Hydrologic Signature Analysis of Select Organic Hydric Soil Indicators in Northeastern Florida

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The magnitude, duration, and return intervals of surface water flooding and dewatering of the landward extent of the hydric soil indicators muck (LM), histic epipedon (LHE), and Histosol (LH) were quantitatively defined, providing a better understanding of the hydrologic conditions maintaining these hydric soil indicators. Land surface elevations were determined for the LM, LHE, and LH at 16 lakes with long-term (30–60-yr) modeled or gauged hydrologic data. The probability of flooding and dewatering of the elevations of the LM, LHE, and LH were determined from frequency analysis of hydrologic data from each lake. The resulting hydrologic signatures for the LM, LHE, and LH are composed of magnitude and return interval of 1, 30, 90, 183, 274, and 365-d duration flooding and dewatering events. As an example, the LM, LHE, and LH were flooded for 30 continuous days with average annual probabilities of 42, 65, and 77%, respectively. As a second example, the LM, LHE, and LH were dewatered for 365 continuous days with average annual probabilities of 49, 24, and 16%, respectively. Probabilities of flooding and dewatering for the LM, LHE, and LH are presented for 1, 30, 90, 183, 274, and 365-d durations. Mean hydrologic signatures reduce variability and may be considered representative of each soil characteristic. Quantitatively defining the hydrology associated with the presence of the LM, LHE, and LH as well as other soil characteristics is essential for environmental protection, assessment of hydrologic impacts, wetlands restoration, wetlands creation, and other environmental management applications.

Abbreviations: DO, dissolved oxygen; LH, landward extent of Histosol; LHE, landward extent of histic epipedon; LM, landward extent of muck; NPP, net primary production; SOM, soil organic matter.

Soil organic matter (SOM) forms when net primary production (NPP) exceeds decomposition. Accumulation of SOM, particularly in subtropical and tropical regions, is common in wetlands where NPP is very high and decomposition is slowed by frequent inundation or saturation (Lucus, 1982; Ingebritsen et al., 1999). Anaerobic conditions are widely reported to retard decomposition (Ingebritsen et al., 1999; Richert et al., 2000). Anaerobic decomposition of plant litter and peat has been reported to occur at approximately one-third the rate of aerobic decomposition (DeBusk and Reddy, 1998). Although hydrology is frequently reported as a key component for the development of SOM and hydric soils (Hurt and Brown, 1995; Richardson et al., 1995; Fennessy and Mitsch, 2001; DeBusk and Reddy, 2003), relatively little information is available that quantitatively defines the natural hydrology associated with organic or hydric soils.

Wakeley et al. (1996) reported the percentage of time that saturated or reduced conditions occurred to identify or verify aquic conditions associated with select soil series or redoximorphic features. The seasonal high saturation associated with specific soil morphologies has been reported (Hurt et al., 2000), but specific magnitudes, durations, and return intervals of saturation or inundation are unknown. The hydrology associated with individual soil series is typically described in county soil surveys and on the official soil series description website (soils.usda.gov/technical/classification/osd/index.html, verified 28 Dec. 2008); however, the magnitude, duration, or return interval, if reported, can be imprecise. For example, the Myakka series (sandy, siliceous, hyperthermic Aeric Alaquods) is reported to have a water table at a depth of <45.7 cm (18 inches) (magnitude) for 1 to 4 mo (duration) in most years (return interval) and the Samsula series (sandy or sandy-skeletal, siliceous, dysic, hyperthermic Terric Haplosaprists) is reported to have a water table at or above the soil surface (magnitude) except during extended dry periods.

Five components of hydrologic regimes have been identified: (i) magnitude, (ii) duration, (iii) frequency (i.e., return interval), (iv) timing (i.e., seasonality), and (v) rate of change (Richter et al., 1996, 1997; Poff et al., 1997). In relatively natural, unregulated systems, the timing and rate of change are less sensitive to anthropogenic alterations than the magnitude, duration, or return interval components (Neubauer et al., 2004). Numerous studies have focused on wetlands hydrology (Duever et al., 1984; Ewel, 1990; Bridgham and Richardson, 1993), but these studies have not focused on all three hydrologic drivers (magnitude, duration, and return interval) of wetland communities in unregulated systems (Neubauer et al., 2004). Recent hydrologic analyses applied to wetland communities,

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capturing the magnitude, duration, and return interval hydrologic components (Neubauer et al., 2004) were applied in this study to specific soil characteristics: the landward extent of muck (LM), landward extent of a histic epipedon (LHE), and landward extent of a Histosol (LH).

Most hydrologic studies of organic soils have focused on subsidence and the management of hydrology to reduce subsidence where organic soils have been drained for agriculture (Stephens and Johnson, 1951; Schothorst, 1977; Snyder et al., 1978; Walter et al., 1980; Parent et al., 1982; Andriesse, 1988; Rojstaczer and Deverel, 1995; Ingebritsen et al., 1999; Schipper and McLeod, 2002). Quantitatively defining the hydrology associated with select soil characteristics will prove critical for environmental protection, assessment of hydrologic impacts, wetlands restoration, wetlands creation, and other environmental management applications.

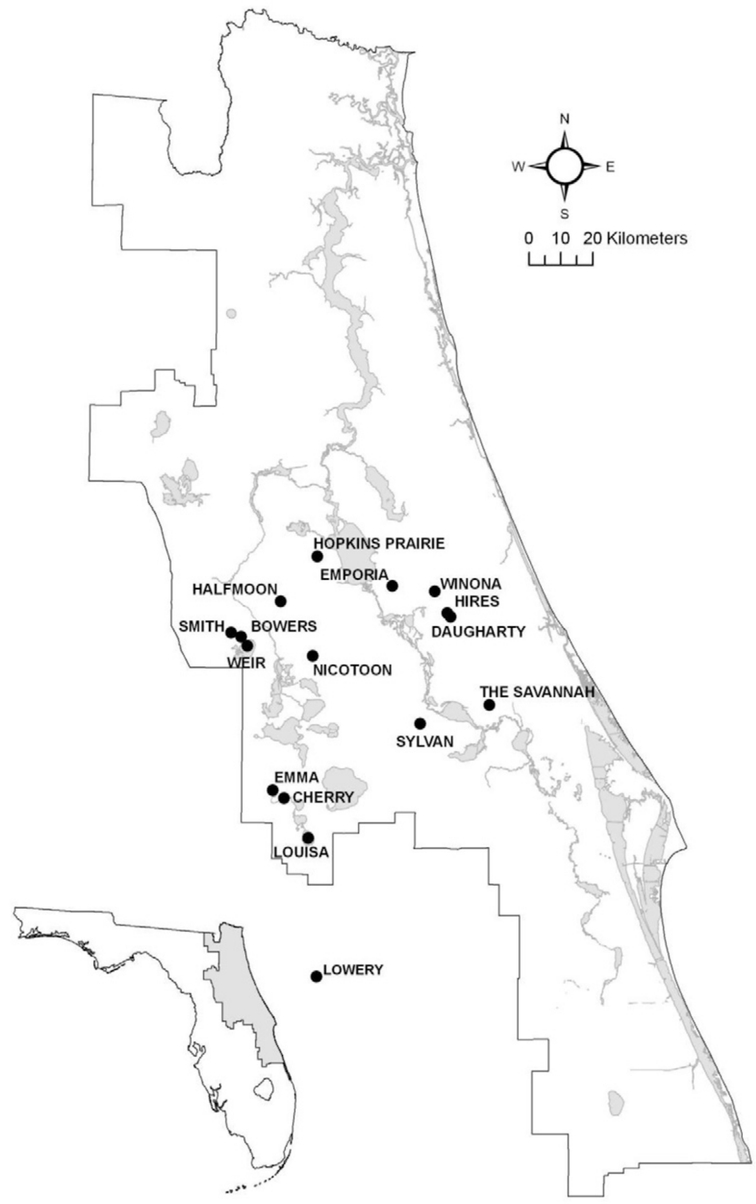

Fig. 1. Study site locations in Florida.

SITE DESCRIPTION

Soils from 16 relatively unimpacted lakes, ranging from sandhill lakes to wetland lakes, in northeastern Florida were investigated (Fig. 1). The topography in this region is nearly level to gently sloping, with a range of elevations from sea level to approximately 61 m above mean sea level.

Average annual rainfall is 132 cm with the mean annual rainfall varying from 127 to 152 cm. Annual precipitation totals range from <102 to >203 cm during more extreme dry and wet years, respectively. Distinct wet and dry seasons exist, with approximately half of the annual precipitation occurring between mid-June and mid-September (Winsberg, 1990).

METHODS

Hydrologic signatures were determined for the LM, LHE, and LH adjacent to 16 lakes with long-term (i.e., 30–60-yr) gauge or modeled water level data obtained from St. Johns River Water Management District's Division of Hydrologic Data Services (field-collected data) and Division of Water Supply Management (modeled data). The vertical accuracy of surface water level gauging stations was attained following the minimum technical standard for general survey, map, and report content requirements [Fla. Admin. Code 61G17-6.003 (2008)].

Hydrologic signatures for the LM, LHE, and LH were determined with the same approach as applied by Neubauer et al. (2004) to define the surface water inundation or dewatering signatures for wetland vegetation communities. The LM was identified as muck presence because all sites were in land resource region U, within which muck presence is applied as a hydric soil indicator (NRCS, 2002). The LHE was identified at the landward extent where 20 cm of surface organic soil material was observed (NRCS, 2002). The LH was identified at the landward extent where 40 cm of the upper 80 cm of soil was composed of organic soil material (NRCS, 2002). The near-saturated rub test was applied in the field to determine if soil materials were mineral or organic. Soil material was considered organic if no grittiness was felt after five rubs of a near-saturated soil sample (Wade Hurt, personal communication, 2006). Ground surface elevations were determined for the LM, LHE, and LH following the minimum technical standard for general survey, map, and report content requirements [Fla. Admin. Code 61G17-6.003 (2008)]. Typically, replicate determinations for each soil characteristic were averaged at each lake, providing one ground surface elevation for each soil characteristic at each lake (Table 1). Single-point observations of the soil characteristics were the only data available at several lakes and were assumed to be representative of the lake (Table 1).

High- and low-stage frequency analysis was performed on long-term daily stage data, collected on site or synthesized with water budget models for each of the 16 lakes investigated. Probabilities or return intervals are assigned to events of a given size with frequency analysis (Gordon et al., 1992), enabling comparisons among systems occurring across a range of elevations. In frequency analysis, the extreme events occurring in each year for a series of years are identified. For analysis of continuously exceeded stage events (i.e., flooding events), the year was taken as 1 June to 31 May (wet water year) to entirely capture Florida's wet season. For analysis of continuously nonexceeded stage events (i.e., dewatering events), the year was taken as 1 October to 30 September (dry water year) to entirely capture Florida's dry season. The use of different water years for flooding or dewatering stage events resulted in independent hydrologic signatures, rather than mirror images for flooding and dewatering, and allowed the extreme hydrologic events in each water year to be quantified. The probability of specific-duration flooding and dewatering events for the LM, LHE, and LH were obtained with output from the stage frequency analysis of each system.

As an example, assume that frequency analysis is being conducted on a 50-yr daily stage record, and a 30-d continuous event equaling or exceeding a certain lake stage is of interest. The stage hydrograph for each wet water year (n = 50) of the 50-yr period of record is analyzed by taking successive 30-d periods and determining the maximum stage that was continuously exceeded for each 30-d period. This is repeated for 336 (i.e., 365 − 30 + 1) periods of 30 d for each year. The maximum stage from those 336 values is recorded. Once the operation is performed for all years of record, the 50 resulting stage values are sorted from highest to lowest, ranked, and assigned probabilities. If a 60-d continuous dewatering event equaling or not exceeding a certain stage is of interest, the stage hydrograph for each dry water year (n = 50) is analyzed by taking successive 60-d periods and determining the minimum stage that is continuously not exceeded for each 60-d period. This is repeated for 306 (i.e., 365 − 60 + 1) periods of 60 d for each year. The minimum stage in those 306 values is recorded. Once the operation is performed for all years of record, the 50 resulting stage values are sorted from lowest to highest, ranked, and assigned probabilities. Frequency analysis was completed for flooding and dewatering events of 1-, 30-, 90-, 183-, 274-, and 365-d durations.

Probabilities associated with the annual flooding and dewatering events of 1-, 30-, 90-, 183-, 273-, and 365-d durations were assigned with the Weibull plotting position formula (Haan, 2002). This is a simple and preferred method of assigning probabilities to hydrologic data (Haan, 2002) and accounts for the fact that the absolute highest and lowest stages probably have not been observed in the period of record (Eq. [1]):

$$P(S \geq \hat{S}_m) = \frac{m}{n+1} \qquad [1]$$

where the term $P(S \geq \hat{S}_m)$ is the probability of S (a stage event) in any year equaling or exceeding $\hat{S}_m$ (a stage event of rank m), m is the rank of the event, and n is the number of years analyzed. The probability of a stage event, S, not exceeding $\hat{S}_m$ in any year is defined as

$$P(S < \hat{S}_m) = 1 - P(S \geq \hat{S}_m) \qquad [2]$$

The probabilities of the annual flooding and dewatering events were reported as percentages. The probabilities of the annual events can also be interpreted as a return interval (T, yr) for any stage event by dividing 100 by the probability (P, %) of that event (Eq. [3]):

$$T = \frac{100}{P} \qquad [3]$$

One could extrapolate beyond the 100-yr return interval or below the 1-yr return interval with stage frequency analysis. Extrapolating beyond the data range is often considered unreliable (Ott and Longnecker, 2001), and in stage frequency analysis would require the assumptions that the stage data encompasses sufficient climatic variability and that the climatic patterns will continue within the observed range in variability. Because of the pitfalls associated with extrapolation, probabilities of <1 or >99% were assigned probabilities of 0.1

Table 1. Elevations of soil indicators landward extent of muck (LM), landward extent of a histic epipedon (LHE), and landward extent of a Histosol (LH) by lake.

Indicator	Observation	Bowers	Cherry	Daugharty	Emma/Lucy	Emporia	Halfmoon	Hires	Hopkins	Kerr	Louisa	Lowery	Nicotoon	Savannah	Smith	Sylvan	Weir	Winona
		m NGVD†																
LM	1	16.93		13.63		12.67	14.93		7.87	7.56	29.25	39.65		9.94	16.16	12.97	17.50	
	2	17.19		13.58		11.59	15.11		7.48					9.75	15.93	12.90	17.64	
	3	17.32							7.86						16.38	12.48		
	4								7.35									
	Mean	17.14		13.60		12.13	15.02		7.64	7.56	29.25	39.65		9.85	16.16	12.79	17.57	
LHE	1	16.55	28.79	13.40	28.59	11.56	14.83	12.67	7.38		29.15	39.46	16.54	9.11	15.83	12.41	17.39	10.64
	2	16.78	29.15	13.52	28.48	11.17	14.64		7.34				16.47	9.24	16.11	12.57	17.39	
	3	16.83	29.50						7.77						15.79	12.17		
	4								7.29									
	Mean	16.72	29.14	13.46	28.53	11.37	14.74	12.67	7.45		29.15	39.46	16.51	9.17	15.91	12.39	17.39	10.64
LH	1	16.40	28.97	13.03	28.31	11.03	14.53	12.51	7.33	6.93	29.15	39.18		9.05	15.74	12.33	17.33	10.45
	2	16.46	29.10	13.28	28.28	11.04	14.51		7.35					9.11	16.04	12.06		
	3	16.63							7.46									
	4								7.19									
	Mean	16.50	29.04	13.15	28.29	11.04	14.52	12.51	7.33	6.93	29.15	39.18		9.08	15.89	12.20	17.33	10.45

† National Geodetic Vertical Datum 1929.

and 99.9%, respectively. These probabilities, 0.1 and 99.9%, should only be interpreted as indicating either very wet or very dry conditions rather than exact probabilities of flooding or dewatering.

Initially, best-fit curves were drawn through the stage frequency output for each selected duration to allow an empirical determination of the probability that a given soil characteristic elevation was exceeded or not exceeded for the defined durations (Fig. 2 and 3). Subsequently, stage frequency output was generated in tabular form only and exceedence or nonexceedence probabilities for the durations of interest for each soil characteristic elevation could be looked up or calculated with linear interpolation. This change in methodology was implemented to increase efficiency and reduce possible bias in the approach to determine the exceedence and nonexceedence probabilities of a given elevation. The best-fit curves vs. linear interpolation to determine exceedence or nonexceedence probabilities typically differ by <3%.

The duration and probability of exceedence or nonexceedence events, determined from the stage frequency analysis, for the LM were plotted along a probability scale (Fig. 4 and 5). The resulting family of curves defines the hydrologic signature for the LM. The family of curves for the LM, LHE, and LH were each summarized as a mean curve and standard deviation (Fig. 6 and 7). The probabilities of exceedence or nonexceedence associated with each duration for the LM, LHE, and LH were compared with an unequal variance t-test. The magnitude of flooding or dewatering associated with the LM, LHE, and LH was determined by extracting the probabilities of exceedence and nonexceedence for the LM, LHE, and LH ± 0.30, 0.61, and 0.91 m (1, 2, and 3 feet).

Several assumptions were made before conducting this analysis. First, the formation of organic soils is controlled largely by hydrology; therefore, the LM, LHE, and LH occurring at similar lakes and under similar climatic conditions will have similar hydrology. Second, it was assumed that the lake hydrology was representative of the adjacent wetland hydrology. This means that during periods of low water, the lake stage was assumed to be flat across the landscape. This assumption is probably valid for the analyses conducted in this study because of the close proximity of the soil characteristics to the lakes and the small elevation changes between the wettest and driest soil characteristics. Lakes with substantial seepage, flow-through systems, and rivers were not included in this analysis.

RESULTS AND DISCUSSION

As expected, the LM had the driest signature and the LH had the wettest, with the LHE intermediate (Fig. 6 and 7, Table 2). The signatures for the LM had a medium probability of flooding for short durations and a slightly smaller probability of long-duration flooding. The LM also had high probabilities of dewatering for short durations and relatively high probabilities of dewatering for long durations. The signatures for the LHE had high probabilities of short-duration flooding and medium probabilities of long-duration flooding. The LHE also had high probabilities of short-duration dewatering and medium probabilities of long-duration dewatering. The signatures for the LH had high probabilities of short-duration flooding and relatively high probabilities of long-duration flooding. The LH also had relatively high probabilities of short-duration dewatering and medium probabilities of long-duration dewatering.

The signatures for the LM appear to be slightly more variable than the signatures for the LHE and LH (Fig. 6 and 7, Table 2). This was expected, since the LM is located farther from each lake and at a slightly higher elevation than the LHE or LH and is likely affected to a greater degree by seepage and other alterations (e.g., structural alterations, consumptive use of water, etc.). In addition, the LM is probably more influenced by recent flood–drought

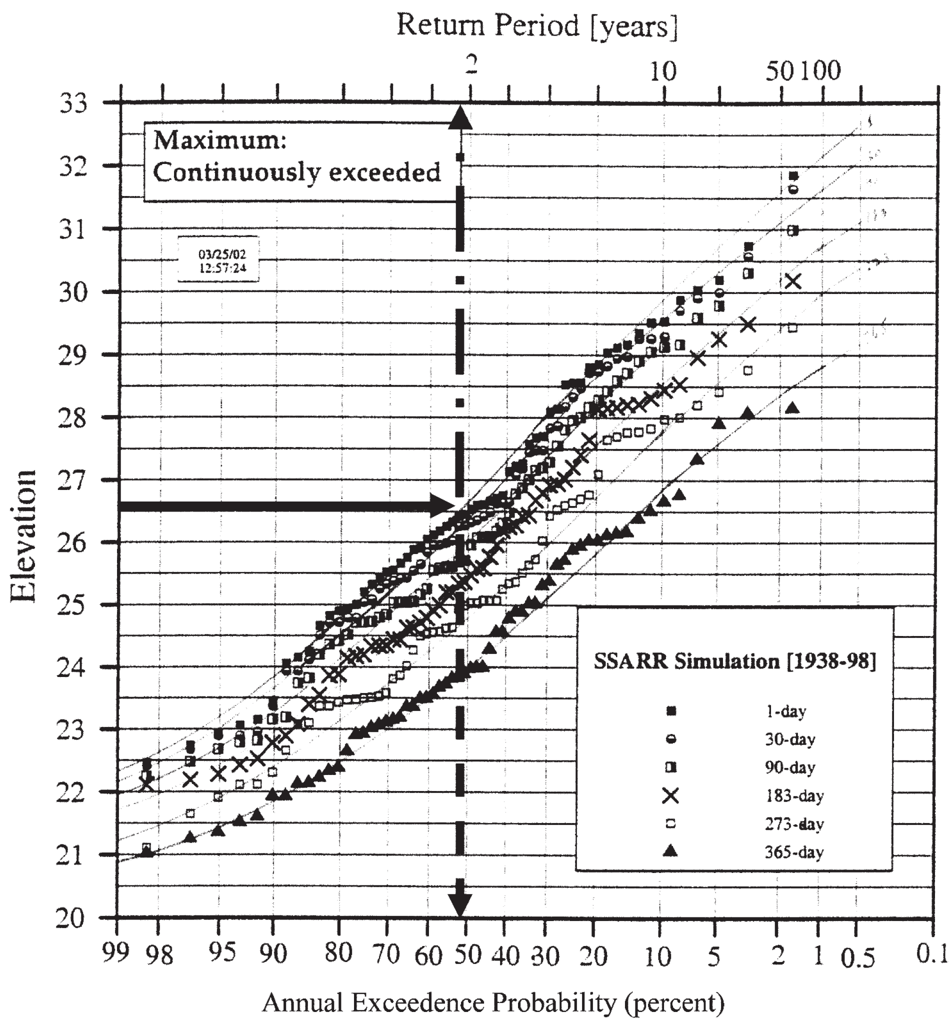

Fig. 2. Example of stage frequency analysis output from the Streamflow Synthesis and Reservoir Regulation (SSARR) mathematical model (U.S. Army Corps of Engineers, 1986) for continuous stage exceedence of 1-, 30-, 90-, 183-, 273-, and 365-d durations with best-fit curves. Note: The elevation of 26.5 (solid arrow) has a probability of approximately 50% of being exceeded for 1 d. This corresponds to a return interval of approximately once every 2 yr.

cycles. The LM signatures from Lake Weir, The Savannah, and Sylvan Lake are partially or wholly outside of the main signature cluster of the other systems investigated (Fig. 4 and 5). The Savannah and Sylvan Lake likely receive a small degree of seepage from the surrounding uplands, maintaining higher moisture contents and resulting in the LM occurring at a higher elevation. The degree of seepage is assumed small since the LHE and LH signatures for The Savannah and Sylvan Lake lie within the main signature clusters.

Lake Weir also likely receives some seepage near the soil surface. In addition, an outlet was constructed at Lake Weir in 1938 (Crisman et al., 1992), likely resulting in less frequent long-duration high-water events and the lake displays indicators of advancing eutrophication (Crisman et al., 1992). The signature for long-duration flooding events for the LM lies outside and on the dry side of the main LM signature cluster (Fig. 4) and short-duration dewatering events are outside of and occur more frequently than the main signature cluster (Fig. 5). The LM has likely adjusted to the structural alterations at Lake Weir, but the confounding effects of eutrophication, seepage, and increased consumptive use in the region inhibit a precise explanation as to why the LM signature is outside of the main flooding and dewatering signature clusters. The LHE and LH at Lake Weir are within but on the dry side of the main signature clusters.

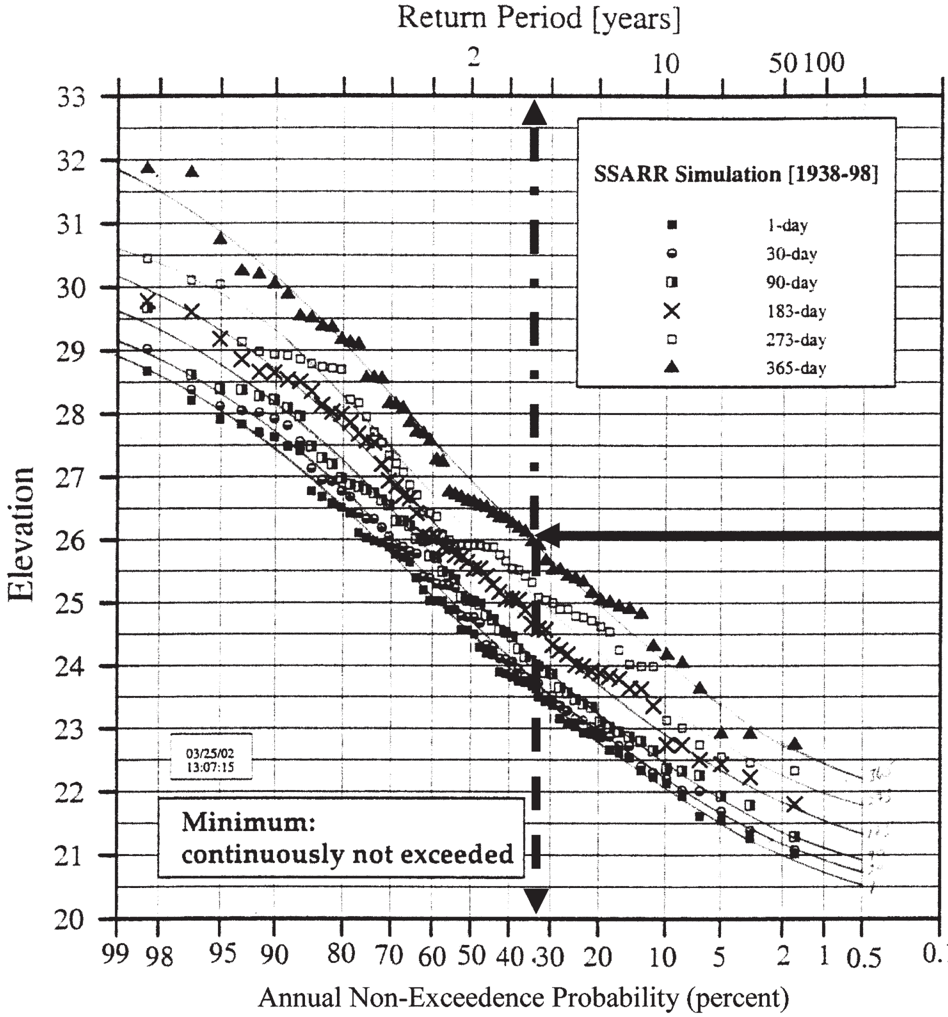

Fig. 3. Example of stage frequency analysis output from the Streamflow Synthesis and Reservoir Regulation (SSARR) mathematical model (U.S. Army Corps of Engineers, 1986) for continuous stage nonexceedence of 1-, 30-, 90-, 183-, 273-, and 365-d durations with best-fit curves. Note: The elevation of 26 has a probability of 33% of being dewatered for 365 d. This corresponds to a return interval of approximately once every 3.3 yr.

Lakes with indications of substantial seepage were not included in this study. Seepage areas were considered to be those areas with vegetation dominated by *Gordonia lasianthus* (L.) J. Ellis, *Persea palustris* (Raf.) Sarg., *Magnolia virginiana* L., and occasionally *Pinus taeda* L., *Pinus elliottii* Engelm., *Ilex cassine* L., or other vegetation indicative of near-surface saturation due to groundwater rather than surface water flooding. A small amount of seepage likely occurs at all of the lakes studied and is probably variable among the lakes. Soil organic matter may be maintained by seepage (Lindbo and Richardson, 2001), although seepage is more difficult to quantify than lake stage (Winter, 1999). Lakes with indications of substantial seepage were intentionally avoided because of the complications associated with quantifying seepage. Lake stage or modeled lake stage was considered the sole source of hydrologic data to define signatures for the LM, LHE, and LH.

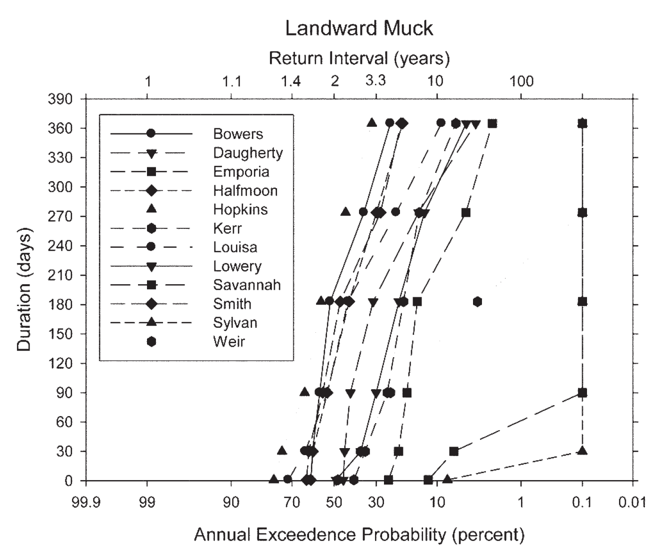

Fig. 4. Exceedence hydrologic signatures for the landward extent of muck (LM).

In general, there is substantial variability in the signatures observed for each of the soil characteristics. Numerous sources

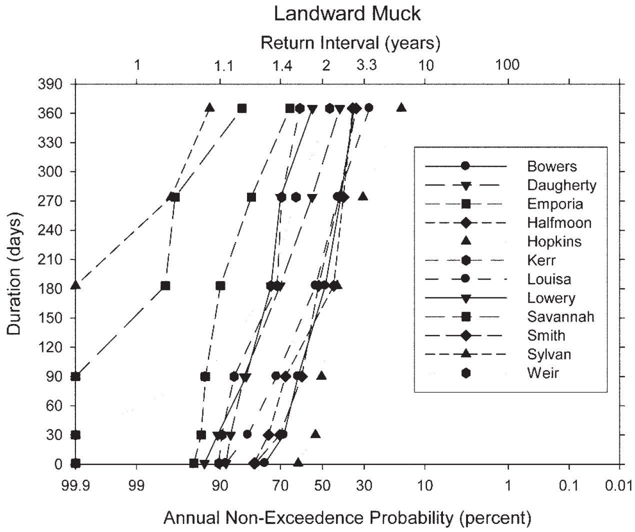

Fig. 5. Nonexceedence hydrologic signatures for the landward extent of muck (LM).

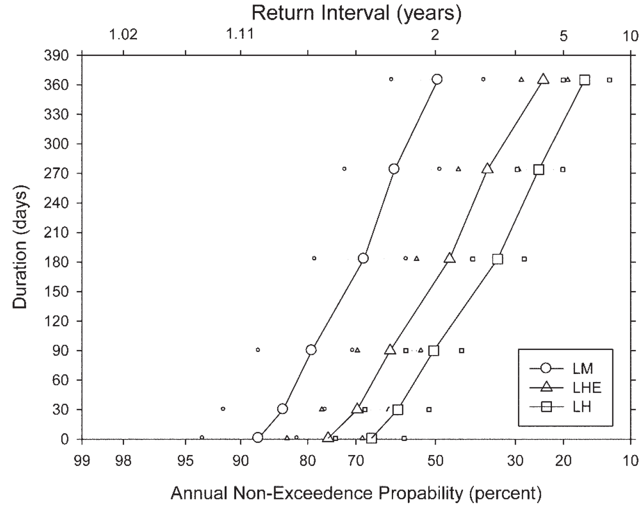

Fig. 7. Mean nonexceedence hydrologic signatures with 90% confidence intervals for the landward extent of muck (LM), the landward extent of a histic epipedon (LHE), and the landward extent of a Histosol (LH).

of variability exist. The lakes ranged from oligotrophic sandhill lakes, to dark water lakes, to wetland-dominated systems. The wetland communities ranged from herbaceous marshes to hardwood swamps, and the systems investigated have varying degrees of seepage and have different nutrient statuses, which would directly affect productivity. Fire history varies among sites, which would in turn affect the organic matter input at a site and potentially the near-surface moisture conditions. Sites with the wettest signatures may be accreting SOM, and subsidence may be occurring at the driest sites. In addition, the amount of labile vs. recalcitrant C in vegetation is a determinant of the accretion or oxidation rates of SOM (Reddy and DeLaune, 2008). A final source of variability arises from the field determination of organic vs. mineral soil materials. This source of variability is probably most pronounced for the LM where the layer of muck was very thin, enabling frequent mixing with the mineral soil materials.

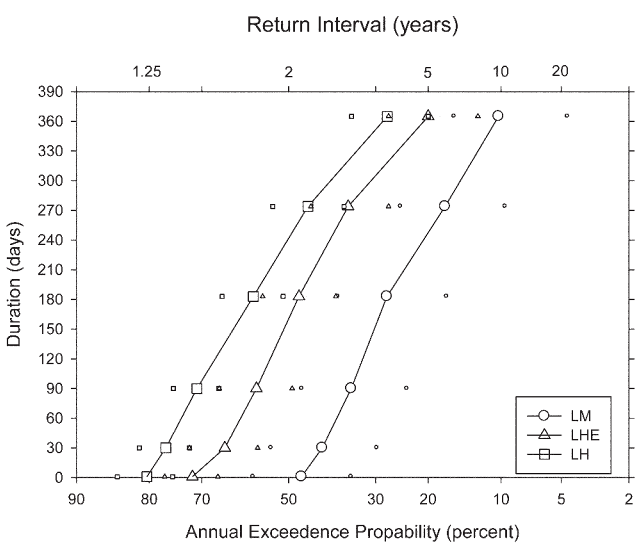

Fig. 6. Mean exceedence hydrologic signatures with 90% confidence intervals for the landward extent of muck (LM), the landward extent of a histic epipedon (LHE), and the landward extent of a Histosol (LH).

The lakes included in this study are thought to be relatively unimpacted, but most have been influenced by humans to some degree. Structural alterations have occurred at several of the systems, such as the creation or lowering of outlets. Hydrologic alterations through the use of groundwater and surface water have also probably occurred and are variable among sites.

Some error exists in the determination of the elevation of soil characteristics, simply because the elevation may have been determined on a small mound or depression. This is probably a negligible source of error since the elevation is typically a mean of several point locations of each soil indicator. In addition, a small change in elevation results in only minor changes to the annual probabilities of exceedence and nonexceedence. Error is also associated with the modeled stage data generated with hydrologic models. This error is expected to be random and if the model is well calibrated to the period of record, should be negligible for this study.

Although numerous potential sources of variability exist, signatures for the LM, LHE, and LH appear to provide a high-quality, quantitative description of the magnitude, duration, and return interval of flooding and dewatering (Fig. 6 and 7, Table 2). Previous hydrologic descriptions for the LM, LHE, and LH have been limited to seasonal high saturation. Hurt et al. (2000) reported that the seasonal high saturation for the LM, LHE, and LH is at the soil surface or that these indicators are inundated above the soil surface; however, return intervals and precise durations were lacking. The NRCS provides a more thorough hydrologic description of organic soils, such as, "the water table is at or above the surface for 6–9 mo in most years" (Hontoon mucky peat [dysic, hyperthermic Typic Haplosaprists], Terra Ceia muck [euic, hyperthermic Typic Haplosaprists], or Tomoka muck [loamy, siliceous, dysic, hyperthermic Terric Haplosaprists]) and "the water table is above the surface except during extended dry periods" (Soil Conservation Service, 1980; Soil Survey Staff, 2007). The hydrologic descriptions for these organic soil series appear to be similar to the signatures reported for the LH (Table 2); however, the return intervals and magnitudes are vague in these definitions.

Table 2. Mean hydrologic signatures and return intervals for landward extent of muck (LM), landward extent of a histic epipedon (LHE), and landward extent of a Histosol (LH).

Indicator	Duration	Exceedence				Nonexceedence			
		Mean probability	SD	Mean return interval	*n*	Mean probability	SD	Mean return interval	*n*
	d	—— % ——		yr		—— % ——		yr	
LM	1	46.9	22.4	2.1	12	87.8	11.4	1.1	12
	30	42.0	23.7	2.4	12	84.2	14.7	1.2	12
	90	35.3	22.3	2.8	12	79.2	16.5	1.3	12
	183	27.6	20.5	3.6	12	68.1	20.3	1.5	12
	274	17.3	14.9	5.8	12	60.6	22.8	1.6	12
	365	10.3	10.9	9.7	12	49.4	23.0	2.0	12
LHE	1	74.5	12.5	1.3	16	71.8	17.6	1.4	16
	30	69.6	13.9	1.4	16	64.6	16.2	1.5	16
	90	63.8	14.3	1.6	16	56.0	15.6	1.8	16
	183	54.3	15.1	1.8	16	39.9	16.5	2.5	16
	274	42.0	18.0	2.4	16	32.1	15.3	3.1	16
	365	23.7	17.7	4.2	16	22.7	12.0	4.4	16
LH	1	80.5	11.3	1.2	16	60.6	16.9	1.6	16
	30	77.2	11.7	1.3	16	54.0	16.2	1.9	16
	90	72.1	12.5	1.4	16	45.3	14.8	2.2	16
	183	63.8	13.6	1.6	16	30.7	13.3	3.3	16
	274	51.9	15.9	1.9	16	24.1	11.9	4.2	16
	365	32.4	17.0	3.1	16	17.1	9.5	5.8	16

The mean flooding and dewatering signatures with 90% confidence intervals for the LM, LHE, and LH (Fig. 6 and 7) show overlap. A comparison of the hydrologic signatures, however, shows that the LM, LHE, and LH are significantly different for all durations (Table 3, unequal variance *t*-test, $\alpha = 0.10$). A comparison of medians is more appropriate for data at the tails of the probability distribution because the tails are inherently skewed. In addition, for data in the tails of the distribution or data with high variability, confidence intervals about the median are more appropriate than confidence intervals about the mean because confidence intervals about the mean can result in probabilities >100% and <0.

The magnitude of flooding and dewatering of the LM and LH was examined with frequency analysis to gain a better understanding of the extent of high and low water levels associated with these hydric soil indicators. The probability of flooding or dewatering of any elevation can be determined after development of the stage frequency analysis. For example, signatures were developed for elevations 0.30, 0.61, and 0.91 m (1, 2, and 3 feet, respectively) above the LM and below the LH. This analysis shows that an elevation 0.91 m above the LM is dewatered for 365 continuous days with a median probability of 99.9% (Table 4). As another example, an elevation 0.91 m below the LH is flooded for 365 continuous days with a median probability of 89.9% (Table 4). The median probabilities of flooding and dewatering of 0.30, 0.61, and 0.91 m above the LM and 0.30, 0.61, and 0.91 m below the LH for 1, 30, 90, 183, 273, and 365 continuous day durations and their associated return intervals are presented in Table 4. These data show that there is rarely 0.91 m of water above the LM elevation because this elevation is dewatered for 365 continuous days almost every year (return interval of 1.00 yr). These data also show that water rarely falls more than 0.91 m below the elevation of the LH because this elevation is flooded for 365 continuous days almost every year (return interval of 1.11 yr).

The signatures for the LM, LHE, and LH defined here are long-term signatures that are applicable in hydrologic management. The mean signatures (Fig. 6 and 7) could potentially be considered optimal for the maintenance of organic soils. For the accretion of organic soils, however, managing the hydrology to mimic a hydrologic signature wetter than the mean (Fig. 6, Table 2) would probably result in success. For example, if accretion of organic matter is a management goal in a wetlands creation project, then the site must be graded to the point where the magnitude, duration, and return interval of flooding and dewatering occur on the wet side of the desired indicator (e.g., LH) signature. If the site is not graded appropriately, augmentation with additional water might be necessary to achieve the desired management goal. If accretion of organic matter is a goal of wetlands restoration, then the same principals described for wetlands creation follow to achieve the desired

Table 3. Comparisons among landward extent of muck (LM), landward extent of a histic epipedon (LHE), and landward extent of a Histosol (LH) with an unequal variance *t*-test (α = 0.10). All comparisons are statistically significant at the α = 0.10 significance level.

Duration	*P*-value		
	LM vs. LHE	LM vs. LH	LHE vs. LH
d			
		Exceedence	
1	0.0007	0.0001	0.0845
30	0.0011	0.0001	0.0518
90	0.0006	0.0000	0.0468
183	0.0006	0.0000	0.0357
274	0.0002	0.0000	0.0553
365	0.0102	0.0002	0.0851
		Nonexceedence	
1	0.0037	0.0000	0.0390
30	0.0013	0.0000	0.0367
90	0.0005	0.0000	0.0279
183	0.0004	0.0000	0.0470
274	0.0007	0.0001	0.0529
365	0.0011	0.0002	0.0775

Table 4. Median hydrologic signatures and return intervals† for 0.30, 0.61, and 0.91 m above the landward extent of muck (LM) and 0.30, 0.61, and 0.91 m below the landward extent of a Histosol (LH).

Soil indicator	Duration	Exceedence		Nonexceedence	
		Probability	Return interval	Probability	Return interval
	d	%	yr	%	yr
LM + 0.30 m	1	23.35	4.28	99.05	1.01
	30	17.28	5.79	97.21	1.03
	90	11.93	8.38	94.83	1.05
	183	7.06	14.17	90.13	1.11
	273	3.41	29.34	87.14	1.15
	365	0.80	125.00	75.16	1.33
LM + 0.61 m	1	5.43	18.42	99.90	1.00
	30	4.32	23.12	99.90	1.00
	90	3.23	30.99	99.90	1.00
	183	1.05	95.33	97.12	1.03
	273	0.10	1000.00	96.27	1.04
	365	0.10	1000.00	92.39	1.08
LM + 0.91 m	1	1.53	65.46	99.90	1.00
	30	0.10	1000.00	99.90	1.00
	90	0.10	1000.00	99.90	1.00
	183	0.10	1000.00	99.90	1.00
	273	0.10	1000.00	99.90	1.00
	365	0.10	1000.00	99.90	1.00
LH – 0.30 m	1	89.51	1.12	41.00	2.44
	30	88.67	1.13	29.23	3.42
	90	86.87	1.15	23.00	4.35
	183	82.00	1.22	17.51	5.71
	273	74.00	1.35	13.03	7.67
	365	54.87	1.82	8.27	12.09
LH – 0.61 m	1	95.96	1.04	22.65	4.42
	30	95.16	1.05	18.85	5.30
	90	93.01	1.08	14.62	6.84
	183	87.95	1.14	8.05	12.42
	273	85.56	1.17	6.34	15.78
	365	73.90	1.35	2.71	36.92
LH – 0.91 m	1	99.90	1.00	9.89	10.11
	30	98.08	1.02	8.25	12.13
	90	97.54	1.03	5.91	16.91
	183	96.29	1.04	2.69	37.18
	273	93.35	1.07	0.10	1000.00
	365	89.90	1.11	0.10	1000.00

† Extrapolation to 1000-yr return interval should only be interpreted as indicating either very wet or very dry conditions for flooding or dewatering, respectively.

outcome. In addition to mimicking the hydrologic signature of a desired indicator, it would be necessary to address the magnitude of flooding and dewatering. For example, an elevation 0.91 m above the LM is usually dewatered for long and short durations and an elevation 0.91 m below the LH is usually flooded for long and short durations (Table 4).

Vegetation must also be considered for accretion of organic matter. If conditions are too wet, then vegetation may die or may not produce sufficient biomass to accrete SOM. If conditions are too dry, then the vegetation may produce less biomass or the senesced vegetation and roots may oxidize rather than accrete as SOM. Hydrologic signatures defined for various wetland communities (Neubauer et al., 2004) can be applied to ensure adequate hydrologic conditions to support the desired vegetation communities and optimize the accretion of organic soil materials.

These signatures can also be used in water supply management. If the goal of management is to withdraw water without causing subsidence, then the hydrology of a system presumably could be pushed at least to the mean signature (Fig. 6 and 7) and possibly toward the dry side of the cluster of signatures (Fig. 4 and 5) for a particular soil indicator without causing subsidence. This would probably prevent long-term accretion of SOM and could result in recalcitrant SOM (i.e., complex forms of SOM resistant to decomposition) through time as the microbial community consumed the more labile components.

Organic soils are probably sensitive to hydrologic alterations. As the elevation at a site increases from the LH to the LM, the hydrologic signature becomes drier and the thickness of SOM decreases across a small elevation range. The mean elevation differences between the LM and LHE and between the LHE and LH were 0.33 and 0.17 m, respectively (Table 5). These differences appear small, but with respect to resource management, they are quite large. For instance, 0.17 m of a 40-ha lake corresponds to approximately 68,000 m^3 of water (about 18 million U.S. liquid gallons or about 55 acre-ft). The elevation differences between the LM and LHE and between the LHE and LH suggest that a relatively small hydrologic change may result in large changes to the depth of SOM. This also suggests that the accretion of SOM is a nonlinear response function of hydrology in that it takes a greater magnitude of flooding for respective durations and return intervals to develop the first 20 cm of SOM (the LHE) than it does the next 20 cm of SOM (the LH). This is logical because the accumulation of SOM has a positive feedback loop to support further accretion of SOM. This is because SOM maintains a high moisture content well above a water table (Clough, 1992) and on decomposition provides nutrients to support plant growth.

CONCLUSIONS

The signatures for the LM, LHE, and LH presented here provide more detailed hydrologic information than is currently available in the literature. In addition, stage frequency analysis in conjunction with the signatures for the LM, LHE, and LH provide a measure of success for management objectives. Some drawbacks include limited data availability and the time needed to amass enough data to assess management objectives with frequency analysis (approximately 10 yr or longer).

The signatures for the LM, LHE, and LH presented here increase our understanding of the hydrology of these hydric soil indicators; however, improvement is still needed. As additional data are collected, the signatures for each of the indicators may be further divided by degree of decomposition (sapric, hemic, or fibric), type of system (e.g., lake, river, wetland, etc.), dominant vegetation associated with the soil, or whether or not the system is accreting SOM. These divisions would probably result in hydrologic signatures that transition from one subclass of indicator to another within the main signature classes, LM, LHE, and LH. These subclasses of hydrologic signatures for organic soils would enable fine-tuning of management activities and higher confidence of successful management. In addition, determination of whether or not the systems with the wettest signatures are accreting SOM and the systems with the driest signatures are subsiding would prove useful for management decisions.

The signatures for the LM, LHE, and LH presented here are only applicable to predominantly groundwater-driven systems underlain by sandy soils in central Florida. The surface water inundation or dewatering signatures method established by Neubauer et al. (2004) to determine the hydrologic signatures of wetland vegetation communities and applied herein to quantitatively define the hydrologic signatures of select hydric soil indicators can be applied to other hydrologic characteristics in any region. As noted by Neubauer et al. (2004), this method is not limited to hydrologic data. Frequency analysis can be applied to salinity, temperature, dissolved O_2 (DO), or other data to determine the tolerance of a biological parameter. For example, frequency analysis of temperature data could show the events that result in the northern extent of mangroves or various species of citrus. Frequency analysis of salinity data could be used to show the tolerance of freshwater, estuarine, and saline submerged aquatic vegetation. Frequency analysis of DO data could reveal the duration of a low-DO event that resulted in a fish kill or the tolerance of different species. The benefit of this method is that the annual probability of events, with magnitude and duration, can be tied to a biological outcome. The drawback is that only a single biological driver can be analyzed, therefore the method is most effective when there is a primary driver of a biological outcome.

Table 5. Elevations of soil indicators landward extent of muck (LM), landward extent of a histic epipedon (LHE), and landward extent of a Histosol (LH) and differences between elevations.

Lake	Elevation			Elevation difference		
	LM	LHE	LH	LM – LHE	LHE – LH	LM – LH
	m NGVD†			m		
Bowers	17.14	16.72	16.50	0.42	0.23	0.65
Cherry	–	29.14	29.04	–	0.11	–
Daugharty	13.60	13.46	13.15	0.14	0.31	0.45
Emma/Lucy	–	28.53	28.29	–	0.24	–
Emporia	12.13	11.37	11.04	0.76	0.33	1.09
Halfmoon	15.02	14.74	14.52	0.28	0.21	0.50
Hires	–	12.67	12.51	–	0.16	–
Hopkins	7.64	7.45	7.33	0.20	0.12	0.31
Kerr	7.56	–	6.93	–	–	0.62
Louisa	29.25	29.15	29.15	0.10	0.00	0.10
Lowery	39.65	39.46	39.18	0.19	0.28	0.47
Nicotoon	–	16.51	–	–	–	–
Savannah	9.85	9.17	9.08	0.67	0.09	0.76
Smith	16.16	15.91	15.89	0.25	0.02	0.27
Sylvan	12.79	12.39	12.20	0.40	0.19	0.59
Weir	17.57	17.39	17.33	0.18	0.05	0.23
Winona	–	10.64	10.45	–	0.18	–
Mean				0.33	0.17	0.50
Median				0.25	0.18	0.48
Min.				0.10	0.00	0.10
Max.				0.76	0.33	1.09
SD				0.22	0.10	0.27

† National Geodetic Vertical Datum 1929.

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