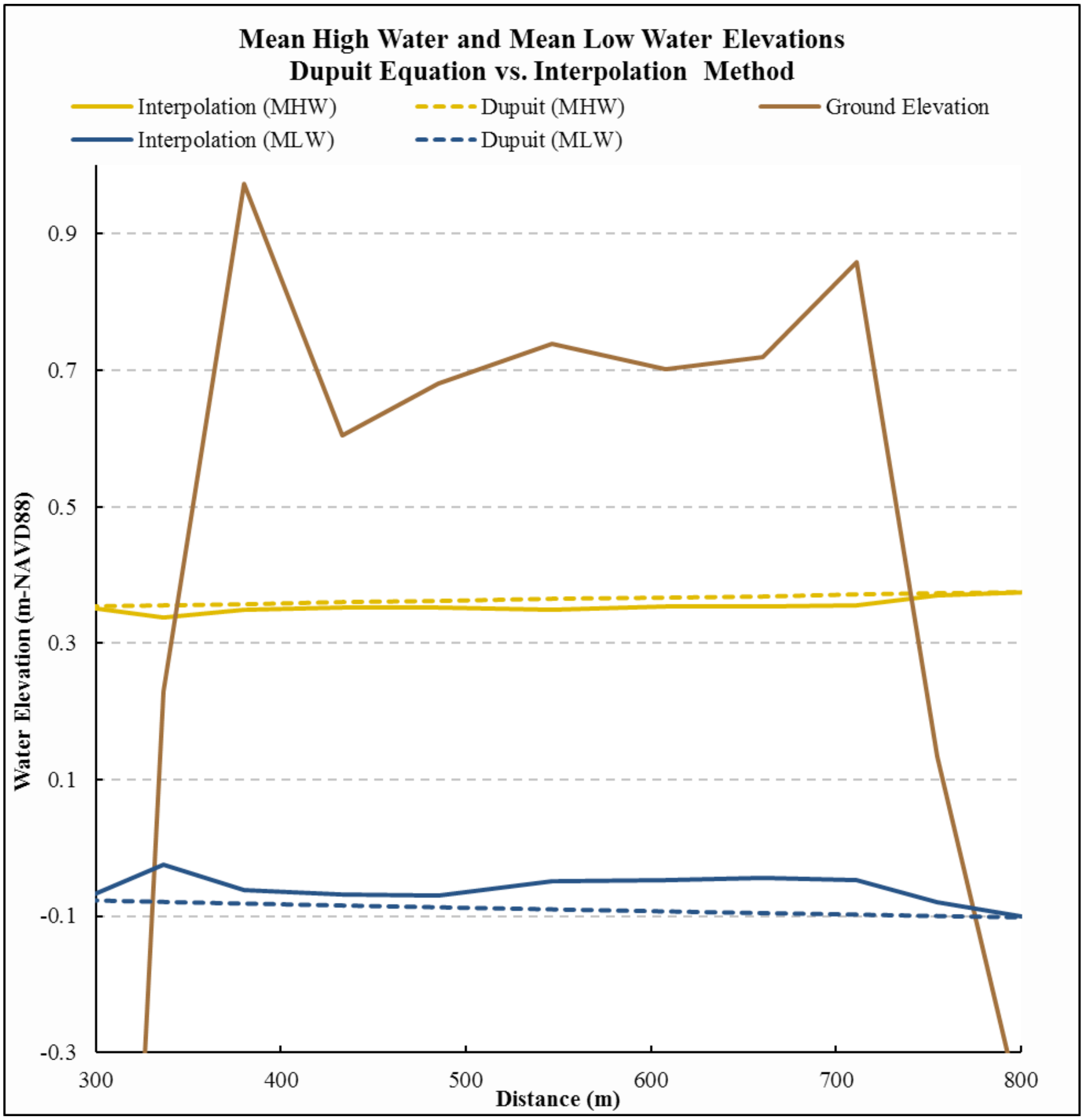
Figure 5: *Difference between calculated MHW and MLW elevations using Dupuit equation and Interpolation method.*



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APPENDIX B

Table 1: Chart of first time step and corresponding elevation of wet/dry nodes.

Node ID	1	2	3	4	5	6	7	8	9	10
Wet/Dry	Wet	Wet	Wet	Wet	Wet	Wet	Dry	Dry	Dry	Dry
MHW (cm)	35.4	35.4	35.4	35.4	35.4	35.4	35.6	35.8	36.0	36.2
	11	12	13	14	15	16	17	18	19	20
	Dry	Dry	Dry	Dry	Dry	Wet	Wet	Wet	Wet	Wet
	36.5	36.7	36.9	37.1	37.3	37.5	37.5	37.5	37.5	37.5

Table 2: Percent difference and absolute difference of MHW and MLW tidal elevations at dry nodes (7-15).

Node ID	MLW % Difference	MLW Abs. Difference (cm)	MHW % Difference	MHW Abs. Difference (cm)
7	105	5.5	5.3	1.8
8	29	2.1	2.4	0.9
9	21	1.6	2.4	0.9
10	21	1.7	2.8	1.0
11	61	4.2	4.6	1.6
12	66	4.6	3.6	1.3
13	73	5.1	4.4	1.6
14	69	5.1	4.3	1.6
15	24	2.1	0.6	0.2

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REFERENCES

Anderson, E. (n.d.). Modeling groundwater–surface water interactions using the Dupuit approximation. *Advances in Water Resources*, 315-327.

Apalachicola National Estuarine Research Reserve Management Plan, June 2013. (2013, June 1). Retrieved November 1, 2014

Bedient, P., & Huber, W. (2013). *Hydrology and floodplain analysis* (5th ed.). Upper Saddle River, NJ: Prentice Hall.

Dietrich, J., Kolar, R., & Westerink, J. (2006). Refinements in continuous Galerkin wetting and drying algorithms. *Estuarine and Coastal Modeling* (2005).

Gu, Y., Liu, F., Turner, I., & Zhuang, P. (n.d.). Finite volume and finite element methods for solving a one-dimensional space-fractional Boussinesq equation. *Applied Mathematical Modelling*, 3860-3870.

Iseri, K., & Langbein, W. (1974). *Large Rivers of the United States. U.S. Geological Survey Circular* (Vol. 686).

Li, L., Barry, D., & Pattiaratchi, C. (n.d.). Numerical modelling of tide-induced beach water table fluctuations. *Coastal Engineering,* 105-123.

Luettich, R., J, W., & N, S. (n.d.). *ADCIRC: An Advanced Three-Dimensional Circulation Model For Shelves, Coasts, and Estuaries, I: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL*. U.S. Army Corps of Engineers.

Medeiros, S., & Hagen, S. (2012). Review of wetting and drying algorithms for numerical tidal flow models. *International Journal for Numerical Methods in Fluids Int. J. Numer. Meth. Fluids*, 473-487.

Morris, J. (n.d.). Economizing Human Responses to Subsidence and Rising Sea Level. *Coastal Systems and Continental Margins Sea-Level Rise and Coastal Subsidence,* 313-325.

Ondovčin, T., Mls, J., & Herrmann, L. (2012). Mathematical Modeling of Tidal Effects in Groundwater. *Transp Porous Med Transport in Porous Media*, 483-495.

Schanz, Martin. "Linear Poroelastic Theories and a Poroelastic Boundary Element Formulation." Technische Universität Braunschweig, Braunschw.

Tidal Datums - NOAA Tides & Currents. (n.d.). Retrieved November 1, 2014, from http://tidesandcurrents.noaa.gov/datum_options.html