Effects of subsurface soil characteristics on wetland–groundwater interaction in the coastal plain of the Chesapeake Bay watershed

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Abstract
Ecosystem services provided by depressional wetlands on the coastal plain of the Chesapeake Bay watershed (CBW) have been widely recognized and studied. However, wetland–groundwater interactions remain largely unknown in the CBW. The objective of this study was to examine the vertical interactions of depressional wetlands and groundwater with respect to different subsurface soil characteristics. This study examined two depressional wetlands with a low-permeability and high-permeability soil layer on the coastal plain of the CBW. The surface water level (SWL) and groundwater level (GWL) were monitored over 1 year from a well and piezometer at each site, respectively, and those data were used to examine the impacts of subsurface soil characteristics on wetland–groundwater interactions. A large difference between the SWL and GWL was observed at the wetland with a low-permeability soil layer, although there was strong similarity between the SWL and GWL at the wetland with a high-permeability soil layer. Our observations also identified a strong vertical hydraulic gradient between the SWL and GWL at the wetland with a high-permeability soil layer relative to one with a low-permeability soil layer. The hydroperiod (i.e., the total time of surface water inundation or saturation) of the wetland with a low-permeability soil layer appeared to rely on groundwater less than the wetland with a high-permeability soil layer. The findings showed that vertical wetland–groundwater interactions varied with subsurface soil characteristics on the coastal plain of the CBW. Therefore, subsurface soil characteristics should be carefully considered to anticipate the hydrologic behavior of wetlands in this region.

KEYWORDS
Chesapeake Bay watershed (CBW), depressional wetlands, groundwater level (GWL), hydroperiod, subsurface soil characteristics, surface water level (SWL)
Depressional wetlands (a.k.a. “Delmarva bays”) are abundant on the coastal plain of the Chesapeake Bay watershed (CBW) due to the flat topography; the close proximity to the groundwater table and the coast; and the high precipitation relative to evapotranspiration (Lang et al., 2015). These densely distributed wetlands provide important ecosystem services for this region as follows: Water purification (Denver et al., 2014; Jordan, Whigham, Hofmockel, & Pittek, 2003; Sharifi, Kalin, Hantush, Isik, & Jordan, 2013), flood control (Lee et al., 2018), wildlife habitat (Russell & Beauchamp, 2017; Yepsen et al., 2014), and carbon storage (Fenstermacher, Rabenhorst, Lang, McCarty, & Needelman, 2016). A dramatic decline in wetland areas, mainly owing to conversion to croplands, is likely to have substantially decreased the provision of these wetland-related ecosystem services (USFWS, 2002). Accordingly, the return of cropland to its original wetland condition (hereafter, referred to as “wetland restoration”) should lead to higher levels of wetland benefits (Van Houtven, Loomis, Baker, Beach, & Casey, 2012).

To achieve wetland management goals, monitoring and assessing wetland functions are essential (Shuman & Ambrose, 2003). Understanding wetland hydrology is critical because ecosystem services provided by a wetland (e.g., water purification and carbon storage) are highly dependent on inflow to, and outflow from, that wetland (Fenstermacher et al., 2016; Sharifi et al., 2013). Wetland–groundwater interactions have been widely examined due to the substantial impact of groundwater on controlling wetland water balance. A variation in hydraulic gradients between wetlands and their contributing areas induces lateral groundwater exchange, resulting in the rise and fall of wetland water levels (Haque, Ali, & Badiou, 2018; McLaughlin & Cohen, 2013; O’Driscoll & Parizek, 2003; Pyzoha, Callahan, Sun, Trettin, & Miwa, 2008; Rassam, Fellows, De Hayr, Hunter, & Bloesch, 2006; van der Kamp & Hayashi, 2009). Seasonal fluctuations of wetland water levels in coastal plain regions were reported to be greatly affected by lateral groundwater flow (McLaughlin & Cohen, 2013; Pyzoha et al., 2008). A downward hydraulic gradient naturally leads to vertical water movement, and this vertical water movement varies by hydrogeological conditions (O’Driscoll & Parizek, 2003; Rains, Fogg, Harter, Dahlgren, & Williamson, 2006; Weng, Giraud, Fleury, & Chevallier, 2002). The presence of a low-permeability soil layer (e.g., clay soils) impedes vertical water movement whereas promoting lateral groundwater flow through a perched zone (Pyzoha et al., 2008; Rassam et al., 2006). However, substantial vertical water movement actively occurs in soils with high-saturated hydraulic conductivity (e.g., sandy and silty soils).

Several attempts have been made to examine wetland hydrologic characteristics at the catchment scale for the coastal plain of the CBW using remotely sensed data (Huang, Peng, Lang, Yeo, & McCarty, 2014; Jin, Huang, Lang, Yeo, & Stehman, 2017; Lang & McCarty, 2009), hydrologic modeling (Lee et al., 2017), and geospatial data (Lang, McDonough, McCarty, Oesterling, & Wilen, 2012). These catchment-scale findings were mostly limited to changes in the surface water of wetlands. A study using a hydrologic model showed that wetland–groundwater interaction was a key hydrologic process affecting fluctuation of downstream flow (Lee et al., 2018). Denver et al. (2014) observed lateral groundwater exchange between depressional wetlands and adjacent upland areas. However, field measurements of wetland–groundwater interaction are limited, and the vertical interaction of wetlands and groundwater remains largely unknown for this region.

Wetland functional assessments among prior converted croplands, natural and restored wetlands, have been carried out extensively in the coastal plain of the CBW under the “Wetland” component of the U.S. Department of Agriculture Conservation Effects Assessment Project (CEAP-Wetlands), Mid-Atlantic Regional (MIAR) study (Lang et al., 2015) focused on the following: Water quality (Denver et al., 2014), plant biomass (McFarland et al., 2016), plant species (Yepsen et al., 2014), carbon storage (Fenstermacher et al., 2016), and dissolved organic matter (Hosen, Armstrong, & Palmer, 2018). Despite being a key area of research for wetland functional assessment, wetland–groundwater interaction has been poorly examined using in situ observations relative to other coastal regions, such as those in South Carolina (Pyzoha et al., 2008) and Florida (McLaughlin & Cohen, 2013).

Furthermore, the Chesapeake Bay (CB) is nationally important, as it is the largest estuary in the United States (CEC, 2000), and it is also listed as a RAMSAR wetland site of international importance (Gardner & Davidson, 2011). The CB is the first estuary for restoration in the United States, and similar efforts for other coastal regions have followed the CB restoration (Executive Order 13508, 2010). Regarding the important ecological value of the CB, monitoring physical processes that have been poorly examined (e.g., wetland–groundwater interaction) contributes to expanding our understanding, leading to developing appropriate and necessary restoration plans for this region.

As a part of the CEAP-Wetlands study, multiple wells and piezometers were installed to monitor the surface water level (SWL) and groundwater level (GWL) of wetlands situated within the mid-Atlantic coastal plain. In this study, we analysed observations obtained from a well and piezometer within the coastal plain of the CBW. These instruments were installed at two wetlands with distinctive subsurface soil characteristics. One wetland site includes a low-permeability soil layer characterized by an extremely low-soil hydraulic conductivity, whereas a fairly high-soil hydraulic conductivity underlies the other wetland. A wetland with a low-permeability soil layer can have a high potential to sustain surface water due to limited water loss by seepage compared with a wetland with a high-permeability soil layer (O’Driscoll & Parizek, 2003; Rains et al., 2006).

The goal of this study is to examine vertical wetland–groundwater interactions with respect to different subsurface soil characteristics on the coastal plain of the CBW. The two depressional wetlands described above with a low-permeability and high-permeability soil layer were selected. Although lateral groundwater flow is one of the key hydrologic components affecting wetland water levels, this study focused on the vertical interaction of depressional wetlands and groundwater, mainly due to limited observation points along a horizontal gradient. We, first, compared the similarity in water level dynamics over time (referred to as consistency, hereafter) between the SWL and GWL for the two wetlands to test the hypothesis that the consistency between the SWL and GWL is positively proportional to the saturated hydraulic conductivity. Then, the magnitude of the vertical hydraulic gradient between the SWL and GWL was compared between the two wetlands
using cross-correlation analysis (see Section 2.3). Finally, the wetland hydroperiod (i.e., the total time of surface water inundation or saturation) between the two wetlands was compared to examine how subsurface soil characteristics affect wetland hydrology.

2 | MATERIALS AND METHODS

2.1 | Study area and wetland characteristics

The two wetland study sites are located within the coastal plain of the CBW (Figure 1). This area is characterized by relatively flat topographic relief (Lang et al., 2012) and a humid temperate climate with an annual precipitation of 1,200 mm (Ator, Denver, Krantz, Newell, & Martucci, 2005). Nearly half of the precipitation is lost via evapotranspiration, and the remainder infiltrates into groundwater or flows into nearby streams (Ator et al., 2005). A restored wetland (referred to as "wetland," hereafter) was examined for this study. Wetlands converted to croplands have been restored under the CEAP-Wetlands, and those restored wetlands are mostly dominated by sedge, grasses, and herbs (McDonough, Lang, Hosen, & Palmer, 2015; Yepsen et al., 2014). According to the Soil Survey Geospatial (SSURGO) database, wetland #1 is underlain by a Whitemarsh silt loam soil with a low-saturated hydraulic conductivity (30–120 mm/day) at depths of 30–157 cm (Figure 2a). In contrast, the soil type at wetland #2 is a complex of Hammonton, Fallsington, and Corsica soil types with a fairly high-saturated hydraulic conductivity (90–61,000 mm/day). Penetration resistance was measured at depths of 10, 20, and 30 cm below the wetland bottom using a soil penetrometer (Eijkelkamp Hand Penetrometer Set, Eijkelkamp Soil & Water, the Netherlands). Observations indicated penetration resistance values ranging from 0.34 to 0.73 and from 0.08 to 0.29 (kPa) at wetlands #1 and #2, respectively (Figure 2b). Because penetration resistance is inversely proportional to the saturated hydraulic conductivity (Shafiq, Hassan, & Ahmad, 1994), the observed penetration resistance agreed well with the SSURGO database. Wetland #1 had high-penetration resistance with low-saturated hydraulic conductivity, whereas wetland #2 had low-penetration resistance with high-saturated hydraulic conductivity. Hydrogeologic data also showed that wetland #1 is within the coastal plain dissected upland characterized by fine sediments and limited infiltration, whereas wetland #2 is within the coastal plain upland characterized by coarse sediments that facilitate infiltration (Ator et al., 2005). Based on SSURGO data, observed penetration resistance and hydrogeologic data, a low-permeability soil layer exists at wetland #1, impeding the vertical water movement between surface and groundwater, whereas the interaction of surface and groundwater is fairly high at wetland #2.

2.2 | Monitoring data

The SWL and GWL values were monitored hourly from January 1, 2016, to December 31, 2016. A well and piezometer were adjacently installed at the wetland invert elevation (i.e., lowest land surface elevation on the wetland bottom) of each wetland to monitor the SWL and
Resistance was collected on July 11 (wetland #2) and 12 (wetland #1), respectively, for wetland #1 and WhA in Queen Anne’s County, Maryland for wetland #2. Soil penetration resistance was collected on July 11 (wetland #2) and 12 (wetland #1), respectively

We, first, investigated the consistency between the SWL and GWL. Before, increased interactions between surface water and groundwater. Strong consistency between the SWL and GWL (referred to as “GSG” hereafter, GSG = SWL - GWL) between the two wetlands was examined with the assumption that the wetland with the high-permeability soil layer would have a relatively consistent GSG compared with the one with the low-permeability soil layer. Accordingly, we calculated the daily forward difference between GSG at day +1 and day -1 (GSGday +1 - GSGday) over the monitoring period and compared the values between wetland #1 and wetland #2. We used the nonparametric Wilcoxon-signed rank test to evaluate whether GSG at wetland #1 is different from GSG at wetland #2 at the significance level of α = 0.05.

We hypothesized that the change in direction between the SWL and GWL would be less consistent in the wetland with a low-permeability soil layer. We calculated a measure defined as the forward difference between water levels (Water levelSWLday +1 - Water levelSWLday) for the two wetlands. When the daily change was extremely small (lower than 0.05 m), it was not included in this analysis. We counted the number of days with the same and different changes in the direction of the SWL and GWL. If the change in direction was the same for the SWL and GWL, the day was considered to indicate the same change in direction and vice versa. Because dry and wet conditions lead to the fall and rise of wetland water levels, respectively, we divided the data sets into dry and wet days for this analysis. This separation can help to compare the responses of the two wetlands with different climatic conditions. Wet (dry) days were defined as days with (without) observed precipitation.

A cross-correlation time-series analysis method was employed to calculate the time-lagged correlation of two wetland time-series data sets using the “tseries” module of the R program (Trapletti & Hornik, 2018). In the present study, GWL overlapped with lagged SWL to measure the similarity between GWL (observed at t) and SWL with positive (observed at t + n, where n is a time step) or negative (observed at t - n) lag times. A strong cross-correlation between the GWL and SWL with positive or negative lag time would indicate that the SWL leads the

GWL, respectively. The well and piezometer reached depths of approximately 0.9 and 3.0 m below the wetland invert elevation, respectively (Figure S1). Wells and piezometers were constructed using polyvinyl chloride (PVC) pipe with a diameter of 2.54 cm. Well screens were placed over the entire length of the wells and the bottom (30 cm) of the piezometers. The piezometer measured the groundwater pressure exerted by the water column, and the well directly measured the water column height. Pressure transducers (Campbell Scientific CS451, Campbell Scientific, Logan, Utah, United States) were deployed in the wells, and the piezometers were physically linked to the data logger (Campbell Scientific CR1000) of the second station. Hourly data were aggregated into daily data for analyses. Any outliers for each day were identified using the Tukey method (Tukey, 1977) and were excluded, and then, hourly data for each day were averaged. Hourly precipitation data measured by a tipping bucket rain gauge (Campbell Scientific TE525) were averaged. Hourly precipitation for each day.

Any outliers for each day were identified using the Tukey method (Tukey, 1977) and were excluded, and then, hourly data for each day were averaged. Hourly precipitation data measured by a tipping bucket rain gauge (Campbell Scientific TE525-L10) at each wetland were used for investigating the relation of water level variations to climatic conditions. Daily precipitation was calculated as the sum of hourly precipitation for each day.

### 2.3 Analytical method

For higher soil hydraulic conductivity, the water levels of the adjacent well and piezometer are closer to equilibrium. In other words, the SWL and GWL were more similar when soil hydraulic conductivity values were higher. Under natural conditions, weather and soil heterogeneity cause the SWL and GWL to rarely have the same value. However, the consistency between the SWL and GWL can be an indicator of how strong the interaction between surface and groundwater is. Strong consistency indicates a higher soil hydraulic conductivity and, therefore, increased interactions between surface water and groundwater. We, first, investigated the consistency between the SWL and GWL for the two wetlands over the monitoring period. Then, a daily gap between the SWL and GWL (referred to as “GSG” hereafter, GSG = SWL - GWL) between the two wetlands was examined with the assumption that the wetland with the high-permeability soil layer would have a relatively consistent GSG compared with the one with the low-permeability soil layer. Accordingly, we calculated the daily forward difference between GSG at day +1 and day -1 (ΔGSG = GSGday +1 - GSGday) over the monitoring period and compared the values between wetland #1 and wetland #2. We used the nonparametric Wilcoxon-signed rank test to evaluate whether ΔGSG at wetland #1 is different from ΔGSG at wetland #2 at the significance level of α = 0.05.

We hypothesized that the change in direction between the SWL and GWL would be less consistent in the wetland with a low-permeability soil layer. We calculated a measure defined as the forward difference between water levels (Water levelSWLday +1 - Water levelSWLday) for the two wetlands. When the daily change was extremely small (lower than 0.05 m), it was not included in this analysis. We counted the number of days with the same and different changes in the direction of the SWL and GWL. If the change in direction was the same for the SWL and GWL, the day was considered to indicate the same change in direction and vice versa. Because dry and wet conditions lead to the fall and rise of wetland water levels, respectively, we divided the data sets into dry and wet days for this analysis. This separation can help to compare the responses of the two wetlands with different climatic conditions. Wet (dry) days were defined as days with (without) observed precipitation.

A cross-correlation time-series analysis method was employed to calculate the time-lagged correlation of two wetland time-series data sets using the “tseries” module of the R program (Trapletti & Hornik, 2018). In the present study, GWL overlapped with lagged SWL to measure the similarity between GWL (observed at t) and SWL with positive (observed at t + n, where n is a time step) or negative (observed at t - n) lag times. A strong cross-correlation between the GWL and SWL with positive or negative lag time would indicate that the SWL leads the

![FIGURE 2](image-url) Comparison of soil characteristics between wetland #1 and wetland #2: (a) Saturated hydraulic conductivity from soil survey geospatial and (b) soil compaction from in situ observations. Note: For wetland #1, saturated hydraulic conductivity is 3,600 – 12,000 (depth of 0 – 5.1 cm), 350 – 1,200 (depth of 5.1 – 30.5 cm), 30 – 120 (depth of 30.5 – 157.5), and 120 – 12,000 (depth of 157.5 – 203.2 cm). For wetland #2, saturated hydraulic conductivity is 3,600 – 61,000 (depth of 0 – 5.1 cm), 690 – 1,600 (depth of 5.1 – 25.4 cm), 1,600 – 3,000 (depth of 25.4 – 81.3 cm), 170 – 2,200 (depth of 81.3 – 116.8 cm), and 90 – 1,300 (depth of 116.8 – 203.2 cm). Soil survey geospatial databases were derived from physical soil properties of HoB in Caroline County, Maryland for wetland #1 and WhA in Queen Anne’s County, Maryland for wetland #2. Soil penetration resistance was collected on July 11 (wetland #2) and 12 (wetland #1), 2017, respectively.
GWL or that the GWL leads the SWL, respectively. This approach can compute the strength of the vertical hydraulic gradient between the SWL and GWL. Regarding the downward hydraulic gradient and flux processes, the SWL is expected first to show changes, and then, the GWL will respond to these changes at the wetland where surface and groundwater are well connected. Thus, we hypothesized that the strongest correlation would be found between the SWL, with a negative lag time, and the GWL at the wetland with a high-permeability soil layer. The correlation would be weaker at a wetland with a low-permeability soil layer relative to one with a high-permeability soil layer. Hourly data were used for this analysis. If missing data were encountered, missing values were replaced with the observation from the hour before. There were 11 and nine missing data points for the GWL and SWL in wetland #2, respectively. Using the Box-Ljung test (R. CT, 2017), we confirmed that all input data are stationary (their mean and variance are steady over the monitoring period), which met the requirements of cross-correlation analysis.

Finally, we sought to explore wetland hydroperiod. Relative to a wetland with a high-permeability soil layer, a wetland with a low-permeability soil layer could sustain a more stable SWL regardless of the variation in the GWL due to limited water infiltration into subsurface layers. We hypothesized that the wetland with a low-permeability soil layer would show a longer hydroperiod compared to the wetland with a high-permeability soil layer. We compared the wetland hydroperiod between the two wetlands by counting the number of days with the SWL above the wetland invert elevation. Additionally, the number of days with GWL above the wetland invert elevation was simultaneously considered to examine the groundwater contribution to the wetland hydroperiod.

3 | RESULTS AND DISCUSSION

3.1 | Surface water and groundwater levels

The SWL and GWL over the monitoring period are presented in daily and monthly time steps (Figure 3). Wetland #1 showed low consistency between the SWL and GWL in daily and monthly time steps. Therefore, we focused on wetland #2 for further analysis.

![Figure 3](image_url)

**FIGURE 3** The surface water level and groundwater level in daily (a,b) and monthly (c,d) time steps. Note: The vertical bars indicate daily and monthly precipitation. Pink (wet periods) and green (dry periods) bands in (b) relate to Figure 9 (Section 3.4), and this figure relates to Section 3.2.
compared with wetland #2 (Figure 3). At wetland #1, the range in variations of the daily SWL and GWL over the monitoring period was from −0.4 to 0.4 m and −1.5 to 0.3 m, respectively. As indicated by the range of variations, the daily SWL at wetland #1 with a small range in variations (0.8 meter) was relatively consistent. However, the daily GWL at wetland #1 with a large range in variations (1.8 meters) indicated noticeable monthly changes, for example, an increase from January to February and a decrease from March to December (Figure 3c). In contrast, wetland #2 showed a smaller difference in daily variations, ranging between the SWL (1.3 meter) and GWL (1.4 meter) compared with wetland #1 (Figure 3b). In addition, the monthly patterns of the SWL and GWL were similar at wetland #2: Both were high from January to April, gradually decreased from May to August, and rose from September again (Figure 3d).

Inconsistencies between the SWL and GWL at wetland #1 are clearly seen in the scatter plot (Figure 4). Points at wetland #1 showed a disproportionate relationship between the SWL and GWL, which represented that the SWL was high, whereas the GWL was low (Figure 4a). As shown in Figure 3, the SWL was consistently high, whereas the GWL tended to decrease from March to December at wetland #1. Strongly correlated points at wetland #2 indicated that when the GWL was high (low), the SWL was also high (low, Figure 4b). Consistent with the point distribution, coefficients of determination (R²) were also greater at wetland #2 (0.95) compared with wetland #1 (0.5). The point within the red circle at wetland #2 shows that the greatest precipitation over the monitoring period at wetland #2 did not coincide with the overall linear trend. This was likely because an extremely heavy rain event (93 mm) caused an abrupt increase in the SWL, but a commensurate increase in the GWL did not occur. In effect, even wetland #2 became perched under extremely high rainfall conditions.

ΔGSG values over the monitoring period at wetland #1 were significantly higher than those at wetland #2 (p value < 0.01, Figure 5). The median values were 0.02 at wetland #1 and 0.008 at wetland #2. High inconsistencies between SWL and GWL at wetland #1 due to the low-permeability soil layer resulted in a high value of ΔGSG, whereas the relationship between the SWL and GWL at wetland #2 indicated high consistency, leading to a small ΔGSG. The findings shown in Figures 3–5 collectively indicate that wetland–groundwater interactions varied by subsurface soil characteristics on the coastal plain of the CBW.

### 3.2 Change in the direction of the SWL and GWL

Changes in the direction of the SWL and GWL are shown in Figure 6. Each plot was divided into four subportions (A, B, C, and D) to represent the days with the same and different changes in the direction of the SWL and GWL, separately. Subportions A and C indicate the days with different changes in direction (A: increasing SWL and decreasing GWL; and C: decreasing SWL and increasing GWL), and subportions B and D indicate the days with the same changes in direction (B: increasing SWL and GWL; and D: decreasing SWL and GWL). Wetland #1 indicated a greater number of days with different changes in direction compared with wetland #2 (Figure 6). Wetland #1 had 44 days with different changes in direction (the number of points in A and C), and those days accounted for 18% of the total days (Table 1). In contrast,
only 10 days were shown to have different changes in direction at wetland #2. As hypothesized, the limited interaction of the SWL and GWL at wetland #1 resulting from the low-permeability soil layer likely led to a greater number of days with different changes in direction between the SWL and GWL relative to wetland #2. The greatest difference in the change in direction between the SWL and GWL at wetland #1 was shown on dry days with a decreased SWL and an increased GWL (subportion C). This case was observed for the dry days following heavy precipitation events (Figure 7a, blue points in Figure 4a). The SWL decreased for a few days after precipitation, whereas the GWL increased (Figure 7a). Lateral groundwater from contributing areas likely flowed into wetland #1, leading to an increase in the GWL for a few days after precipitation. In contrast, both the SWL and GWL at wetland #2 decreased during the same period due to high-saturated hydraulic conductivity (Figure 7c). The same case (i.e., decreasing SWL and increasing GWL, subportion C) was also observed at wetland #1 on wet days with light rain following a heavy rain event (Figure 7b, green points in Figure 4a). Rain events with a small amount of precipitation might not be sufficient to increase the SWL, but the GWL increased, likely owing to lateral groundwater flow from contributing areas (Figure 7b), as shown in Figure 7a. During the same period, the responses of the SWL and GWL to climatic conditions were consistent at wetland #2 (Figure 7d).

Interestingly, two consecutive rain events with heavy precipitation (start day and the following day) led to large increases in the SWL at wetland #2 (Figure 7c.d). However, an increase in the SWL occurred only for the first rain event at wetland #1 (Figure 7a,b). Minimal water infiltration through the low-permeability soil layer at wetland #1 likely caused the wetland to hold a large amount of surface water and, therefore, reach its maximum SWL at the first heavy rain. As a result, an increase in the SWL at wetland #1 did not occur during the following rain event. When the amount of precipitation was extremely small (0.3 mm), the SWL and GWL decreased at wetland #2 (Figure 7d).

### Table 1

The number of days with a different change direction of the surface water level and groundwater level

| Site   | Dry point in A | Dry point in C | Wet point in A | Wet points in C | Total (%) |
|--------|----------------|----------------|----------------|-----------------|-----------|
| Site #1| 6              | 24             | 5              | 9               | 44 (18)   |
| Site #2| 2              | 3              | 1              | 4               | 10 (6)    |

Note. The percentage value in parentheses denote the proportion of the day with a different change direction to the total days.

3.3 | Cross-correlation time-series analysis

The strongest cross-correlation between the SWL and GWL, of 0.98, was observed at wetland #2 (Figure 8). The response to precipitation events occurred first in the SWL and then in the GWL after 10–18 hr, which clearly indicated a strong vertical gradient between the SWL and GWL (Figure 8a). The cross-correlation between the SWL and GWL was much weaker ($R = 0.7$) at wetland #1, with no observed lag period for responses (Figure 8b). These findings were indicative of a very weak hydraulic gradient between the SWL and GWL at wetland #1 relative to wetland #2. Considering the downward hydraulic gradient and soil heterogeneity, any variations shown in the SWL would eventually appear in the GWL after a specific time that differs by site physical characteristics. Thus, this finding confirmed that the SWL and GWL were well connected at wetland #2, whereas the connection of the SWL with GWL at wetland #1 was limited due to differences in subsurface soil characteristics.

At wetland #2, the cross-correlation pattern and lag time at which it peaked differed by climate conditions (Figure 9). During dry periods (pink band in Figure 3), the correlation of SWL and GWL with no lag time was the strongest, and the correlation of SWL with negative lag

![Figure 6](https://example.com/fig6.png)

**Figure 6** Daily change in the surface water level and groundwater level on wet and dry days at wetland #1 (a) and wetland #2 (b). Note: Days with a daily change <0.05 m are not considered. One hundred twenty-two and 198 days are not included in (a) and (b), respectively. A dry (wet) day is defined as a day without (with) observed precipitation. The number of dry and wet days are 174 and 70 in (a) and 114 and 54 in (b), respectively. The number of dry and wet days for each portion is available in Table S1. To clearly show the differences between wetland #1 and wetland #2, the range of axes was limited from −0.2 to 0.3 m, and therefore, a few extreme observations are not shown here. All data are shown in Figure S2.

![Figure 7](https://example.com/fig7.png)

**Figure 7** The range of axes was limited from −0.2 to 0.3 m, and therefore, a few extreme observations are not shown here. All data are shown in Figure S2.
time and GWL was the strongest during wet periods (pink bank in Figure 3). This was because precipitation caused the downward water movement from surface to groundwater, leading to varying responses of the SWL and GWL. However, downward water movement rarely occurs during dry periods. The degree of change in water levels during wet periods was rapid and large and was measurable by our sensors. In contrast, the timing and magnitude of changes in water levels during dry periods were extremely slow and small, respectively, resulting in an extremely small change in hydraulic head differential that was not detectable. Thus, no lag between the SWL and GWL could be measured during the dry period.

3.4 | Wetland hydroperiod

Contrary to our hypothesis, the two wetlands exhibited a long hydroperiod. SWLs for the two wetlands were found to exceed the wetland invert elevation for more than 320 days out of the year (Figure 10). Similar to wetland #1, the SWL was mostly higher than the wetland invert elevation at wetland #2, although substantial infiltration at wetland #2 was expected to cause a short hydroperiod. However, the groundwater contribution to the wetland hydroperiod differed between the two wetlands. GWL was higher than the wetland invert elevation for 48 and 215 days out of the monitoring period at wetlands #1 and #2, respectively. It can be deduced that wetland #1 had a high capacity to sustain surface water with minimal groundwater contribution compared with wetland #2.

The unexpectedly long hydroperiod of wetland #2 might be attributed to the short monitoring period or lateral groundwater flow from contributing areas. Short-term groundwater observations could be inadequate to generalize wetland inundation patterns at wetland #2. Lateral subsurface flow from surrounding areas could be one factor causing the observed seasonal changes in the horizontal groundwater direction (Denver et al., 2014). In conjunction with additional sensors, data collection over a longer period of time could help elucidate the role of lateral groundwater movement and, therefore, the contribution of lateral groundwater water to the long hydroperiod of wetland #2.

4 | IMPLICATIONS AND LIMITATIONS

The strong relationship between GWL and wetland inundation at wetland #2 demonstrates the strong sensitivity of wetland hydroperiod to GWL within the surficial aquifer. Ditch drainage is prevalent in the region and can readily draw down surficial GWLs adjacent to a ditch. The use of irrigation, primarily for corn and soybean production, has
increased markedly within the last 30 years. As an example, over a 20-year period, irrigated croplands in Maryland increased from 162 to 283 km², leading to substantial groundwater withdrawal, usually from the surficial aquifer (Wolman, 2008). Increased water use by crops via increased evapotranspiration may lower GWLs, which may further amplify the downward vertical gradients and subsequently dewater wetlands faster. Our findings help to characterize wetland hydrologic dynamics and potential responses to physical conditions and human activities. This information can be used to better develop watershed management plans that preserve wetland ecosystem services.

Based on the observed hydrological processes (Figure 7), it is expected that a wetland with a low-permeability soil layer might be less effective at mitigating peak flows from consecutive heavy rain events compared with a wetland with a high-permeability soil layer. Limited water infiltration from wetland #1 led the wetland to reach the maximum water storage in one heavy rain event; therefore, the SWL of wetland #1 rarely changed in response following heavy rain (Figure 7 ab), potentially causing spillage from wetland #1 during subsequent heavy rain events. However, the SWL of wetland #2 continued to increase in response to subsequent heavy rain events (Figure 7cd). High infiltration at wetland #2 quickly drained water within the wetland into the groundwater system, sustaining the water-holding capacity. Therefore, wetland restoration plans for areas that frequently experience heavy rain events should consider subsurface soil characteristics to effectively control flooding conditions.

In this region, GWLs are known to exhibit seasonal variations. For example, a high level during early spring, a declining pattern from early summer (June) to late fall (November), and increasing the levels during the winter (Fisher et al., 2010). Responding to this pattern, inundated

FIGURE 8 Cross-correlation of the lagged surface water level and groundwater level at (a) wetland #1 and (b) wetland #2. Note: The cross-correlation computed the relationship between SWLt+lag and GWLt. Note: Red points indicate the highest cross-correlation values between the lagged SWL and GWL. Note the differing ranges of the vertical axes between the two wetland figures: 0.66–0.70 for (a) and 0.94–0.98 for (b)

FIGURE 9 Cross-correlation of the surface water level and groundwater level during (a) dry and (b) wet periods at wetland #2. Note: Dry (September 3rd–18th) and wet (July 28th–Aug 22nd) periods are shown as green (n = 383) and pink (n = 622) bands in Figure 3, respectively. Note: Red points indicate the highest cross-correlation values between the lagged surface water level and groundwater level. Note the differing ranges of the vertical axes between the two wetland figures: 0.67–0.98 for (a) and 0.52–0.91 for (b)

FIGURE 10 The number of days when the surface water level or groundwater level exceeded the wetland invert elevation. Note: There were 118 and 116 wet days (daily precipitation > 0) at wetlands #1 and #2, respectively
wetlands are frequently observed during early spring (Huang et al., 2014). Overall, the SWL and GWL at wetland #2 were consistent with the local seasonal pattern observed in the study of Fisher et al. (2010). However, the SWL and GWL at wetland #1 were less consistent with previous observations than those at wetland #2. Because wetland #2 and the groundwater gauge location in Fisher et al. (2010) are in the same hydrogeologic region (coastal plain upland), wetland #2 might better compare with previous observations. Contrary to prior observations, the SWL at wetland #1 did not show a sharp increase and decrease during the summer season due to the presence of a low-permeability soil layer, and the GWL at wetland #1 was low during the winter season. Regarding observed seasonal changes in groundwater direction for this region (Denver et al., 2014), lateral subsurface flow at wetland #1 might lead to a low GWL during the winter season. As mentioned above, evidence for the interaction of lateral groundwater flow and wetland conditions was limited in this study due to the lack of supporting measurements. Thus, the installation of additional wells and piezometers is essential for improved understanding of wetland–groundwater interactions in this region.

In addition to a low GWL at wetland #1 during the winter season, several hydrological processes observed in this study offered clues to the impact of lateral groundwater flow on wetland water levels as follows: The sudden increase in the GWL in February relative to the small amount of precipitation at wetland #1 (Figure 3c), the increased GWL with decreasing SWL at wetland #1 (Figure 7ab), and the long hydroperiod of wetland #2 (Figure 10). As noted in the previous studies (McLaughlin & Cohen, 2013; Pyzoha et al., 2008), lateral groundwater flow is a key driver that impacts the fluctuation of wetland water levels in the coastal plain region. Thus, examination of lateral groundwater flow is essential to accurately interpret wetland hydrologic processes and to understand wetland behaviors in this region. Additional sensors will be implemented on the coastal plain of the CBW under ongoing CEAP-wetland projects. With these new measurements, a future study will explore lateral groundwater impacts on wetland hydrology.

5 | CONCLUSIONS

This study demonstrates distinctive patterns of the SWL and GWL between two wetlands with differing subsurface soil hydraulic conductivity conditions. The wetland with a low-permeability soil layer (wetland #1) showed low consistency (similarity in water level dynamics over time, $R^2: 0.50$) between the SWL and GWL, whereas high consistency ($R^2: 0.95$) was seen at the wetland with a high-permeability soil layer (wetland #2). A cross-correlation time-series analysis further demonstrated the strong vertical hydraulic gradient between the SWL and GWL at wetland #2, although there was limited vertical connection between the two water levels at wetland #1. This was likely caused by the low-permeability soil layer at wetland #1 that limited vertical water recharge to groundwater. As a result, wetland #1 did not reflect substantial groundwater contributions to maintaining the hydroperiod, whereas the hydropetiod of wetland #2 heavily relied on groundwater contributions. This is the first study to document the dependence of wetland hydrologic characteristics on subsurface soil characteristics within the nationally and internationally important coastal plain of the CBW. This study is unique because it documents high-temporal resolution water levels both near the surface and at deeper depths. By pairing two sites in close proximity but with different subsurface soil characteristics, the side-by-side results document the differing hydrologic dynamics brought on by the differences in subsurface soil characteristics. Therefore, the findings of this study contribute to the understanding and interpretation of various wetland ecosystem services for this region and the critical importance of subsurface soil characteristics to wetland inundation behavior.

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Additional supporting information may be found online in the Supporting Information section at the end of the article.

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