Use of the Effective Monthly Recharge model to assess long-term water-level fluctuations in and around groundwater-dominated wetlands


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Effective Monthly Recharge ($W_{\text{em}}$) calculations use historical weather data to estimate monthly-scale water level changes in precipitation-and-groundwater-driven wetlands. This time-weighted water-budget procedure relates first-of-the-month hydraulic heads measured in a monitoring well or small pond with precipitation and evapotranspiration data for preceding months and generates a regression equation used to estimate historic water levels. This study developed an enhanced procedure more robust than used with previous $W_{\text{em}}$ studies. Two data sets of water-table fluctuations in humid-temperate southeastern Virginia (U.S.A.) allowed verification of the model procedure—a 30-year record from a shallow well maintained by the U.S.G.S., and a 6.5-year record from a mitigation wetland measured before and after construction. Analyses of Predicted Heads and Observed Heads at both sites indicate that the $W_{\text{em}}$ model can replicate reasonably the seasonal patterns of water-table fluctuations and the range of values of hydraulic heads at a monthly scale. Within the limitations set by the assumptions of the procedure and the range of water fluctuations during the calibration period, $W_{\text{em}}$ calculations may be used to generate synthetic hydrographs for periods with appropriate weather data. Analyses of two sites in Missouri and Nebraska (U.S.A.) suggest that the $W_{\text{em}}$ procedure may prove useful also in climatic regions with relatively strong seasonal forcing, but additional testing is needed to verify the range of model applicability. These reconstructions could support long-term decisions in the management of wildlife habitats or design of mitigation wetlands.

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1. Introduction

An accurate history of water table elevations at a given site provides valuable information to wetland scientists, particularly in the management of wildlife habitat within groundwater-driven wetlands and in the siting and design of constructed wetlands. For many sites the most useful information concerns the magnitude and frequency of relatively extreme hydrologic conditions, particularly droughts. However because evaluating subsurface water sources at potential wetland sites requires more time and a different work effort than surface water calculations, the current industry practice for calculating monthly-scale water budgets (e.g. USACE, 2004) for mitigation wetland design often coarsely approximates or disregards groundwater flux through the site (e.g. Pierce, 1993; Favero et al., 2007). There is need for monthly-scale models that generate design-grade approximations of groundwater flux available to small wetlands.

Long-term observation-well records provide the best assessment of groundwater levels at a site over time but few sites have such data available. Previous workers proposed using heads (Socolow et al., 1994) or stream flow measured in reference sites (Zampella et al., 2001) from neighboring areas to approximate groundwater levels. However the limited number of stream-gage and well sites that have long-term records restricts application of these techniques.

Some models based on physical principles used to approximate groundwater fluctuations in and around wetlands focus on relatively rapid rainfall-runoff relationships and processes that produce daily- or hourly-scale fluctuations at the catchment-scale (e.g. TOPMODEL, Beven and Freer, 2001) or the hillslope-scale (e.g. Weiler and McDonnell, 2004). For watersheds in a humid-temperate area, Dripps and Bradbury (2007) quantify daily

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recharge rates by use of water-balance calculations that use meteorological, topographic, soil, and land use data; they estimate spatial and temporal patterns of groundwater recharge by combining such calculations with GIS techniques. Analyses of wetlands based on MODFLOW (Harbaugh, 2005) incorporate Darcy’s Law and adjustable boundary conditions to simulate 2-D or 3-D flow through time (e.g. Winston, 1996; Restrepo et al., 1998; Gerla, 1999; Bradley, 2002; Galvão et al., 2010). Some MODFLOW models, WETLAND (Lee et al., 2002) and WETSAND (Kazezyilmaz-Alban et al., 2007), simulate water-quality parameters as well as surface and subsurface flows. Another useful approach, DRAINMOD (Skaggs et al., 2012), uses hourly rainfall and values for daily temperatures, potential evapotranspiration (PET), volumetric water contents, and effective soil water suction at the wetting front. Soil drainage rate calculations depend upon lateral distances to drainageways and the local relief of the system. Designed principally for hilltop and sideslope settings, DRAINMOD models calibrated for a given site and time period can generate hydrographs with daily water-balance elevations for other time periods given appropriate weather data (Skaggs et al., 2012).

A significant goal of many physical models can be to evaluate interactions between many processes that affect water movement through soil and surficial aquifers. When used to understand complex relationships the parameters must be calibrated using numerous field measurements and the results validated to assess errors in the predictions of the calibrated model. In contrast, when used for engineering design, the goal of the analysis may be to estimate how the future system will operate over the range of natural variability, particularly during the near-extreme conditions. Precision in replicating fine-scale responses during mid-range conditions is not a high priority when models are used for design purposes. For example, permits for mitigation wetlands commonly require monthly water-budget calculations for three years representing wet, normal, and dry conditions (Pierce, 1993; NRCS, 1995; USACE, 2004).

The original Effective Monthly Recharge \( (W_{em}) \) approach was developed as a design-grade tool using water-budget calculations to allow estimation of groundwater fluctuations based upon weather data sets that began in the 1800s (Whittecar and Johnson, 1990; Whittecar and Lawrence, 1999). The following explanation details how the present, more robust, version of the \( W_{em} \) index is calculated. In addition, the present study evaluates this version in three ways: (1) validate the model using a long well record from Suffolk, Virginia; (2) test whether the model can be used with a short calibration period using data from a mitigation wetland in southeastern Virginia; and (3) assess model performance at two sites with larger amounts of evapotranspiration and greater interannual variability (Steele, Missouri, and Crescent Lake National Wildlife Refuge, Nebraska) (Fig. 1).

2. Methods

Generation of a synthetic hydrograph for the water table at a site by using historical weather records requires five steps (Dobbs, 2013).

2.1. Step one—collect head data

Select measured heads that represent the water table fluctuations in a relatively small ground-water-driven system, one without substantial surface water flow into or out of the study site. Ideal measurements are taken in monitoring wells or groundwater-through-flow ponds on the first day of each month and have no influence of recent rainfall. For each month where recent rainfall generates a sizable rise in the first-of-the-month water levels, consider removing that month from the calibration process. Measure the wells for at least 8 successive months, but multi-year data sets are best. For optimal results these months should include a wide range of moisture conditions ranging so that the water table varies as much as possible.

2.2. Step two—collect weather data

Gather daily precipitation and temperature data from the nearest recording station available. Any estimate of potential evapotranspiration may be used to calculate the \( W_{em} \) index, but note that different methods require varying types of data which may not be available for the location or time period of interest. For example the Thorneithwaite (1948) method often proves to be the most useful for hydroperiod reconstructions during long historical periods because it requires only monthly air temperature measurements which are available for the long time periods. Other estimation procedures, including FAO Penman-Monteith (e.g. Jensen et al., 1990), may provide daily resolution but can require solar radiation data that are collected at fewer weather stations for only recent decades.

2.3. Step three—calculate \( W_{em} \) time series

Calculate monthly recharge \( (W_{mo}) \) for every month throughout the period of hydraulic head data collection. Monthly recharge \( (W_{mo}) \) equals the total monthly precipitation \( (P_{mo}) \) less the total monthly evapotranspiration \( (ET_{mo}) \):

\[
W_{mo} = P_{mo} - ET_{mo}
\]

With that list of \( W_{mo} \) values, calculate the Effective Monthly Recharge index \( (W_{em}) \), the time-weighted sum of the recharge during a series of prior months:

\[
W_{em} = \sum_{d=1}^{N} W_{mo} \times D^{d-1}
\]

where \( N \) = number of prior months, and \( D \) = a decay factor <1 (often between 0.99 and 0.50).

2.4. Step four—calibrate \( W_{em} \) variables \( N \) and \( D \)

With the time series of monthly data produced using a given \( N \) and \( D \), use a linear regression analysis of \( W_{em} \) index (calculated) vs. Observed Head (measured) values paired by month to produce a coefficient of determination \( (R^2) \). Repeatedly recalculate the \( W_{em} \) index using different combinations of \( N \) and \( D \) values and generate the \( R^2 \) values for each of those time series. Construct a matrix of \( R^2 \) values that prove to be statistically significant to determine the \( N \)-and-\( D \) combination that produces the largest \( R^2 \) value.

2.5. Step five—generate the synthetic hydrograph

With the selected \( N \) and \( D \) values, and with sufficient weather data, use values generated from Eq. (2) to calculate the \( W_{em} \) index for any month in the past. Use the best regression equation (identified in Step Four) to calculate a Predicted Head for each of the calculated \( W_{em} \) index values. Plot the pattern of Predicted Heads over time to visualize the synthetic hydrograph. In many situations, this hydrograph can represent groundwater variations in systems driven solely by precipitation and ET.

3. Model assumptions

Users must recognize the assumptions inherent in the \( W_{em} \) index calculations and decide if it is an appropriate tool for their site.
For example, the index was developed for analyses of groundwater-and-precipitation-driven toeslope wetlands and ponds in highly permeable landscapes. The calculations presume all precipitation falling on the hillside upland of the wetland infiltrates the soil and generates no runoff. The calibration procedure in this empirical approach does not require quantification of the many potential controls on runoff generation. Instead it compares the combined effects of infiltration controls across the adjacent hillside over time with the actual response of groundwater levels measured on-site upland of the wetland. For time periods when the proportion of infiltration and runoff remain relatively constant over time, this method to estimate temporal changes in groundwater levels may be acceptable for planning purposes.

A second limiting characteristic of the \( W_{em} \) index is that it was designed as a monthly-scale value, to be used as a planning tool providing comparisons over multiple seasons and years. Because solar radiation data needed for the more recently-developed PET calculations were not collected regionally before 1960, only monthly Thornthwaite ET estimates (based solely on temperature) are available for earlier periods. Because the original \( W_{em} \) model was designed to incorporate weather records that may extend back to the 1800s, the index is calculated at monthly intervals.

Another assumption is that the effect of precipitation during a given month on groundwater levels in later months diminishes over time exponentially, as described by the power law in Eq. (2). That assumption follows from the use of exponential equations to describe the decline of recession curves in hydrographs of soil moisture, of groundwater levels, and of stream base flow after rainfall events (e.g. Linsley and Kohler, 1951; Wisler and Brater, 1959; Singh and Stall, 1971).

4. Model validation—USGS well 58B 13, Suffolk, Virginia

The best data set for calibration and verification of the \( W_{em} \) procedure would be a multi-decade record of monthly water levels measured in a sandy unconfined aquifer recharged exclusively by precipitation and not affected meaningfully by pumping from nearby wells. Also essential would be data from an adjacent weather station recording for the same time period. Daily water levels collected by the U.S. Geological Survey (USGS) at well 58B 13 in Suffolk, Virginia from 1982 to 2012 and weather data from the Suffolk municipal airport 5 km away met these needs.

The well sits on an isolated interfluve (Fig. 2) underlain by dissected marine sediment of the Atlantic Coastal Plain. Loamy fine sand and sandy loam soil profiles developed across this broad, flat-topped hill have moderate permeability (Reber et al., 1981). Well 58B 13 penetrates 4.5 m (15 feet) into the surficial aquifer. Seasonally, depth to water in the well varies between 1 and 4 m (3–13 feet) (USGS, 2013). Weather data recorded at the Suffolk Municipal Airport records included daily precipitation, daily air temperature values, wind speed, and dew point. Solar radiation data came from the Norfolk International Airport. Estimates of total monthly evapotranspira-
Table 1
Effective Monthly Recharge Model calibration period results for Suffolk, Virginia site using FAO Penman-Monteith and Thornthwaite PET.

<table>
<thead>
<tr>
<th></th>
<th>FAO P-M PET</th>
<th>Thornthwaite PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>D</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.82</td>
<td>0.81</td>
</tr>
<tr>
<td>NSE</td>
<td>0.73</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Note: N = number of months prior, D = decay factor, \(R^2\) = coefficient of correlation, NSE = Nash-Sutcliffe Efficiency.

Table 2
Comparison of highest coefficients of determination (\(R^2\)) for regressions (\(W_{em}\) index values v. Observed Monthly Head) using both filtered and unfiltered data sets for 2010–2012 at Suffolk, Virginia site.

<table>
<thead>
<tr>
<th>Calibration Period</th>
<th>Unfiltered for prior rainfall</th>
<th>Filtered for prior rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010–2012 (FAO Penman- Monteith PET)</td>
<td>0.81</td>
<td>0.82</td>
</tr>
<tr>
<td>2010–2012 (Thornthwaite PET)</td>
<td>0.81</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 3
Coefficients of determination \(R^2\) and Nash-Sutcliffe Efficiency (NSE) values comparing Predicted Head with Observed Head for separate decades and the full 30-year historical record at the Suffolk, Virginia site.

<table>
<thead>
<tr>
<th>Years</th>
<th>Thornthwaite PET</th>
<th>FAO Penman-Monteith PET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(R^2)</td>
<td>NSE</td>
</tr>
<tr>
<td>1980s</td>
<td>0.73</td>
<td>0.65</td>
</tr>
<tr>
<td>1990s</td>
<td>0.73</td>
<td>0.70</td>
</tr>
<tr>
<td>2000s</td>
<td>0.68</td>
<td>0.66</td>
</tr>
<tr>
<td>1982–2012</td>
<td>0.70</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Discussion

The \(W_{em}\) analysis of weather data from 1982 to 2012 generated a synthetic hydrograph for the Suffolk, Virginia site (Fig. 4) which portrays seasonal rhythms and the approximate range of values of the groundwater hydrograph. Even a casual examination, however, of Predicted Heads and the Observed Heads suggests that the data match better during some periods than during others. For any given month the Predicted Heads can be inaccurate by half a meter or more; average monthly Mean Absolute Errors for the 31-year reconstructions using Penman-Monteith and Thornthwaite PET were 40 cm and 26 cm, respectively. Quantitative comparisons suggest two factors cause the largest deviations—the method of PET estimation, and exceedingly heavy rainfall.

Differences between Predicted and Observed Head values arise in part from the PET estimates. Data in Table 3 compare results during for three separate decades. Using the ranges suggested by Skaggs et al. (2012) for monthly models, these NSE values (0.65–0.70) for most of the comparisons indicate “good” or “adequate” results when using Thornthwaite but are mostly “inadequate” (e.g. NSE <0.4) when using Penman. Predictions were most accurate when using the Thornthwaite method of estimating ET for the 31-year reconstruction (Mean Absolute Error = 0.27 m). Overall, under-predictions were much more common (72% of 31-year reconstruction) when using Penman-Monteith and over-predictions predominate (53% of 31-year reconstruction) when using Thornthwaite. The annual range of monthly PET (Fig. 5) is greater with the Thornthwaite method, where monthly PET is governed solely by temperature.

Over-predictions were also common following months with tropical cyclones (e.g. summer-fall). Although the cultivated soils at this site are moderately permeable they would not have been able to absorb much of the rain during those months.

In addition to potential shortcomings of PET estimates, accuracy may develop because the model presumes the water-table elevation declines linearly through time, controlled by variations in recharge and by a steady rate of groundwater outflow. However, because this site is in the middle of a fluctuating groundwater mound where water in the surficial aquifer seeps away in multiple directions, the rate of groundwater outflow, and thus water-table elevation decline, slows as the lateral gradients decrease during dry periods. During other months, causes of model inaccuracy may include timing of rainfall and temperature fluctuations (the model simplistically assumes uniform daily recharge throughout the month) and differences in precipitation and other weather conditions between the weather station and the study site.

This analysis of the well and weather data for the site in Suffolk, Virginia demonstrate that with the Effective Monthly Recharge (\(W_{em}\)) index one can generate a synthetic hydrograph of groundwater levels which approximates the general magnitude and timing of fluctuations in heads over time. To use this technique in wetland design, cost-conscious users want the calibration period to be as short as possible. In order to assess factors that made for the most effective calibration data set, we analyzed an eight-year hydrologic record from a constructed wetland in southeastern Virginia.

5. Model assessment—mitigation wetland, Virginia Beach, Virginia

Wetland scientists with the Virginia Department of Transportation (VDOT) assessing a potential site for a constructed wetland requested a hydrologic analysis of a former sand mine on land
owned by the U.S. Navy (Fig. 6). They planned to re-grade the uphill sides of two adjacent water-filled pits into a single slope that would intercept the groundwater draining towards the site. In their design, water would discharge out of the broad seepage face, move overland down to the ponds, and exit the system on its lower end via an overflow pipe and groundwater seepage. VDOT personnel wanted a quantitative analysis of groundwater input into the site in order to obtain approval of this proposed plan. To address these issues for this sandy 0.56 ha site, we analyzed the hydrogeological setting, collected water-level data for seven months (May–November 1999) from a network of monitoring wells and staff gages, and evaluated the response of those wells to rainfall using the original versions of the Wem equations. Following approval of the plan by the U.S. Army Corps of Engineers and completion of the mitigation wetland, Navy personnel continued to collect monthly head data from ponds and monitoring wells (January 2000 to February 2007).

Oceana Ridge formed as a barrier island complex during the Late Pleistocene (Mixon et al., 1989; Scott et al., 2010) and now remains as a broad sandy ridge that crests locally at approximately
soils
ular
approximately
wetlands.

Fig. 6. Topographic map of Oceana Ridge area, Virginia Beach, Virginia. This Late Pleistocene barrier island complex is now a broad sandy ridge that crests locally at approximately 6 m. Sandy soils are marked with uniform stiple; mined land, irregular stiple. Study area, denoted by dashed line, contains ponds and constructed wetlands. Contours (feet) after USGS Princess Anne, Virginia quadangle (1:24,000); soils information after Hatch et al. (1985).

6 m elevation (Fig. 6). Well-drained sandy loam soils with rapid to moderately rapid permeability mantle the surface of the 16-ha groundwater-catchment area uphill of the study site (Hatch et al., 1985). Most of the drainage basin surface consists of mowed fields or pine and hardwood groves planted to restore mine scars.

Head measurements came from 14 monitoring wells and staff gages hand-measured approximately monthly between May 1999 and August 2000 prior to and during construction. Analyses of these data revealed that groundwater passes through and below the study site from a local ridge crest towards a natural swale with an artificially-deepened drain along the northern end of the study site. Fig. 7 illustrates groundwater levels and seepage directions for the site after two wet months in 1999. Post-construction head measurements were collected monthly from the remaining wells and staff gages, as soon after the first of each month as practical, from September 2000 to March 2007.

Weather data from Oceana Naval Air Station 1 km away and Observed Head data from one well (#10) were used to determine the ability of the \( W_{em} \) model to predict monthly head elevations during an 8-year period (1999–2007) with observation well data. PET rates were estimated with both Thornthwaite and FAO Penman-Monteith methods.

Well #10 data reflected water table fluctuations immediately uphill of the constructed wetland, at the lower end of a long gentle slope (Fig. 7). To generate the Observed Head data set for Well #10, we used all head measurements except those taken more than 7 days after the first of the month, or those taken on days when more than 8 mm of rain fell since the first of that month. These restrictions were based on examination of rainfall events and subsequent water table responses during dry periods.

Calibration procedures to determine the N and D values to use in the Effective Monthly Recharge equation for predicting monthly heads followed the revised techniques described above. For time periods where measured head data existed, we calculated Nash–Sutcliffe Efficiency values to compare Observed and Predicted Heads.

To compare the predictive power of the \( W_{em} \) index developed for different calibration periods with various ranges of measured head, we clustered all of the available Observed Head data into four calibration periods—3 subsets (A, B, C) of post-construction data (26 mo each), and the complete post-construction observation period (79 mo) (Tables 4 and 5). Before filtering for rain effects, the periods of the three post-construction subsets had the same number of months (Table 5). Using these data sets, we developed calibrated \( W_{em} \) equations for these four periods; the NSE rating in Table 4 describes the ability of each equation to reproduce Observed Head elevations for the entire post-construction observation period.

5.1. Discussion

Data in Table 4 show there are robust R² values between \( W_{em} \) index and Observed Heads for many of the calibration periods. The 6.5-year hydrograph of Predicted Heads generated using the calibration equations developed using the 79-month "entire post-construction" data set (R² = 0.74; NSE = 0.64) (Fig. 8) best mimics the Observed Heads for the entire study period (1999–2007). The average absolute relative error between these Predicted and Observed Heads was 0.11 m for both the Thornthwaite- and Penman-Monteith-based data sets. As at the Suffolk site described above, the model performed poorly following months with heavy rains (e.g. September 1999 with 38.8 cm).

High R² values do not necessarily reflect an ability of that calibration equation to reproduce head elevations observed at other times. Note in Table 5, NSE values generally increase as the range of the water levels during the calibration periods increases. These data suggest that the range of water levels during a given calibration period can influence the predictive ability of the \( W_{em} \) equation developed for that period; this trend is shown graphically in Fig. 8 in the degree of match between the Observed Heads and those predicted by the different calibrated equations. Examination of these hydrographs reveals that during each 26-month calibration period, the Predicted Heads calculated for that period mimic the Observed Heads closely, even those calibrations that produce poor NSE values when used to predict the rest of the Observed Heads. These analyses suggest that at some sites, calibrating the model for a time period where the range of water levels is relatively small may result in a calibration equation unable to adequately describe larger water table fluctuations.

The \( W_{em} \) model developed for a site could serve as a planning tool to help assess whether enough groundwater may be available
to support a future mitigation wetland. As an example, we used the best-calibrated equation from the post-construction periods to predict head elevations for a 30-year period from 1977 to 2007 (Fig. 9). With Oceana station weather data we calculated Wem index values for that period, which were converted to Predicted Heads with the regression equations generated using FAO Penman-Monteith PET.

In order to use this synthetic hydrograph for a historical period to assess future groundwater flow into the site, one must assume that the range of weather conditions and general frequency of their changes during the future will generally mimic those of the period of the hydrograph. The user must also know what wetness conditions existed at the study site during the calibration period. For example, at the Oceana site, when water levels in Well #10 were lowest (e.g., <2.5m), groundwater continued to seep from the lower portions of the regraded seepage face and the central pond contained water. According to the synthetic hydrograph those low levels occurred no more than four times during the past three decades, and then only during the driest months of a dry season. Such low levels would not support wetland conditions if they were common, but the Wem analysis suggests they would be rare.

Table 4
Oceana, Virginia site Wem calibration period results that generated the highest $R^2$ values using linear regressions of Wem index vs. Observed Head during each calibration period. Calibrations and predictions made using both FAO Penman-Monteith PET (P-M) and Thornthwaite PET (T) values. Nash-Sutcliffe Efficiency values (NSE) reflect ability of calibrated equations to predict the heads observed during the complete post-construction period. See Table 5 for period dates.

<table>
<thead>
<tr>
<th>Calibration period</th>
<th>N (# of prior months)</th>
<th>D (decay factor)</th>
<th>$R^2$</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-construction (P-M)</td>
<td>2</td>
<td>0.65</td>
<td>0.88</td>
<td>−0.18</td>
</tr>
<tr>
<td>Pre-construction (T)</td>
<td>2</td>
<td>0.55</td>
<td>0.86</td>
<td>−0.11</td>
</tr>
<tr>
<td>Post-construction A (P-M)</td>
<td>10</td>
<td>0.90</td>
<td>0.86</td>
<td>0.42</td>
</tr>
<tr>
<td>Post-construction A (T)</td>
<td>10</td>
<td>0.95</td>
<td>0.87</td>
<td>0.42</td>
</tr>
<tr>
<td>Post-construction B (P-M)</td>
<td>5</td>
<td>0.80</td>
<td>0.71</td>
<td>0.18</td>
</tr>
<tr>
<td>Post-construction B (T)</td>
<td>5</td>
<td>0.60</td>
<td>0.22</td>
<td>−0.28</td>
</tr>
<tr>
<td>Post-construction C (P-M)</td>
<td>5</td>
<td>0.55</td>
<td>0.70</td>
<td>0.49</td>
</tr>
<tr>
<td>Post-construction C (T)</td>
<td>2</td>
<td>0.70</td>
<td>0.56</td>
<td>0.27</td>
</tr>
<tr>
<td>Entire post-construction period (P-M)</td>
<td>12</td>
<td>0.80</td>
<td>0.74</td>
<td>0.64</td>
</tr>
<tr>
<td>Entire post-construction period (T)</td>
<td>12</td>
<td>0.90</td>
<td>0.66</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 5
Data for Wem calibration periods for Oceana, Virginia site listed in order of increasing range of measured heads. NSE values from Table 4.

<table>
<thead>
<tr>
<th>Calibration period</th>
<th>Useable months</th>
<th>Total months</th>
<th>Range of measured heads (m)</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-construction B (Nov 2002–Dec 2004)</td>
<td>21</td>
<td>26</td>
<td>0.43</td>
<td>0.18</td>
</tr>
<tr>
<td>Post-construction C (Jan 2005–Feb 2007)</td>
<td>23</td>
<td>26</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>Post-construction A (Sept 2000–Oct 2002)</td>
<td>19</td>
<td>26</td>
<td>0.77</td>
<td>0.42</td>
</tr>
<tr>
<td>Entire post-construction period (Sep 2000–Mar 2007)</td>
<td>65</td>
<td>79</td>
<td>0.93</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Fig. 8. Hydrographs for the Oceana wetland in Virginia Beach, Virginia during the entire study period (Aug 1999–Feb 2007) showing monthly Observed Heads and five sets of Predicted Heads generated using different calibration periods and using both FAO Penman-Monteith and Thornthwaite PET estimators.
Analyses of these two sites in the Coastal Plain of southeastern Virginia—vegetated, relatively permeable sites—provide guidance for future projects in humid-temperate locations that use \( W_{em} \) calculations. The greatest sources of error between Observed Heads and Predicted Head at these sites occurred during relatively wet months when the water table was near the surface or when heavy rains probably generated significant overland flow, which the model presumes does not happen; \( W_{em} \) analyses at sites where these situations occur frequently would not reconstruct accurate explanations of water-level fluctuations. The strongest predictions at these two sites follow from calibration periods which contain a wide range of water levels, relatively uniform monthly rainfalls, and a preponderance of statistically dry and normal months. PET values generated by both Thornthwaite and Penman-Monteith equations proved useful; because neither one of them consistently produced better results, both should be used to generate parallel data sets for comparisons of \( W_{em} \) results.

5.2. Model assessment in climate settings with greater variability

As an initial, rapid assessment of the ability of the \( W_{em} \) index to estimate recent water levels in regions with stronger seasonal and annual differences, we analyzed recent USGS water table records from sandy aquifers at two sites in Missouri and Nebraska (Fig. 1). The average monthly precipitation and PET values for southeastern Virginia suggest recharge occurs most years during all but four months (May-August) (Fig. 10), and the inter-annual variability in water table elevations is usually low compared to seasonal changes. Even though southern Missouri is also humid-temperate, the lower precipitation and greater potential ET common during the summer can produce a stronger seasonal recharge pattern. The western Nebraska site is semi-arid with modest recharge usually occurring in spring and fall (Fig. 10); water levels in wells may show considerable inter-annual variation compared to seasonal changes (e.g. Winter et al., 2001). Wells at both sites are constructed in surficial sand aquifers and have no discernable influence from nearby pumping wells.

The Steele, Missouri site (Fig. 11) lies on thick Quaternary alluvium in the intensely cultivated Mississippi River bottomland, 10 km west of the river channel and protected by levees from all but very large floods. It is situated on a low terrace covered by loamy sand and sandy loam soils with moderate to high permeability (Brown, 1971). In this 39.3 m (131 ft) deep well, water levels vary between 1.5–5.4 m (5–18 ft) seasonally (USGS, 2016a).

Well CL–25 sips in the Nebraska Sandhills (Fig. 1), a vast stabilized dune field that was active most recently during the past 10,000 years (Ahbrandt et al., 1983; Stokes and Swinehart, 1997; Loope and Swinehart, 2000). Excessively well drained soils underlie the vegetated dunes in the area (Hetzer et al., 1985) which form the top of the widespread and thick High Plains aquifer. Located near Goose Lake in Crescent Lake National Wildlife Refuge (CLNWR) (Fig. 12), the USGS well penetrates sand for 3.6 m (12 ft). Water level depths fluctuate between 0.46–1.68 m (1.5–5.5 ft) on a decade scale but during a single year, seasonal fluctuations can be less than half as much (Winter et al., 2001; USGS, 2016b).

For both sites, precipitation amounts, weather data, and solar radiation values were collected from the weather stations nearest...
to the study site—Blytheville, Missouri and Dyersburg, Nebraska (21 and 47 km distant, respectively). Daily data missing from each station (<2% of total record) were patched in from the next nearest station. As before, monthly evapotranspiration estimates were calculated using aggregated daily data (Penman–Monteith method) or monthly values (Thornthwaite method), and water-level data reduced to a first-day-of-the-month record. The hydrologic data used included well data available on-line from USGS (9 years for Steele, 8 years for CLNWR; USGS, 2016a,b). Calibration periods were chosen as the three consecutive calendar years with the greatest range of water levels.

The Wem procedure worked well at both sites for the calibration periods. At the Missouri site, the best R² value (0.90) for the calibration period (2009–2011) came from data sets that had not been filtered for recent rainfall and used Thornthwaite ET estimates (Table 6). The equation developed for this regression predicted measured water levels for 2008–2015 moderately well (NSE = 0.59). At CLNWR, the best R² value (0.95) for the calibration period (2011–2013) came from data sets that had been filtered and used Penman-Monteith ET values. For the validation period (9/2009-6/2015) the hydrograph constructed with this equation matched Observed Heads moderately well (NSE = 0.65).

At both sites, during months outside of the calibrations periods, the Wem equations predicted water levels nicely during some periods but were notably more inaccurate for others (Fig. 13). At the Steele site, both predictive equations (Penman–Monteith and Thornthwaite) performed well, replicating both the timing and magnitude of water levels fluctuations. The exceptions occurred during the summer months of 2012, and all months post-March 2014 when both models under-predicted by up to a meter. At CLNWR over-predictions of 0.2–0.4 m were common during dry periods in 2014–2015.

The cause of discrepancies in the predictions is unclear. The two methods of calculating ET generate values quite similar through these periods. The unknown amounts of variation in precipitation between the well site and the weather stations (21 and 47 km away) are the more likely causes of the monthly predications that are relatively inaccurate.

Although these initial assessments suggest that the Wem procedure may prove be applicable in regions with relatively high variation in recharge compared to humid-temperate areas such as Virginia, caution is required, especially for sites in the interior of North America, like Nebraska, that experience significant variation in precipitation over decadal scales (e.g. Winter et al., 2001; Schubert et al., 2004; Ryberg et al., 2016). Wem regression equations developed for calibration periods chosen during an extended period of relatively low or high water tables may not accurately predict water levels during other phases of such cycles.

6. Discussion

Applications of the Wem index can permit design-grade model estimation of groundwater influx to proposed mitigation sites during periods when no wells existed at the site. Other research-grade models (e.g. DRAINMOD) can generate daily-scale hydrographs for specific sites but may require on-site measurements (e.g. soil properties) that are not required for the Wem procedure. Basin-scale analyses that take similar approaches to estimating recharge (e.g. Dripps and Bradbury, 2007) evaluate water budgets over large areas for design purposes. Wem calculations can serve the same function in water budget analyses developed for smaller sites. The Wetbud water budgeting package combines Wem-based estimates of groundwater levels with calculations of hillside runoff and stream channel overflow to generate rapid calculations of water budgets needed for mitigation wetland design (e.g. Dobbs and Whittlecar, 2012).

7. Conclusions

These analyses verify that for groundwater-driven systems in humid-temperate climates where precipitation and evapotranspiration are the principal factors that control recharge, the temporal pattern of the Effective Monthly Recharge (Wem) index can replicate reasonably the seasonal patterns of water-table fluctuations and the range of values of hydraulic head at a monthly scale. Regression equations developed by comparing water levels and Wem index values for the calibration period allow estimation of groundwater levels during periods, past and future, when values of rainfall and temperature were measured or can be estimated. Synthetic hydrographs, generated for long periods with historic weather data, that illustrate the seasonal trends and magnitudes of groundwater fluctuations can be used to aid the management of wildlife habitat and the design of mitigation wetlands, if those sites meet the limits imposed by the assumptions of the model. Initial assessments
suggest that the $W_{\text{cal}}$ index calculations may work in permeable landscapes located in climatic zones that have inter-annual water level variations larger than annual seasonal changes. Future work is need to verify the range of model applicability.

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