Locating nested monitoring wells to reduce model uncertainty for management of a multi-layer coastal aquifer

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ABSTRACT

Although the aquifers below the Eastern Shore of Virginia serve as the region's only sources of fresh water, increased development and intensifying groundwater demands have put this resource as risk. Simulation modeling is used as a tool to evaluate impacts of groundwater withdrawals on the aquifers. Using available monitoring data, a regional three-dimensional variable-density groundwater model (SEAWAT) was previously calibrated to the Eastern Shore's aquifer system. In general, distributed parameter values were determined by kriging values around specified or calibrated parameter values at 21 pilot point locations spread across the Eastern Shore of Virginia. After calibration, an uncertainty analysis of the model's performance was completed, and it was concluded that in order to most cost-effectively improve the model accuracy to facilitate management, it is important that any additional data collection be focused on the key modeling objectives, which are predicting hydraulic head and chloride concentrations under pumping conditions. The work described in this paper develops and demonstrates a methodology to identify the most useful locations, with respect to improving model accuracy, for installation of new multi-layer nested groundwater monitoring wells.

INTRODUCTION

The Atlantic coast aquifer systems provide water to more than 20 million Americans (dePaul *et al*. 2008). Compared to pre-development conditions, water levels in these coastal aquifers have seen extensive declines; in some Virginian aquifers, water levels have fallen by more than 60 m (dePaul *et al*. 2008). Groundwater serves as the sole source of freshwater on the Eastern Shore. Both the Virginia Department of Environmental Quality (VaDEQ) and the Eastern Shore regional planning agency, Accomack-Northampton Planning District Commission (ANDPC), acknowledge that intensifying groundwater demands from commercial, residential, industrial, and agricultural development have placed the Eastern Shore's groundwater aquifer system at risk (Sanford *et al*., 2009). With the Atlantic Ocean to the east and the Chesapeake Bay Estuary to the west, careful management of the groundwater resource is required to prevent saltwater intrusion and reduction of the sustainable freshwater supply.

The Eastern Shore SEAWAT model was developed and calibrated by the U.S. Geological Survey (USGS) to aid the VaDEQ in evaluating groundwater permits. The Eastern Shore SEAWAT model is capable of simulating current and projected aquifer heads given permitted withdrawals, as well as evaluating current and projected locations of the saltwater interface. However, the existing model has parameters with large uncertainties resulting in reasonably accurate water levels but high degree of uncertainty in chloride predictions.

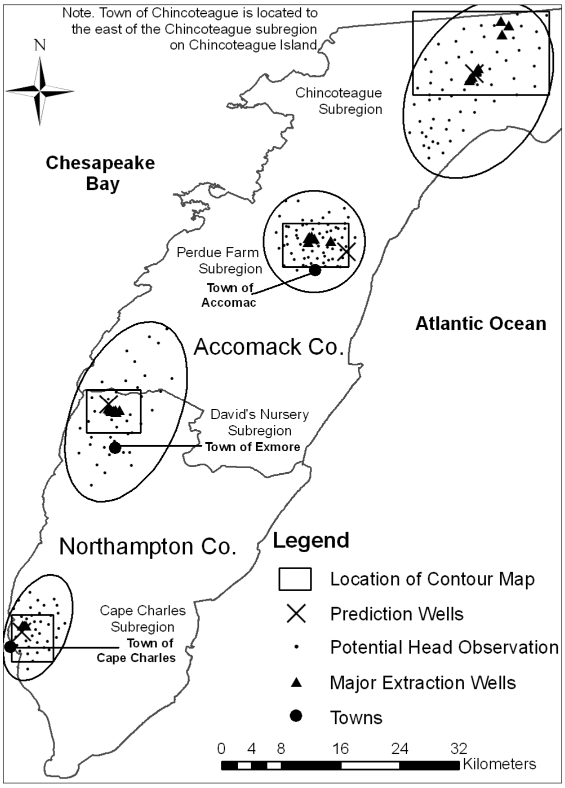

Figure 1. Four model subregions located along Virginia's Eastern Shore used in sensitivity analysis

Sanford *et al*. 2009 concluded that water level errors were not consistent throughout the region, and in localized subregions of large residual errors, adjustments in parameter values or the modeling framework, as well as additional data collection, may be required to improve model performance.

Sensitivity analysis has been an important tool to guide calibration of a model to existing historical data (Tiedeman *et al*. Oct. 2004). Sensitivity analysis has also been used to evaluate whether or not to continue to monitor existing observation wells (Hill *et al*. 2001). In addition, there is a need to identify the locations where additional monitoring well installations would most effectively improve a groundwater model's predictive ability. Applying sensitivity analysis to a calibrated model can be an important tool to guide future data collection efforts (Shoemaker 2004; Tiedeman *et al*. 2008).

METHODS

Building off of the uncertainty analysis performed in Sanford *et al*. (2009), this research develops and demonstrates a methodology to identify the locations for installation of new nested observation wells that will provide the most useful data to reduce model uncertainty. First, a set of hypothetical new nested observation wells is evenly distributed throughout each critical model subregion with high uncertainty (Figure 1). The four subregions include Chincoteague, Perdue Farm, David's Nursery, and Cape Charles. For each potential observation well site, the cumulative impact of data collection at that location is estimated using the cumulative sensitivity of the relevant pilot point parameters to data at the new observation well. Once these cumulative sensitivities are calculated for each potential observation well site, maps of the influence of new observations are created and used to identify the most effective location within each critical subregion to install a new nested observation well.

Identification of locations where VaDEQ should install groundwater monitoring wells was conducted by determining what uncertain model parameters were most important in predicting hydraulic heads and chloride concentrations and then determining prospective observation locations that would provide additional information in the estimation of these parameters. Several UCODE simulations were completed to obtain pertinent sensitivity data in order to estimate where prospective observation data should be collected in the critical subregions. Dimensionless scaled sensitivities (DSS) were calculated in UCODE for each observation (upper, middle, and lower aquifer) associated with each parameter of interest. Prediction scaled sensitivities were calculated for each parameter of interest.

RESULTS

To determine the relative usefulness of each prospective location for a nested observation well, the composite dimensionless scaled sensitivity (CDSS) was developed and calculated for each prospective location with respect to all the parameters of interest for that critical subregion. Areas with larger CDSS values indicate regions of the domain where triple nested observation wells should be installed and where additional hydraulic head data, collected during long-term pumping conditions, would be beneficial to improve future model calibration. Even though observation wells installed in regions with the highest CDSS values would provide more data for the estimation of the parameters of interest, other prospective observation locations within a subregion may also benefit the model, but the benefit decreases with decreasing CDSS value.

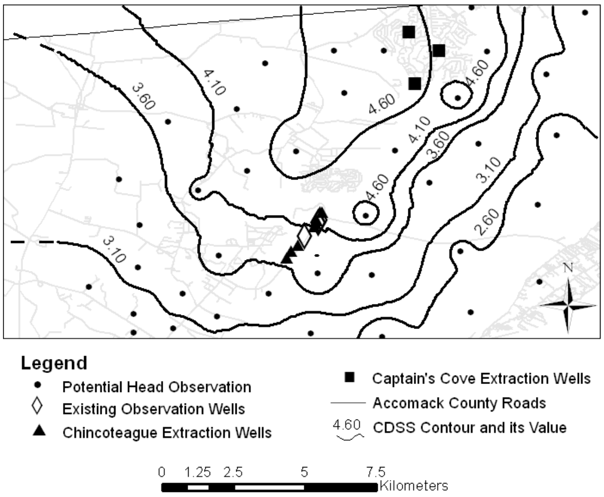

Figure 2. Chincoteague subregion CDSS results for improving prediction of hydraulic head

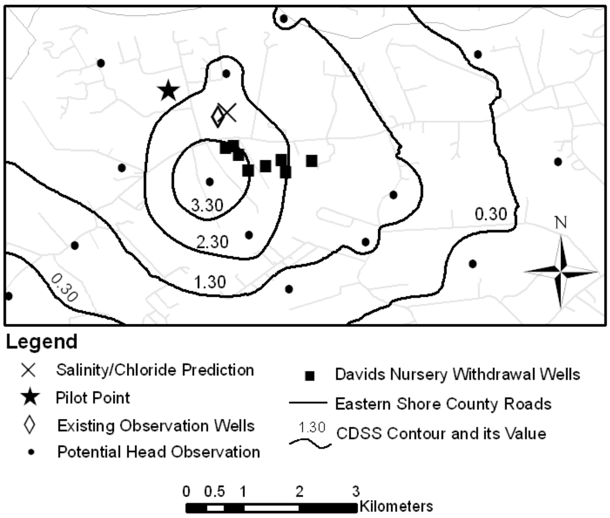

Figure 3. David's Nursery subregion CDSS results for improving prediciton of chloride concentrations

Within the Chincoteague critical subregion, there are two existing nested observation wells in among the Chincoteague Extraction wells, as shown in Figure 2. The high CDSS values north of the existing observation wells and to the west of the Captain Cove withdrawal wells (see Figure 2) indicate where collection of long-term hydraulic head measurements at a new triple nested observation well would provide the most useful additional data to improve parameter estimates.

In order to determine relative importance of head observations at new nested well locations with respect to improving chloride concentration predictions, PSS values relative to the chloride concentrations were calculated for each parameter of interest. A large PSS value indicates that the chloride concentration is sensitive to a change in the parameter value. Therefore, improving the estimation of the parameter(s) that is most sensitive to the prediction will improve prediction accuracy. Based on PSS results, the most sensitive parameters were identified for each subregion.

In the Chincoteague and David's Nursery subregions, where the majority of sensitive parameters had both high PSS values and large confidence intervals, an appropriate location of a new nested monitoring well should improve the prediction of chloride concentrations and saltwater intrusion. For these regions, the CDSS values with respect to just the most sensitive parameter were recalculated for each possible nested well location. Larger CDSS values indicate regions where data collection efforts should be focused to improve the model's ability to better predict chloride concentrations in the immediate area. Figure 3 illustrates the resulting contour maps for the regions of highest CDSS for David's Nursery subregion. To improve the model's ability to predict chloride concentrations, data collection efforts should be focused southwest of the withdrawal wells in the David's Nursery subregion (Figure 3).

DISCUSSION AND CONCLUSIONS

The practical benefits of evaluating existing models using sensitivity analysis include gained knowledge on where future data collection efforts should be focused to provide the most information for modeling objectives. Water managers and regulators, such as the VaDEQ, should be proactive in implementing this knowledge to improve the accuracy of models used in managing and regulating resources. By optimizing locations where data collection efforts should be focused, finances involved with data collection efforts can be minimized, while maximizing the value of data collected.

Even though the analysis described in this paper has been applied to improving the groundwater modeling objectives on the Eastern Shore, this analysis approach can also be applied to other groundwater systems to determine where data collection efforts should be focused to support modeling objectives. Utilizing readily available sensitivity information, this work developed a straightforward methodology to quantify the relative importance of a new observation or of a set of observations at a new nested observation well to improving the estimation of multiple uncertain parameter values.

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