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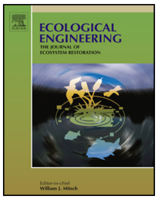

Use of the Effective Monthly Recharge model to assess long-term water-level fluctuations in and around groundwater-dominated wetlands

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ABSTRACT

Effective Monthly Recharge (W_{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_{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_{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_{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_{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.

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 (Kazezyılmaz-Alhan 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-table 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 Thornthwaite (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 longest 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}):

$$W_{mo} = P_{mo} - ET_{mo} \tag{1}$$

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:

$$W_{em} = \sum_{a=1}^{N} W_{mo} \times D^{a-1} \tag{2}$$

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

2.4. Step four - calibrate Wem 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.