**The Impact of Stormwater Recharge Practices on Boston Groundwater Levels**

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## ABSTRACT

Over the past century, the City of Boston has periodically experienced a decline in water table elevations and the associated deterioration of untreated timber piles which support building foundations. To combat declining water tables, Boston has instituted a groundwater conservation overlay district enforced by City zoning boards to require stormwater recharge practices for any new development or redevelopment project that increases impervious area. The primary goal of this research was to determine if such stormwater recharge best management practices (BMPs) have had an impact on groundwater levels in Boston.

Recharge to the water table in Boston results from the infiltration of rainfall and snowmelt, leakage from water mains, and recharge from man-made systems (Aldrich and Lambrechts, 1986). As water providers in Massachusetts strive to meet requirements of Massachusetts General Law Chapter 21G, which requires unaccounted-for water (e.g. leaking water pipes) to less than 10 percent (<10%), investigations have been conducted to isolate and remediate leaking water pipes throughout the city. Given the high percentage of impervious cover area of Boston, the remaining sources of recharge are primarily man-made systems, including pump and infiltrate systems and stormwater recharge BMPs.

The goal of this study was to determine the extent to which installed stormwater recharge BMPs have led to increased groundwater levels. Regional multivariate regression models were developed to determine the potential effects of recharge BMPs on observed groundwater elevations. Our final models reveal that the installation of recharge BMPs has a slight but significant positive impact on groundwater levels in the Back Bay with the effect being proportional to their capacity and inversely proportional to their distance from the location of interest. The resulting models can be used to predict the impact on average well elevations at a particular location, of installing a recharge BMP (or a set of such BMPs) of a particular capacity at a particular distance from that location.

## Introduction

Anthropogenic alterations have affected urban hydrology by shifting natural systems and land-use changes in surface and groundwater regimes. In Boston, Massachusetts, such alterations include increased directly-connected impervious cover which has reduced natural groundwater recharge. This impact has resulted in a periodic decline in water table elevations which caused deterioration of untreated timber piles supporting building foundations within the city, especially within the Back Bay section of Boston (Figure 1).

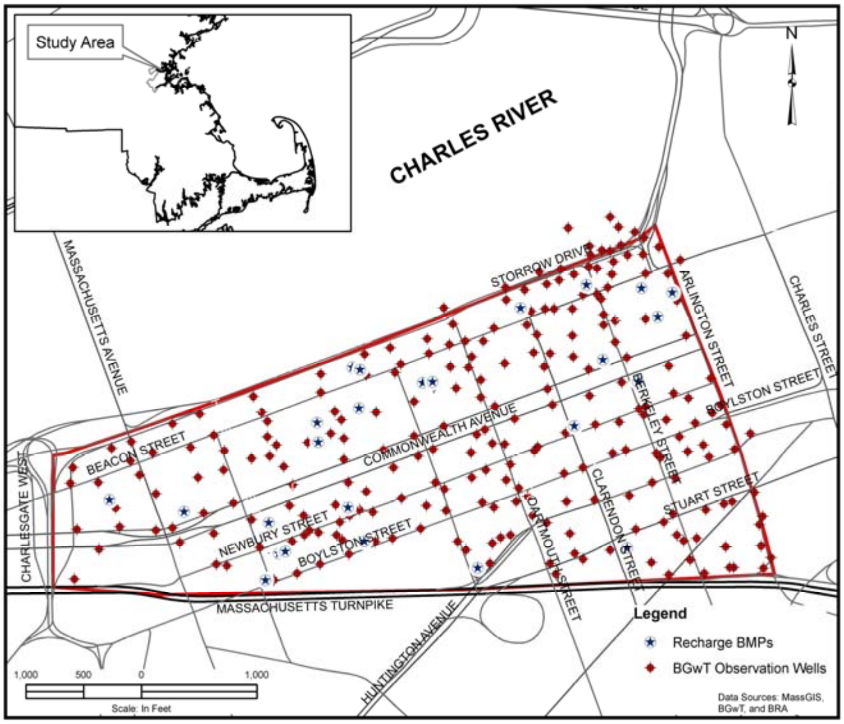


**Figure 1: Locus map of Back Bay section of Boston.**

In an effort to alleviate the anthropogenic impact to groundwater recharge in the city, Boston enacted a zoning code (Article 32), which created a Groundwater Conservation Overlay District (GCOD) that requires installation of a stormwater collection and recharge system for any specified activity that triggers the zoning requirement. Since 2006, a total of 69 recharge best management practices (BMPs) totaling an estimated 163,450 gallons of recharge per 1-inch storm event have been installed within the city. Of these, a total of 23 recharge BMPs have been installed in the Back Bay section of Boston (Figure 1) totaling an estimated 70,400 gallons of recharge per 1-inch storm event, or approximately 0.01 inches of precipitation over the Back Bay per storm event.

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Water and Sewer Commission, the water supplier for the Back Bay section, has reduced unaccounted-for water since beginning aggressive leak detection surveys in 2003. Given the high percentage of impervious cover area of Boston, the remaining sources of recharge are primarily man-made systems, including pump and infiltrate systems and stormwater recharge BMPs.

The purpose of this paper is to document the application of initial multivariate regression analyses for predicting groundwater elevations and to identify the extent to which installed recharge BMPs have effected groundwater levels within Back Bay using observable explanatory variables which are known to influence groundwater levels. Multivariate regressions are used here to both predict observed groundwater elevations in addition to evaluation of the hypothesis that recently installed recharge BMPs create a positive increase in observed groundwater elevations in Back Bay.

## Background

Park and Parker (2008) derived a model for water table prediction based on precipitation utilizing a discharge term. The authors' equation related hydrogeologic parameters and precipitation rates at a time ($\tau$) where $\tau$ is assumed to be small ($\tau_{lag} = 0$) for one-dimensional flow in an unconfined aquifer. Although the model utilized assumptions during derivation, including rapid precipitation response to water level ($\tau_{lag}$), the model was documented to generally predict water table response as a function of precipitation events. Hodgson (1978) was one of the first to document the use of multivariate statistical methods for modeling groundwater levels by developing a groundwater water-balance assuming that the water table response was a function of recharge and discharge. Hodgson recommended including the autocorrelation coefficient ($\lambda_1$) to account for dependence of the water table elevations related to previous time steps ($GW_{t-1}$). In the case of Boston, groundwater levels were not measured at regularly-spaced time intervals to accurately estimate such autocorrelations. Therefore, our initial multivariate model retained only a $GW_{t-1}$ term.

Previous unpublished research by Tufts students relating to Boston groundwater levels used a ***single*** well site with hourly water table elevation measurements collected by a pressure transducer installed in select observation wells. Their work documented a high level of dependence of observed groundwater elevations on precipitation events over time. Their multivariate statistical model included terms for previous groundwater observations, precipitation, and a recharge BMP dummy variable to predict the time history of groundwater elevations. This initial study indicated that groundwater levels are largely driven by previous groundwater levels combined with precipitation-derived recharge. In addition, the research documented the effect of recharge BMPs to be significant on observed groundwater elevations at specific individual well sites.

A second unpublished study by Tufts students was conducted on ***single*** well sites utilizing groundwater elevation data collected by hand with a water level probe. The multivariate statistical model used in this second study included the location, capacity, and date of the recharge BMP installation in near proximity to select observation wells with a long historical record (approximately 10 years). The purpose of the second study was to determine if hand level observations collected at irregular time intervals can be used with similar multivariate methods as described above. For example, recently collected hand level observations have been conducted at approximate 6-week intervals; however, mean time between observations for the hand level data record is 53 days with a standard deviation of 22 days. The results of the second study supported previous results and documented the potential to determine significance of recharge BMPs and prediction of groundwater elevations in a regional model using hand level observations by incorporating a time variable measured between groundwater elevation observations.

This study reports the development of a regional model of groundwater elevations which is based on recorded groundwater elevations at many wells in the Back Bay. The following sections describe the development and application of such a regional groundwater model for the Back Bay.

## Development of a Regional Groundwater Model for Back Bay

The regional groundwater model was developed utilizing 234 observation wells with recorded groundwater elevations starting between 1999 and 2005 and continuing to September of 2009. The goal of the regional model was to determine if variability in groundwater elevations could be explained by the observable characteristics summarized in Table 1 in addition to determining the extent to recharge BMP effects to the groundwater elevation at observation well sites. Multivariate linear regression was used to evaluate the relationship between observed groundwater elevations and characteristics in Table 1.

Groundwater observations were collected from 1999 to present day by Boston Groundwater Trust (BGwT) at irregular time intervals at 234 observation wells within Back Bay. To account for the irregular timing of groundwater elevation observations, a time element (k or Days) was used in the analysis as shown in Table 1. Between each groundwater observation measurement, daily precipitation data collected for Boston, collected at Boston Logan International Airport, was aggregated to represent the cumulative precipitation between well observations from daily precipitation data.

**Table 1**: Explanatory Variables used in Model Development

| Characteristic | Code | Source | Comments |
|---|---|---|---|
| Observed Groundwater level at time t | $GW_t$ | BGwT | 234 observation wells used in this study |
| Previous recorded groundwater level | $GW_{t-1}$ | BGwT | |
| Cumulative precipitation between observations | P | NCDC | P term did not include precipitation that occurred on the date of reading |
| Number of days between observations ($\Delta t$) | k | BGwT | |
| Cumulative number of days from the first observation in the record | Days | BGwT | Day 1 was assumed to be 1/1/1999 |
| Recharge BMP interaction terms | BMP*CAP/D | BGwT/GIS | Storage capacity in cubic feet |
| Recharge BMP Interaction terms | BMP*CAP*P/D | BGwT/GIS | Distance (D) in feet from observation well to BMP |

The installation of recharge BMPs is regulated under Boston Article 32. Property owners are required to document construction and inspection of recharge BMPs and submit documentation to Boston Redevelopment Authority (BRA) to comply with zoning requirements. This documentation includes dates of construction, inspection, and activation of the recharge system in addition to the capacity of the recharge systems. Relevant data for recharge BMPs was supplied by BGwT documenting the dates of system activation in addition to the volume capacity (in cubic feet of available storage for each system). Since all recharge systems are designed to capture, store, and recharge the first inch of rainfall from a storm event, the contributing surface area (in square feet) can be calculated. For this study, BMP explanatory variables were represented as dummy variables defined as 0 (if no BMP installed at a given time interval) or 1 (if BMP installed), as recharge BMP capacity (CAP, in cubic feet of storage), or as interaction terms between distance of specific recharge BMPs to observation wells (D, in feet) combined with the variables BMP, CAP and P (Table 1).

As documented by Hodgson (1978), the water balance equation for a general groundwater regime can be expressed as

$$GW_t = GW_{t-1} + SR + UR - UD - P - T \qquad \text{(Equation 1)}$$

Where:
$GW_{t-1}$: Initial water table elevation
$GW_t$: water table at end of observation period
SR: recharge from surface
UR: recharge from underground sources
UD: underground discharge/leakage
P: pumping
T: transpiration

Aldrich and Lambrechts (1986) reported groundwater recharge within Back Bay as being limited to infiltration of rainfall and snowmelt, leakage from water mains, and recharge from man-made recharge systems. Therefore, it is unlikely that transpiration (T) and aquifer pumping (P) are necessary given the urban environment for this study. Additionally, as recharge BMPs currently installed vary in terms of spatial location and storage capacity, additional terms may be necessary in Equation 1 to account for potential effects of recharge BMPs to observed groundwater levels. For example, distance of recharge BMPs to observation wells in addition to BMP capacity could potentially effect well observations. Therefore, for this study, the following multivariate model will be investigated:

$$GW_t = f(GW_{t-1}, P, k, \text{recharge BMP interaction terms})$$

Minitab® (release 15) was used to develop initial multivariate regression including stepwise analysis, best subsets, and multivariate linear ordinary least squares regression. Goodness of fit of regression models was conducted by minimizing Mallows Cp statistics, minimizing PRESS in model comparisons, and maximizing the value of correlation coefficients, including prediction $R^2$.

Mallows Cp mathematically represents the expected number of explanatory variables to be included in a model; therefore, Mallows Cp was expected to be small and close to the number of model parameters to reduce bias in resulting predictions. PRESS, the prediction sum of squares, is defined as

$$PRESS = \sum_{i=1}^{n} e_{(i)}^{2}$$

Where $e_{(i)}=(y_i - \hat{y}_i)$ represents the regression estimate computed by deleting the $i^{th}$ observation. In practice, PRESS is essentially a "deleted one" residual and provides a validation estimate of error. Additional model comparisons were conducted using root mean square error (RMSE) and the coefficient of variation of model residuals ($CV_{\varepsilon}$) where the standard deviation of model residuals is calculated by

$$S_{\varepsilon} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\varepsilon_i - \bar{\varepsilon})}$$

Where $\varepsilon_i$ represents the error between observed and simulated groundwater table elevations while $\bar{\varepsilon}$ represents the mean error. $CV_{\varepsilon}$ is found by dividing $S_{\varepsilon}$ the average observed groundwater elevation. In general, small values of $CV_{\varepsilon}$ indicate good model fits.

Multivariate linear regression was applied to obtain the best model following diagnostic methods applied above. To improve model prediction, influence and leverage statistics were calculated to isolate observations that exhibit influence to the position of the regression line. In this study, observations were selectively removed only if influence was exhibited with high values of DFFits defined as:

$$DFFits = 2\sqrt{\frac{p}{N}}$$

Where p refers to the number of explanatory variables in the regression equation while N refers to the number of observations. Stepwise regression procedures were performed to identify explanatory variables for the regional regression model. To determine goodness of fit performance of the model, results were analyzed by using estimates of model bias and efficiency using the Nash-Sutcliffe efficiency criterion:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(GW_{obs_i} - GW_{sim_i})^2}{\sum_{i=1}^{N}(GW_{obs_i} - \overline{GW})^2}$$

Where $GW_{obs}$ represents the observed groundwater elevation at any time t, $GW_{sim}$ represents the simulated or predicted groundwater elevation at any time t, and $\overline{GW}$ representing the mean observed groundwater elevation. Perfect agreement between observed and simulated groundwater elevations is obtained if NSE is equal to 1.

## Results of Regional Groundwater Model for Back Bay

Multivariate linear regressions were estimated using the explanatory variables summarized in Table 1 combined with stepwise selection procedures. The overall goal of this analysis was to document the extent to which installed recharge BMPs have effected groundwater levels within Back Bay. To evaluate the influence of a particular BMP on groundwater levels at a nearby well, the following explanatory term is employed

$$\frac{BMP_{i,t} * CAP_i}{D_{i,j}}$$

Where $BMP_{i,t}$ is an indicator variable which takes the value of 1 if the BMP is installed at site i in year t, and zero otherwise. The variable $CAP_i$ is simply the capacity of the BMP in cubic feet and the variable $D_{i,j}$ is the distance from the $BMP_i$ to the well of interest, j.

The cumulative effect of recharge BMPs was conducted by deriving two different multivariate models for the entire Back Bay region. Model 1 assumes that the impact of recharge BMPs are additive so that the explanatory variable could be defined as

$$\sum_{i=1}^{n} \frac{BMP_{i,t} * CAP_i}{D_{i,j}}$$

Where i refers to a specific recharge BMP and $D_{i,j}$ refers to the distance between BMP i and observation well j and n is the number of BMP's. Regional model 2 assumed that, at any time t, groundwater observed was affected by an explanatory variable which included the term based on $\frac{BMP_{i,t} * CAP_i}{D_{i,j}}$. This analysis resulted in multiple observations for each well measurement which accounts for the impact of a particular recharge BMP. The resulting regression models for predicting groundwater elevations at time t is summarized in Table 2. Both regional regression models were found to depend on previous groundwater elevation observations $GW_{(t-1)}$, elapsed time between observations (k), cumulative precipitation (P), and the BMP terms described above.

As shown in Table 2, regional recharge BMP explanatory variables resulted in very slight but significant positive impacts on observed groundwater elevations collected at approximately 6-week intervals within the Back Bay region of Boston. Without the BMP explanatory variables, prediction $R^2$ of 92.61% and 90.49% were obtained for model 1 and model 2, respectively compared to the values of 92.64 and 90.50 with the BMP variables, respectively. Both regional models goodness of fit statistics summarized in Table 2 document small $CV_{\varepsilon}$, NSE values approaching 1 and bias approximately equal to zero.

**Table 2**: Results of Initial Regional Groundwater Model.

| Variable (see Table 1) | Regional Model 1 | Regional Model 2 |
|---|---|---|
| Constant | 0.0663 (2.96)[1] | 0.1259 (24.17) |
| k | -0.0084 (-25.81) | -0.0087 (-115.49) |
| $GW_{(t-1)}$ | 0.9427 (306.24) | 0.9345 (1271.71) |
| P | 0.0987 (57.96) | 0.1005 (239.54) |
| Regional Recharge BMP Term | 0.0125 (5.13) | 0.0832 (11.81) |
| **n:** | 8021 | 176,460 |
| **Adjusted $R^2$:** | 92.6% | 90.5% |
| **Pred. $R^2$:** | 92.64% | 90.5% |
| **Pred. $R^2$ (w/o BMP variable)** | 92.61% | 90.49% |
| **Bias:** | 0.0030 | 0.0092 |
| **RMSE:** | 0.6265 | 0.6261 |
| **$CV_{\varepsilon}$:** | 2.72E-09 | 0.0150 |
| **NSE:** | 0.8520 | 0.8522 |

[1] Values represent model coefficient and t-ratios (in parentheses).

The overall goodness of fit for both regional models is illustrated in Figure 2, documenting the relationship between predicted and observed groundwater elevations. Figure 3 compares the predictions based on the multivariate regression models with groundwater well observations at randomly selected observation wells. Given that groundwater level observations are a time series, Figure 3 documents the ability of both regional models to predict variability in observed groundwater levels over time.

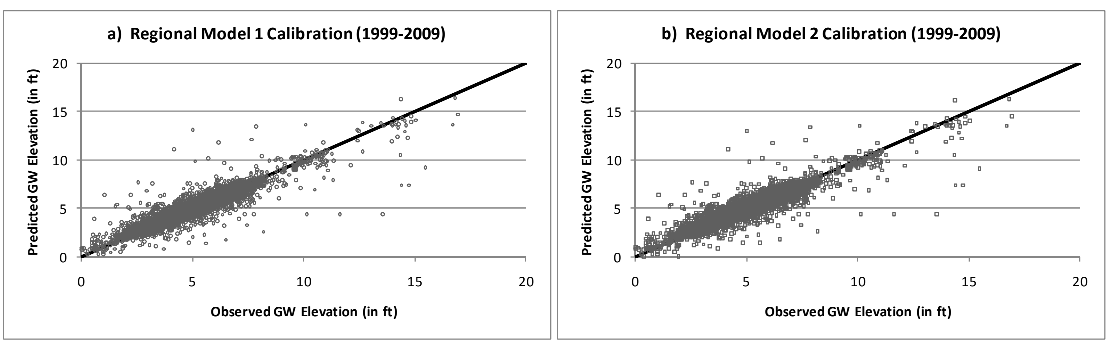


**Figure 2: Comparison between observed and simulated groundwater elevations. The solid line represents a 1:1 fit.**

Model prediction error was further evaluated by calculating the residual errors using the regional models to predict recently collected groundwater elevations which were not used during model calibration. The model validation was conducted by employing data for model variables summarized in Table 2 for time periods not used for model calibration. Model validation results are presented by comparing observed with simulated groundwater elevations in Figure 4. Goodness of fit variables for the initial validation are included in Table 4. The results document good model fits with low $CV_{\varepsilon}$ and bias, with E values of near 1. Results from regional model 2 exhibit bias and generally inferior performance in initial model validation compared to regional model 1.

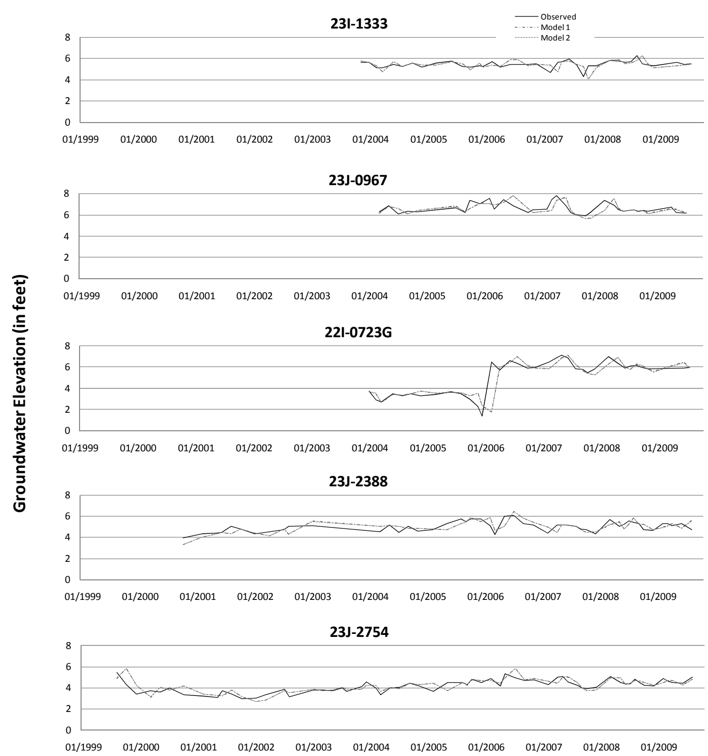


**Figure 3: Time series comparison between observed and simulated groundwater elevations.**

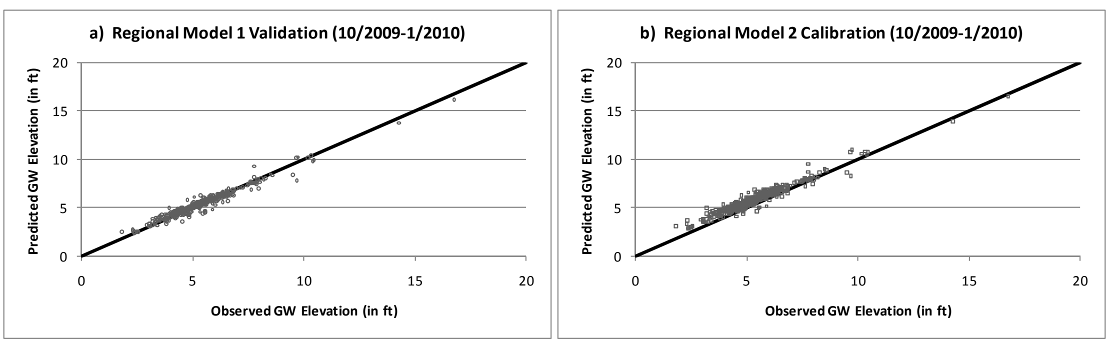


**Figure 4: Validation data showing relationship between observed and simulated groundwater elevations. The solid line represents a 1:1 fit.**

**Table 4**: Summary of Regional Groundwater Model Validation Goodness of Fit

| Parameter | Regional Model 1 | Regional Model 2 |
|---|---|---|
| Bias: | -0.050 | -0.524 |
| RMSE: | 0.3164 | 0.6347 |
| $CV_{\varepsilon}$: | 1.30E-09 | 0.1278 |
| NSE: | 0.9516 | 0.8054 |

## Conclusions

The results of the regional regression models document that the inclusion of recharge BMP explanatory variables into the regression equations leads on average, to very small, but positive and significant impacts on groundwater levels across the Back Bay region of Boston. Our initial regional models indicate that previous well elevations are impacted primarily by previous well elevations and the recharge which results from the precipitation which occurred since those previous well elevations were observed. The resulting models can be useful for determining the influence of future BMP installations on groundwater levels in the Back Bay region of Boston.

The regression models introduced are analogous to the water balance equation introduced by Hodgson (1978) for a typical groundwater system (see eqn. 1). The terms for transpiration and pumping in equation 1, are unlikely to be important in the Back Bay except for isolated pumping activities associated with construction or other activities. A comparison of each of the explanatory variables in our regressions with the variables in Equation 1 is given below:

| Hodgson (1978) Groundwater Regime | | Regional Multivariate Model |
|---:|:---:|:---|
| $GW_t$ | → | $GW_t$ |
| $GW_{t-1}$ | → | $GW_{t-1}$ |
| SR | → | P (precipitation) |
| UR | → | Regional BMP Term |
| UD | → | Regression constant and k |

The regression constant and the k variable, or days between groundwater elevation observations, represents a combination of natural aquifer drainage in addition to reduced groundwater storage as a result of anthropogenic influences such as municipal infrastructure and conduits of groundwater flow. The inclusion of previous groundwater levels indicates that relationship between current and previous groundwater levels reflects the physical geohydrologic structure of the aquifer in the vicinity of each well which is known to be quite heterogeneous.

We examined the ability of a regional multivariate groundwater model to predict groundwater elevations within the Back Bay region of Boston using observable and easily measured explanatory variables. The model validations illustrated in Figure 4 document the performance of the regional models to predict observed groundwater table elevations within Back Bay with well data not included in the calibration of either regional model. Although initial goodness of fit parameters including RMSE, the Nash-Sutcliffe efficiency criterion, and adjusted $R^2$ indicates high goodness of fit with observations, future work is anticipated to include additional model testing including more rigorous cross validation methods and geographic differential split sampling will be performed to determine final model selection.

Perhaps the most important result of this initial study is that the regional models described here can be used to predict the impact of future BMP installations on groundwater levels, because the models relate the increase in groundwater levels at a particular location to the capacity, time of installation and location of a particular BMP recharge tank or a set of such tanks. Since the models are based on well known statistical theory, it is also possible to give confidence intervals for resulting predictions as will be shown in future studies.

## References

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