The Impact of Stormwater Recharge Practices on Boston Groundwater Elevations

Project Report Prepared for the Boston Groundwater Trust

By

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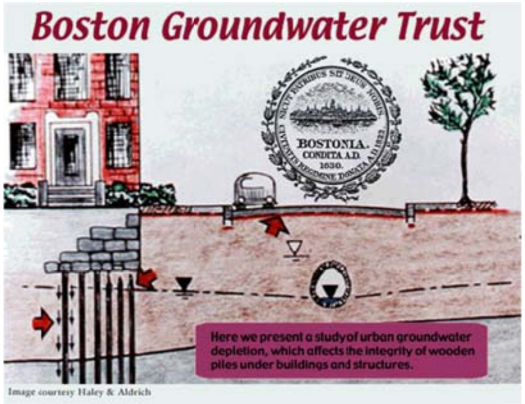

Executive Summary

Periodic declines in groundwater elevations in the Back Bay section of Boston have resulted in deterioration in untreated wood piles which support building foundations. To combat declining water tables, Boston enacted a groundwater conservation overlay district enforced to require stormwater recharge practices for any activity that triggers zoning bylaws. The primary goal of this research was to exploit existing information on groundwater elevations and recharge practices to quantify the impact of the required recharge best management practices (BMPs) on the behavior of groundwater elevations in the Back Bay. Our results indicate that individual recharge BMPs as well as groups of recharge BMPs that have been installed have resulted in a small yet statistically significant and positive impact on average groundwater elevations in the Back Bay.

A review of previous studies illustrates the utility of using hybrid statistical/physical approaches for predicting groundwater elevations. Our final predictive model of groundwater elevations employs numerous easily measured explanatory variables including rainfall, potential evapotranspiration, as well as the location, capacity and date of installation BMP's. The use of multivariate statistical methods enabled us to evaluate and ensure the significance and confidence of our resulting models. We obtained extremely high confidence in model coefficients, including the magnitude of average groundwater increases which result from installed recharge BMPs. Our approach was successful in large part due to the wealth of groundwater elevations collected throughout Back Bay by the Boston Groundwater Trust.

Our final regional model predicts the average increase in groundwater elevation which results from a system of recharge BMPs, taking into account the capacity of each BMP and the distance between the particular location of interest and all BMP's in the region. We found that a 1 cubic foot capacity recharge BMP installed 1 foot from an observation well would increase average groundwater elevations by 0.016 feet. We also show how this result can be used to evaluate the impact of future recharge BMPs within Back Bay. Several future scenarios are considered in the report which illustrate the use of the model in future stormwater recharge BMP planning.

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Technical Abstract[1]

Over the past century, the City of Boston has periodically experienced a decline in groundwater elevations and the associated deterioration of untreated wood piles which support building foundations. To combat declining water tables, Boston enacted a groundwater conservation overlay district enforced by City zoning boards to require stormwater recharge practices for any activity that triggers the zoning bylaw. The primary goal of this research was to exploit existing information on groundwater elevations and recharge practices to quantify the impact of the required recharge best management practices (BMPs) on the behavior of groundwater elevations in the Back Bay.

In Boston, recharge to the water table results from the infiltration of rainfall and snowmelt, leakage from water mains, and recharge from man-made systems. Increased mitigation activities to reduce unaccounted-for water have reduced leakage from water mains in the city. Given the high percentage of impervious cover in 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 elevations. 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 small but highly statistically significant positive impact on groundwater elevations 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 groundwater elevations at a particular location resulting from the installation of a recharge BMP (or a set of such BMPs) of a particular capacity at a particular distance from the location of interest.

Introduction

Anthropogenic alterations associated with urban development can have a profound hydrologic impact on both surface and ground water systems. In Boston, Massachusetts, the urban hydrologic system has been impacted by the man-made filling of estuaries and wetlands, increased impervious cover which has reduced natural groundwater recharge, and installation of urban infrastructure that impacts the natural flow direction and velocity in groundwater systems.

The impact of urbanization on the urban groundwater system includes: decreased infiltration which results in reduced groundwater elevations (Gilroy and McCuen, 2009; Horner et al., 1994) and increased groundwater elevations due to leakage from water and sewer systems (Foster et al., 1990; Lerner, 1990). Changes in urban groundwater elevations which result from anthropogenic alterations can result in expensive consequences. For instance, declining groundwater elevations can cause land subsidence, building damage, and ecological habitat

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[1] This abstract will be replace the executive summary when this work is submitted for publication in a refereed journal.

deterioration in groundwater-fed streams and wetlands. Likewise, rising groundwater elevations can cause increased infiltration into sewer and stormwater infrastructure, increased flooding in basements, and augmented building costs associated with dewatering activities for new development.

In Boston and other urban environments, alteration of the landscape limits recharge to the water table by restricting infiltration of rainfall and snowmelt, leakage from water mains, and recharge from man-made system (Aldrich and Lambrechts, 1986). American Rivers (2002) estimates lost groundwater infiltration within Boston of between 43.9 to 102.5 billion gallons annually due to increased impervious areas. There are a variety of impacts on groundwater recharge due to urbanization (Lerner, 1990). Overall, the Back Bay area of Boston has experienced periodic declines in groundwater elevations which were probably caused by a combination of decreased infiltration due to increased impervious areas and active mitigation management for both water and sewer leaks. In the Back Bay area of Boston (Figure 1), the decline in groundwater elevations has resulted in multiple adverse effects. As described by Aldrich and Lambrechts (1986), the Back Bay was filled and untreated wood piles were used for structural supports of building foundations. Exposure of the wood piles by periodic declines in groundwater elevations creates favorable conditions for degradation of the piles by fungus, insects, and bacteria. Degradation of the piles affects the stability of foundations throughout Back Bay. Such conditions have been commonplace, resulting in cracking of walls, and has required structural underpinning of the wood piles to support foundations.

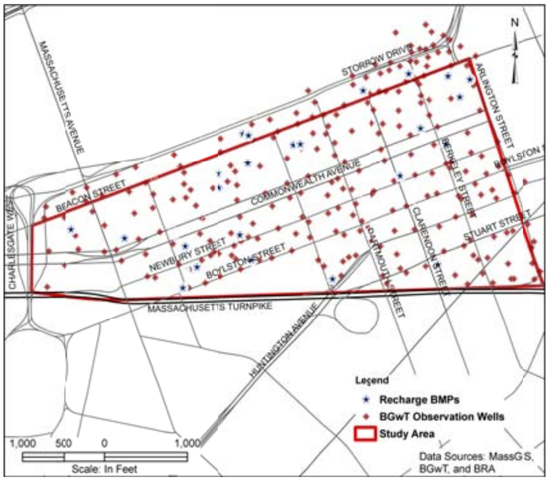

Figure 1: Boston Back Bay Model Domain

In an effort to mitigate the anthropogenic impacts of urbanization on groundwater elevations in the city, Boston enacted a zoning code, Article 32, which created the Groundwater Conservation Overlay District (GCOD). Article 32 requires installation of a stormwater collection and recharge system, also termed a recharge best management practice (BMP), for any specified activity that triggers the zoning requirement. Regulations require the capture, storage and infiltration of the volume of rainfall no less than 1.0 inches from the portion of the project triggering the zoning article. From 2006 to 2010, a total of 79 recharge BMPs had been installed in the City. This potential recharge capacity of the installed recharge BMPs totaled 313,730 gallons of recharge per 1-inch storm event. Of these, 24 recharge BMPs have been installed within the study area in the Back Bay section of Boston (Figure 1) totaling an estimated potential recharge of 67,650 gallons per 1-inch storm event, which averages to 0.01 inches of precipitation over the Back Bay per 1-inch storm event.

Stormwater management using infiltration strategies has been shown to reduce stormwater runoff, increase groundwater recharge and urban baseflow, reduce erosion and stream scour, and potentially improve surface water quality (Holman-Dodds et al. (2003), Prince George Country (1999), U.S. EPA (2002)). To date, few studies have investigated temporal and spatial impacts of such stormwater management practices. Recently, studies have investigated changes to peak-flow discharges in urban environments using infiltration-based strategies (Holman-Dodds et al., 2003) which indicated sensitivity of mitigation benefits due to the location of infiltration sites. Similarly, Gilroy and McCuen (2009) found that stormwater benefits would be minimal if detention basins were not placed properly to mitigate stormwater runoff. Spatial stormwater management strategies have been evaluated for their ability to impact groundwater elevations. For example, Gobel et al. (2004) found that decentralized infiltration systems have limited influence on the groundwater surface. Endreny and Collins (2009) found that groundwater mounding could result due to spatial arrangements of bioretention basins.

Understanding the impact stormwater mitigation strategies such as recharge BMPs on urban groundwater systems is difficult due to the transient nature of the system (Foster et al., 1999) in addition to continued land-use modifications in urban environments. Lerner (2002) recommended piezometric methods to identify signatures of point recharge in urban systems similar to the water table fluctuation method described by Scanlon et al. (2002). Boston, Massachusetts, is a unique urban environment because groundwater elevations have been recorded regularly at observation wells to monitor the potential impact of changes in groundwater levels on wood piles which support the buildings. Therefore, a large spatial and temporal dataset of urban groundwater elevations is available that predates efforts to install recharge BMPs and these elevations continue to be collected as newly permitted recharge BMPs are installed in the Back Bay region of Boston.

Study Goals

The primary goal of this project is to determine the impact of recently introduced recharge best management practices (BMPs) on the behavior of groundwater elevations in Boston. We were unable to find any previous studies which developed modeling methods which could be readily applied to evaluate the impact of BMPs on groundwater elevations on a regional basis. A mathematical model is needed which is able to sort out the complex interactions among all the factors which control groundwater elevations in an urban environment. Groundwater elevations are impacted by the heterogeneous subsurface environment as well as by leaks in the stormwater, water and sewer systems, climatic controls, vegetation, land-use, BMPs and a variety of other minor factors including pumping and dewatering activities. It would be extremely difficult to develop a physically based mathematical model which accounts for all of these factors. Previous investigations which have attempted to model groundwater elevation changes due to stormwater management (Endreny and Collins, 2009; Gobel et al., 2004) have used site-specific groundwater flow models to determine groundwater impacts from infiltration. The difficulty in creating a model of an urban groundwater environment arises from the heterogeneity of the system due to both variability in subsurface conditions and urban infrastructure. A transient groundwater model becomes even more difficult to calibrate, validate, and simulate scenarios due to continued and variable disturbance of the hydrologic system (Lemonsu et al., 2007). Furthermore, even if one could develop a physically based modeling system, without statistical methods, one is unable to determine whether observed changes due to recharge practices are statistically significant.

Since a very large database of groundwater elevations is available from 234 observation wells throughout the study area over the period 1999-2010, we took a hybrid multivariate statistical/physical modeling approach which is able to exploit all available well data combined with climatic, land use as well as BMP location and capacity data. Our approach was to develop a spatial multivariate statistical model which accounts for the primary determinants of changes in groundwater elevations in an urba environment. Such a regional statistical approach is useful because it enables us to make quantitative and rigorous statements regarding the significance of the various factors which govern groundwater elevations in an urban environment. The resulting model is then used to evaluate the impact of various future stormwater zoning strategies

A second goal of the study was to identify the regional average impact of all the currently installed recharge BMPs on groundwater elevations under historical conditions as well as a variety of future stormwater recharge BMP planning scenarios. Although the model described here was developed for the case study of Boston, Massachusetts, the modeling approach taken and its application for evaluating future stormwater BMP policies could be applied to any urban environment.

Previous work

Early investigations into the use of multivariate linear regression (MLR) for groundwater elevations studies (Hodgson, 1978) identified that groundwater elevations could be expressed as a general groundwater balance

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

where GW_t is the observed groundwater elevation at time t, GW_{t-1} is the previously observed groundwater elevation, SR is the surface recharge term, UR is the recharge from underground storage, UD is the underground discharge/leakage term, P is pumpage, and T is transpiration. Hodgson (1978) used a regression method along with a monthly version of (1) with data on pumpage and monthly rainfall in addition to a lagged groundwater elevation to accurately simulate groundwater elevations. Similarly, Azmon (1989) documented an MLR relationship between groundwater elevation and pumpage and rainfall in Israel, with correlation coefficients between 0.82 and 0.97 across multiple well fields. Adamowski et al (1986) used an MLR approach with a water balance model which incorporated hydrogeologic characteristics such as specific yield. This study uses MLR, but takes a different approach by using only observable physical characteristics in the model while adhering to the physical groundwater balance equation in (1).

William and Williamson (1989) used MLR to estimate the depth to groundwater for the purpose of developing an initial conditions database within a finite-difference groundwater flow model. Their MLR model incorporated both land-surface topography and a topographic factor as a result of the 5-mile block grid size to be used for the model cell dimensions. The model was able to accurately predict steady-state groundwater elevations as an initial condition in modeling efforts as compared to a complex groundwater flow model simulation using topographic information, potentially saving time and effort to simulate starting heads for model simulations.

Park and Parker (2008) derived a model for water table predictions based on precipitation utilizing a discharge term. Their approach related hydrogeologic parameters and precipitation rates at a time (τ) where τ was assumed to be small ($\tau_{lag} \approx 0$) for a one-dimensional flow in a confined aquifer. Although the model utilized assumptions during derivation, including rapid precipitation response to water levels (τ_{lag}), the model was documented to generally predict water table responses as a function of precipitation.

In summary, several previous studies used MLR to estimate groundwater elevations based on physical explanatory variables including pumpage, precipitation, and lagged groundwater elevations in addition to physical hydrogeologic characteristics of the aquifer. The results of these previous studies identify the physical influences to groundwater systems that should, at a minimum, be used to predict groundwater elevations.

Brief History of Back Bay

The history of the filling of Back Bay can be traced to 1814 when the Boston and Roxbury Mill Corporation was granted approval to build Mill Dam along a line today underlying Beacon Street (Newman and Holton, 2006). Regulation of the dam continued until 1848, at which time the Commissioners of Boston Harbor and the Back Bay was established. Despite potential political reasons for establishment of the state Commission, Seasholes (2005) and Newman and Holton (2006) document increasing pollution concerns with the dammed Back Bay estuary as the impetus for filling the estuary. For example, in the 1850s, reports documented “a greenish scum…stretches along the shores of the basin” and “surface of the water beyond is seen bubbling…with noxious gases”. Actual filling of the Back Bay commenced in 1858, initially with sands and gravels brought to Back Bay from Needham, Massachusetts. Although Newman and Holton (2006) report brisk land sales within Back Bay, Seasholes (2005) reports decreasing fill material budgets which later restricted the use of sands and gravels for a mixture of urban fill, dredged silts, and sand and gravel. This mixture of fill material, as described in Seasholes (2005), creates a heterogeneous media for groundwater flow within Back Bay, even prior to the installation of urban infrastructure that exists today.

METHODOLOGY

This section describes the development of a regional multivariate statistical model to estimate groundwater elevations within Back Bay. 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. Although pumping activities are known to exist near the study area due to dewatering for public transit tunnels, pumping records were not available and therefore were not included in the model. Installed recharge BMPs vary in terms of their location and storage capacity in addition to the timing of their installation, requiring additional model terms than those included in equation (1) to account for their potential impact on groundwater elevations. For example, the distance between a recharge BMP and an observation well as well as the capacity of the BMP should impact observed groundwater elevations. In the following sections we attempt to fit multivariate statistical models which predict the groundwater elevation at a particular location and time period as a function of numerous potential explanatory variables including previous groundwater elevation, previous precipitation and potential evapotranspiration, and the distance and capacity of recharge BMPs as well as several other explanatory variables described below.

Data

The data necessary for the proposed models include time series of daily precipitation and historic groundwater elevations, as well as recharge BMP capacity and locations of all recharge BMPs and observation wells within the model domain.

Groundwater elevations: Groundwater elevations have been collected by the Boston Groundwater Trust (BGwT) since 1999 throughout the proposed study area at geospatially-referenced observation wells. In addition, new observation wells are installed annually resulting in varying record lengths of groundwater observations. Given the urban location of the observation wells, it is sometimes difficult to locate and measure groundwater elevations during winter months due to snow and ice cover. This variability in data collection resulted in an average time between measurements of 56 days with a standard deviation of 23 days, indicating high variability in the timing of groundwater observations. Because the largest spatial dataset of groundwater elevations are manually collected observations, a time-lag, k, (in days between observations) was used to account for the irregular time intervals between observations.

Precipitation: Daily weather observation data was collected from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center for the Boston Logan International Airport (KBOS) weather station to serve as a proxy for precipitation inputs to the model. Due to the variability in the elapsed time between observations (k), various precipitation terms were tested as explanatory variables. The following precipitation variables (in feet) were considered: precipitation that occurred the day of the well observation (P_{day}), the precipitation on the previous day (P_1), the cumulative precipitation a week prior (P_7), and the cumulative precipitation between well observations (P).

Potential Evapotranspiration: Hodgson (1978) suggested that transpiration can affect an observed groundwater elevation at time t (see eqn. 1). To mimic the impact of variations in transpiration we estimated daily potential evapotranspiration (PET) using the Hargreaves method (Shuttleworth, 1993) where

$$PET = 0.0023 S_O (T + 17.8)\sqrt{\delta_T} \quad \text{(mm/day)} \qquad (2)$$

where PET is the daily potential evapotranspiration in mm/day, S_O is the extraterrestrial radiation measured in water equivalent in mm/day, T is the average daily temperature in degrees Celsius, and δ_T is the difference between daily maximum and daily minimum temperatures in degrees Celsius. PET variables were adjusted to feet per day for inclusion in the model. PET is the maximum rate at which evapotranspiration would occur with access to an unlimited supply of water. Therefore, the estimated PET represents the maximum actual evapotranspiration (ET) that could possibly occur. The Hargreaves method was the highest ranked temperature based method for computing PET reported in comparisons reported in the ASCE Manual 70 (Jensen et al., 1990). Allen (1993) showed that the Hargreaves method performs well in a wide range of latitudes and climates for periods of five days or longer, without significant error. Among all temperature-based methods, the Hargreaves method is the only one recommended by Shuttleworth (1993).

BMP Recharge Capacity: A total of 79 recharge BMPs have been installed and were operational in Boston with 24 recharge BMPs installed within the study area. The total storage capacity of installed recharge systems within the study area is 9,050 cubic feet. Boston Redevelopment Authority (BRA) completes site reviews for requirements under Article 80 of the Boston code (zoning code) for any proposed new development or redevelopment within the city. Site plans submitted to BRA document recharge BMP designs to meet city requirements under both Article 80 and Article 32 in addition to State regulations for stormwater (310 CMR 10.00 and 314 CMR 9.00). The BRA maintains a database of impervious areas that contribute stormwater flow to onsite recharge BMPs, thereby reducing directly-connected impervious area within the study area. The location and capacity of all operational recharge BMPs were obtained from the BGwT. From this data, distances were obtained using geographic information systems (GIS) between each observation well and recharge BMP.

Multivariate Statistical Analyses:

Model Development: Ordinary least squares (OLS) multivariate regression procedures were used to estimate the model parameters of the following hybrid physical/statistical regional model:

$$GW_t = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n + \varepsilon_t \qquad (3)$$

where GW_t represents groundwater elevation at time t, X_1-X_n are observable physical explanatory variables, β_0-β_n are model coefficients, and ε_t are normally distributed model errors with zero mean and constant variance σ^2_ε. We expect a variety of explanatory variables to produce changes in water table elevations including recharge BMP capacity (Endreny and Collins, 2009); proximity of recharge BMPs to wells and other recharge BMPs; rainfall events and previous groundwater elevations.

To evaluate the influence of a single recharge BMP on groundwater elevations at a nearby well, the following explanatory variable is employed

$$BMP_i = \frac{Y_{i,t} * CAP_i}{D_{i,j}} \qquad (4)$$

where $Y_{i,t}$ 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 at site i in cubic feet and the variable $D_{i,j}$ is the distance in feet from the BMP_i to the well of interest, j.

The cumulative effect of recharge BMPs was computed for the entire Back Bay region as follows. The model assumes that the impact of recharge BMPs are additive so that the cumulative impact of BMPs could be defined as

$$\sum BMP = \sum_{i=1}^{n} \frac{Y_{i,t} * CAP_i}{D_{i,j}} \tag{5}$$

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 total number of BMPs in the region. The assumption inherent in (5) is the principle of superposition. In general, superposition assumes that two differential equations, in this case two-dimensional groundwater flow and a recharge BMP, are linear and additive (for a full description of superposition, the reader is referred to Bear (1972) and Stack (1989)). As described by Stack (1989), superposition is valid for unconfined groundwater flow with rainfall and radial flow toward a well. In this instance, the well represents the recharge BMP with a negative discharge, and hence we must assume radial flow away from the well. Explicit assumptions for the principle of superposition are that the lower aquifer boundary is impermeable, flow in the aquifer is horizontal, and that the hydraulic conductivity is uniform. As documented in historic reports, fill material was deposited on estuarine clays which can be considered impermeable. Horizontal flow within the groundwater system can be assumed as suggested by Freeze and Witherspoon (1967) since the groundwater system has little variability in topographic elevation in addition to being identified as a local system without deep recharge of a regional groundwater system. Local variability in hydraulic conductivity is likely given the urban infrastructure within the study area; however, as described later in this report, explanatory variables included in the regional model were found to reflect the physical geohydrologic structure of the aquifer.

Although our primary regional model employs the $\sum$BMP term in (5), a second regional model, which determines the average impact from individual BMPs, was also developed using similar methods as described here. A description of that model, including results and analysis for the individual BMP model is provided in Appendix A.

Table 1 summarizes the explanatory variables considered for inclusion in the final multivariate statistical model

Model Screening: To decide which of the explanatory variables in Table 1 to include in the model, various multivariate model selection methods were employed in Minitab® (Release 15) including stepwise regression analyses and best subsets regression. Backward elimination and forward selection stepwise regression methods were used to identify explanatory variables to predict groundwater elevations using potential explanatory variables summarized in Table 1. Goodness of fit of resulting models was evaluated by comparing Mallows Cp, prediction sum of squares (PRESS), Nash-Sutcliff Efficiency (NSE) and prediction R^2.

Table 1: Potential Explanatory Variables

Explanatory Variable Description	Variable Name	Data Source	Units	Comments
Observed Groundwater elevation at time t	GW_t	BGwT	ft	234 observation wells used in this study
Previous recorded groundwater elevation k days prior to GW_t	GW_{t-k}	BGwT	ft	Same as above
Precipitation	P_{day}, P_1, P_7, P	NCDC	ft	Precipitation obtained from Boston Logan Airport
Time Lag Between Two Groundwater Elevation Measurements	k, Days	BGwT	day	k: cumulative time between observations. Days: Day 1= January 1, 1999
Potential evapotranspiration	PET_{day}, PET_1, PET_7, PET	BGwT/ Eqn 2	ft/day	PET is cumulative PET between observations.
Recharge BMP terms	$\sum BMP = \sum Y \cdot CAP/D$	BGwT/GIS Eqn 5	ft^3/ft	CAP is storage capacity in cubic feet, Y is indicator variable (1 or 0), D is distance in feet

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

$$PRESS = \sum_{i=1}^{n} e_{(i)}^2 \qquad (6)$$

where $e_{(i)}=(y_i - \hat{y}_i)$ represents the regression residual computed by deleting the i^{th} observation. In practice, PRESS is termed a delete-one residual and provides a validation estimate of regression error. To improve model prediction, influence and leverage statistics were also calculated to isolate observations that exhibit unrealistic influence on regression model parameter estimates. Another attractive metric of the overall goodness-of-fit is the Nash-Sutcliffe efficiency criterion:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (GW_{t,i}^{obs} - GW_t^{pred})^2}{\sum_{i=1}^{n} (GW_t^{obs} - \overline{GW})^2} \tag{7}$$

where GW_t^{obs} represents the observed groundwater elevation at time t, GW_t^{pred} represents the predicted groundwater elevation at 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. An advantage of NSE over other goodness fit metrics is that it is impacted by both cross correlation and bias between the observations and predictions.

After evaluating dozens of alternative models using the above model screening and diagnostic procedures, the following general model form was chosen:

$$GW_t = \beta_0 + \beta_1 GW_{t-k} + \beta_2 P + \beta_3 k + \beta_4 PET_1 + \beta_5 \sum BMP + \varepsilon_t \tag{8}$$

A summary of the model coefficients for the multivariate model given in (8) is provided in row 5 of Table 2. Table 2 reports numerous models each with improved goodness-of-fit as significant explanatory variables are introduced. The final model shown in the fifth row is recommended for use in practice because it exhibits the lowest PRESS and the highest Prediction R^2, both validation type statistics which are likely the best overall measures of goodness of fit. The values shown in parentheses in Table 2 are the t-ratios of each model coefficient defined as the ratio of the model coefficient divided by its standard deviation. The t-ratios reported in Table 2 are uniformly large, which indicates that the estimated model coefficients are extremely stable. For example, a t-ratio of 63.99 for the model coefficient for the precipitation term indicates that the model coefficient is 63.99 standard deviations away from zero! Such large t-ratios indicate that the model coefficients are known with an extremely high degree of precision.

Table 2: Summary of Regional Groundwater Model

$$GW_t = \beta_0 + \beta_1 GW_{t-k} + \beta_2 P + \beta_3 k + \beta_4 PET_1 + \beta_5 \sum BMP + \varepsilon_t$$

Model	β_0	β_1	β_2	β_3	β_4	β_5	Adj-R^2	Pred-R^2	NSE	SE	PRESS
1	0.36 (16.6)	0.93 (234.3)					87.5%	87.5%	0.88	0.52	2151.
2	-0.16 (-7.33)	0.94 (273.5)	0.83 (48.4)				90.6%	90.6%	0.91	0.46	1683
3	0.12 (5.23)	0.94 (281.8)	1.19 (52.9)	-0.009 (-25.4)			91.2%	91.2%	0.92	0.45	15911
4	0.28 (11.9)	0.95 (303.6)	1.24 (59.5)	-0.01 (-31.1)	-389.2 (-21.7)		92.4%	92.4%	0.92	0.41	1345
5	**0.24** (10.5)	**0.95** (324.5)	**1.25** (64.0)	**-0.01** (-31.7)	**-401.0** (-24.0)	**0.016** (5.85)	93.4%	93.4%	0.92	0.38	1091

Goodness of fit

Table 2 documents that for our recommended model, the prediction R^2 value was 93.4%, indicating that the model accounts for approximately 93% of the variability in groundwater observations within Back Bay. Since the prediction R^2 is a validation type statistic, we expect similar goodness of fit when the model is employed in prediction mode. The NSE value is 0.92, with average prediction error (SE) of 0.38 feet. Figure 2 illustrates the model goodness of fit by comparing the calibration results with actual observed values. The calibration data included observations collected from June, 1999, to September, 2009. Results in Figure 2 indicate that the regional groundwater models can predict observed groundwater elevations with a relatively high level of confidence and little or no bias.

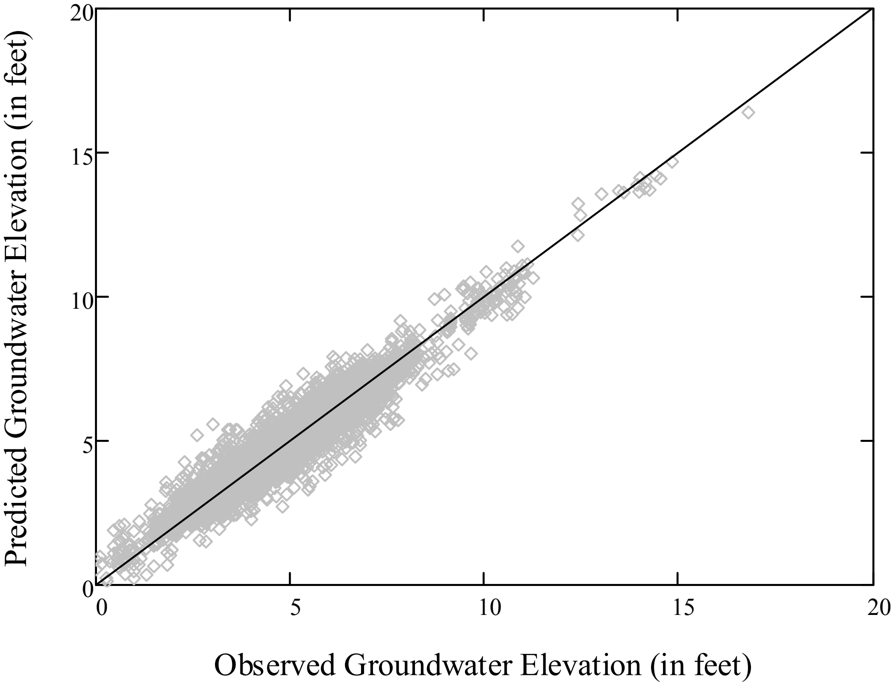

Figure 2: Comparison of Predicted and Observed Groundwater Elevations Corresponding to Model Calibration

<u>Discussion</u> It is important to realize that regression methods yield an estimate of the conditional mean value of the variable of interest, in this case the groundwater elevation at a particular well location. Thus our regression model provides an estimate of the conditional mean groundwater elevation as a function of previous groundwater elevations, time lag since that observation, precipitation and potential evapotranspiration, and the impacts of the location and capacity of various installed BMPs. The final regional model given as model 5 in Table 2 can be summarized as

$$GW_t = 0.24 + 0.95GW_{t-k} + 1.25P - 0.01k - 400.99PET_1 + 0.016\sum BMP \qquad (9)$$

The regional regression model documents that the recharge BMPs have a statistically significant positive impact on average groundwater elevations. The model coefficient for the BMP term was found to be 0.016 with a t-ratio of 5.85. This implies that the model coefficient has a standard deviation of only 0.0027; thus, we are quite confident of the value of this coefficient. The BMP model coefficient 0.016 represents the positive change in predicted groundwater elevation, on average, that would occur by holding all other explanatory variables constant. For example, a 1 ft^3 recharge BMP installed 1 foot from an observation well would, on average, increase the observed groundwater elevation by 0.016 feet. It is important to note that this coefficient represents the average expected increase in groundwater elevations across the region; this assumption is important given that possible conditions at specific well locations will display either more or less of an increase in observed groundwater elevations. However, across Back Bay, the coefficient provides an average impact that will likely occur at any specific location.

Model validation Cross validation methods were conducted to evaluate the application of the recommended model to situations not considered when fitting the original model summarized in Table 2. Model cross validation was conducted using a standard method of blind testing, or validating the model with new data not used in the model calibration. Additionally, repeated random sub-sampling was employed where the calibration data was randomly split into validation and training data sets. Model split-sample validations were conducted by using 50% of the calibration data (4,007 observations) as the training data set, with the remaining 50% of the data used for cross validation. The random sub-sampling procedure was repeated 100,000 times to increase the probability that observations were selected for both the calibration and validation data sets during the validation procedure.

Figure 3 illustrates box plots for estimates of the model coefficient associated with the variable $\sum$BMP obtained in the random sub-sampling validation compared to the multivariate model results included in Table 2. Figure 3 illustrates that the variability in the $\sum$BMP term coefficient is small and averages to the value summarized in Table 3. These results indicate that it is highly likely that a similar model coefficient would be obtained, regardless of the particular observations used in the development of the model. The results also indicate that the model predicts the impact of recharge BMPs on observed groundwater elevations with a relatively high degree of precision. Also reported in Figure 3 is the variability in the NSE for the validation and training sets. Apparently the variability in NSE values was quite similar for both the calibration and validation datasets. Overall, Figure 3 documents that the model effectively predicts observed groundwater elevations. Analyses of other model coefficients given in (9) are included in Appendix B.

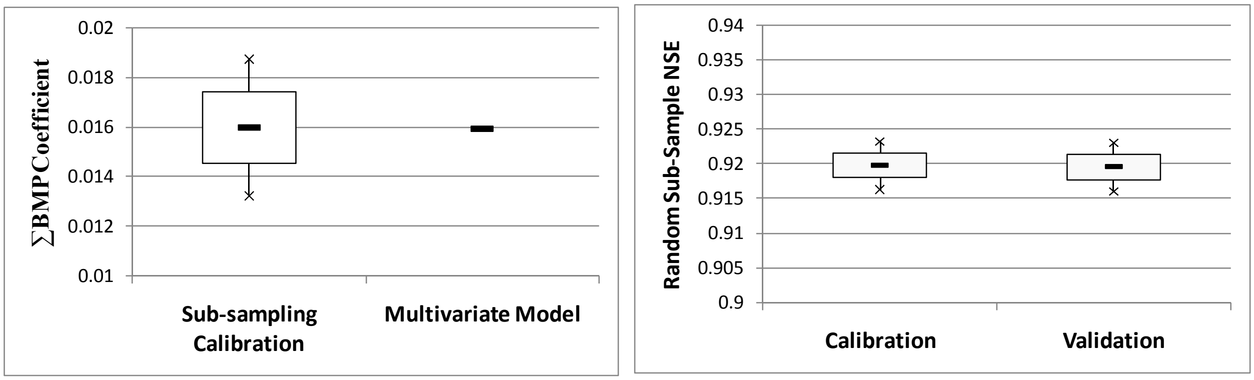

Figure 3: Nash Sutcliffe Efficiency and BMP Model Coefficient Cross- Validation Results

Blind-sample validation

A second data set of observed groundwater elevations from October, 2009, to June, 2010, was obtained from BGwT and used to conduct a blind-sample validation. These observations were not used in the development of the regression model reported above. Model performance was tested by comparing observed data to predicted groundwater elevations as illustrated in Figure 4. Results indicate once again, that the model in equation (9) was able to accurately reproduce observed values with a NSE of 0.87.

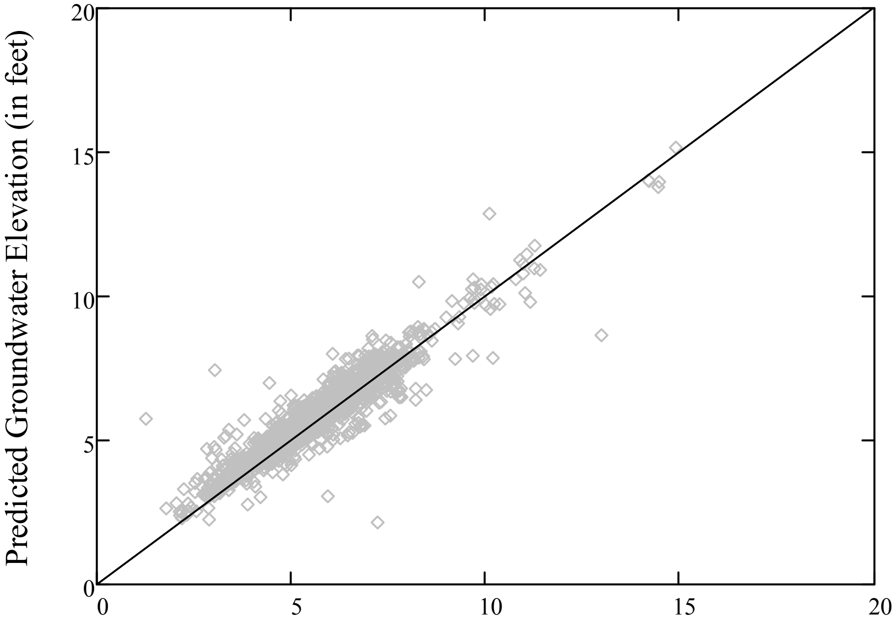

Figure 4: Blind Sample Model Validation

Overall, our validation results indicate a high degree of stability in model parameter estimates and model performance. These results indicate that the model coefficients are stable and within a reliable range to conduct additional analyses which employ the resulting models to explore the impact of future stormwater BMP recharge facilities in the Back Bay on groundwater elevations.

Application of Regional Groundwater Model

Impact of an Individual Recharge BMP: The model coefficient for the ∑BMP term given in Table 2 can be used to predict the average increase in groundwater elevations at a particular location which will result from a recharge BMP of known capacity located a specific distance from the location of interest. Given the resulting model coefficient for the ∑BMP term, the impact of a particular recharge BMP can be represented graphically as illustrated in Figure 5. Figure 5 documents the expected average rise in groundwater elevation given a specific recharge BMP capacity located a particular distance from a location of interest. For example, Figure 5 illustrates that a recharge BMP of 1,000 ft^3 capacity placed 500 feet from an observation well would, on average, increase groundwater elevations by 0.03 feet.

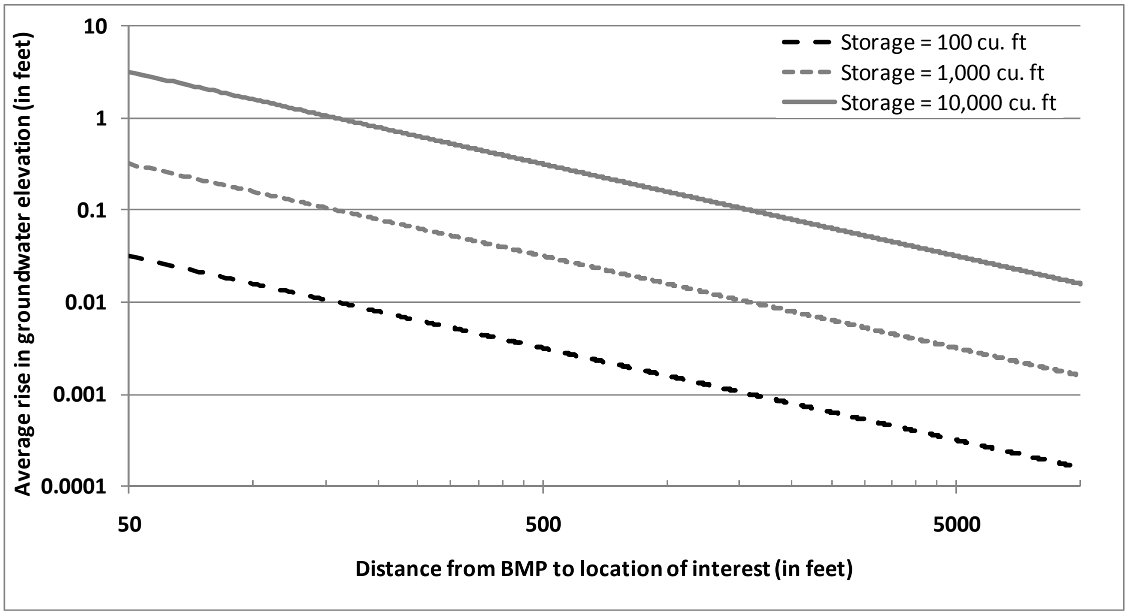

Figure 5: Relationship between the average rise in groundwater elevations and the distance from the BMP to the location of interest for several different BMP storage capacities

Figure 6 also illustrates how the ∑BMP model coefficient can be used for recharge BMP planning. For example, if an increase in groundwater elevation of 0.20 feet was desired, with a recharge BMP storage capacity of 400 ft^3, the recharge BMP should be placed approximately 30 feet from the groundwater observation well.

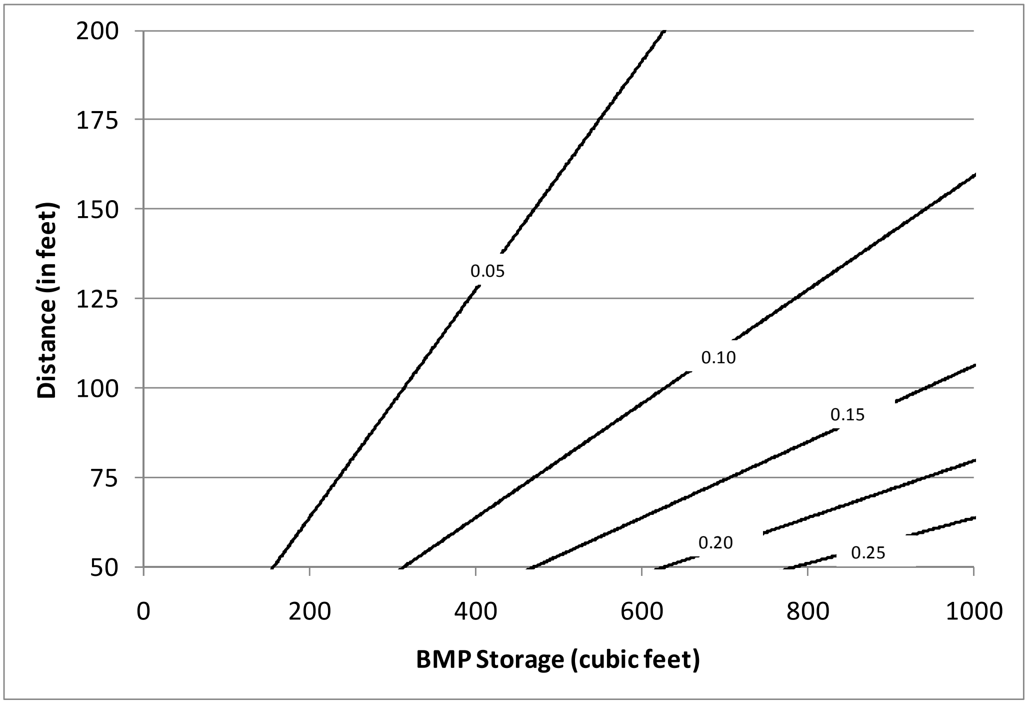

Figure 6: The average rise in groundwater, in feet, resulting from a recharge BMP of a particular installed capacity located a distance from a particular location of interest

The two graphical summaries shown in Figures 5 and 6 illustrate the predictive power of the model in equation (9). Figures 5 and 6 provide guidance on how to interpret the implications of the model for use in future stormwater recharge BMP planning.

We emphasize that the results in Figures 5 and 6 are based on the model summarized in equation (9) and Table 2 which was developed using all the existing recharge BMPs installed as of September 2009. As future BMPs are added to the Back Bay region, the results shown in Figures 5 and 6 may change and may need to be updated. However, our validation experiments reported earlier indicate rather robust results, regardless of the number of well observations considered in the development of the model.

The Impact of a System of Recharge BMPs The BMP groundwater model given in equation (9) can also be used to evaluate the impact of an installed system of future recharge BMPs. For illustrative purposes, three recharge BMP scenarios were developed to illustrate the application of equation (9) for stormwater planning. The following three scenarios are considered:

Case 1: Single recharge BMP per block; located centrally; 280 ft^3 capacity
Case 2: Two recharge BMPs per block; located centrally; 280 ft^3 capacity
Case 3: BMPs placed at approximately every 10th building; approximately 6 BMPs per block; 280 ft^3 capacity
Case 4: Remove all existing BMP's so that there are no recharge BMP's installed

For each of the above cases, the ∑BMP term given in equation (5) is estimated using assumed location and capacities for each case and the results of the analysis are illustrated in Figure 7. Case 1 resulted in an average groundwater elevation increase of 0.12 feet, with local areas experiencing an increase of up to 0.15 feet. Case 2 resulted in an average increase of 0.23 feet, with local areas seeing an increase of up to an average of 0.30 feet. Case 3 increased average groundwater elevations by 0.74 feet, with areas with multiple recharge BMPs experiencing up to a 0.95 foot increase in groundwater elevations.

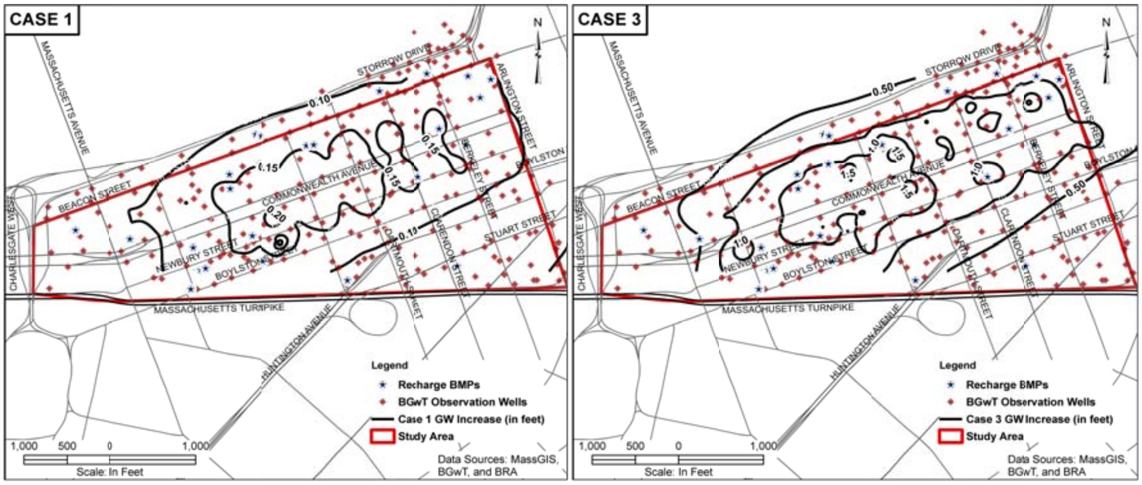

Figure 7: Results from Case 1 (left) and Case 3 (right) documenting the average impact of recharge BMPs to groundwater elevations.

These results indicate that the regional BMP groundwater model can be used to assess the potential average groundwater increase across the Back Bay Region resulting from various installed BMP recharge facilities.

In addition case 4 considered the removal of all existing recharge BMP's from the Back Bay region. This was accomplished by simply setting the BMP term in the model to zero and reapplying the model at each of the well locations. This resulted in decreases in the average groundwater levels for all regions across the site. The average reduction in groundwater elevation was 0.09 feet, however, reductions ranged from -0.04 to -0.32 feet when the existing recharge BMP were artificially removed from the Back Bay region.

Conclusions

Multivariate statistical methods were employed to develop a relationship between groundwater elevations in the Back Bay region of Boston and various explanatory variables, including rainfall, potential evapotranspiration, previous groundwater elevations and the location and capacity of installed stormwater recharge BMPs. Our results document that the inclusion of recharge BMP variables into the regression equations leads, on average, to very small but positive and significant increases on groundwater elevations across the Back Bay region of Boston. Our regional model indicates that well elevations are most impacted by previous well elevations and the recharge which results from the precipitation which occurred since those previous well elevations were observed. We also show how the resulting models can be useful for determining the influence of future BMP installations on groundwater elevations in the Back Bay region of Boston.

The multivariate statistical regression models introduced here are analogous to the water balance equation introduced by Hodgson (1978) for a typical groundwater system (see eqn. 1). 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-k}
SR	→	P
T	→	PET_1
UR	→	$\sum BMP$
UD	→	Regression constant and k

Although our approach is based primarily on the theory of statistics, it is also based on the physical water balance given by Hodgson (1978) which is similar to Scanlon et al. (2002). The regression constant and the time lag between well observations, k, 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 elevations indicates that the relationship between current and previous groundwater elevations 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 the regional model. Goodness of fit statistics including the Nash-Sutcliffe efficiency criterion and prediction R^2 indicate excellent goodness of fit. Additional model split-sample, cross-validation and blind-validation analyses were performed to ensure that model coefficients exhibited the type of stability needed to ensure that model applications would be meaningful.

Perhaps the most important result of this study is that the regional models described here can be used to predict the impact of future BMP installations on groundwater elevations, because the models relate the average increase in groundwater elevations at a particular location to the capacity, time of installation and location of a particular BMP recharge tank or a set of such tanks. The results of the various case studies documents that groundwater elevations generally are not drastically increased over the site until multiple recharge BMPs are placed throughout the study site given the small but significant effect of the recharge BMPs to observed groundwater elevations.

We caution users of the model developed in this study to be aware that the model should only be used within the limits of the study region considered, and for recharge BMP’s which are within the range of capacities considered in the development of our model (168 – 2,168 cubic feet).

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Appendix A – Regional Model for Impact of a Single Recharge BMP

Multivariate Statistical Analyses:

Model Development: Given the heterogeneity in the subsurface aquifer material and potential interference due to urban infrastructure, it was assumed that each recharge BMP would impact the observed groundwater elevation differently for the model described in this section which treats the effects of each BMP separately. In this section we include the impact of each BMP using the term BMP_i given in equation (4). Recall that BMP_i describes the impact of each individual recharge BMP_i on the well of interest j. This analysis resulted in a regression dataset that included 24 observations (corresponding to 24 BMP's) for each groundwater elevation observation at time t at well j.

The explanatory variables summarized in Table 1 were also considered for inclusion in the final multivariate statistical model as described in Appendix A.

Model Screening:

After evaluating dozens of alternative models using model screening and diagnostic procedures as described in the preceding report, the following general model form was chosen:

$$GW_t = \beta_0 + \beta_1 GW_{t-k} + \beta_2 P + \beta_3 k + \beta_4 PET_1 + \beta_5 BMP_i + \varepsilon_t \tag{A.1}$$

Equation (A.1) has a similar form to Equation (8) except that BMP_i replaces $\sum BMP$. A summary of the model coefficients for the multivariate model given in (A.1) is provided in row 5 of Table A.1. Table A.1 reports numerous models each with increasingly better goodness-of-fit as significant explanatory variables are introduced.

Table A.1: Summary of Individual BMP Groundwater Model

$$GW_t = \beta_0 + \beta_1 GW_{t-k} + \beta_2 P + \beta_3 k + \beta_4 PET_1 + \beta_5 \sum BMP + \varepsilon_t$$

Model	β_0	β_1	β_2	β_3	β_4	β_5	Adj-R^2	Pred-R^2	NSE	SE	PRESS
1	0.40	0.92					86.6%	86.6%	0.89	0.56	47540
	(78.1)	(988)									
2	-0.14	0.94	0.81				90.0%	90.0%	093	0.48	34511
	(-27.1)	(1158)	(201)								
3	0.13	0.94	1.19	-0.008			91.2%	91.2%	0.93	0.45	30090
	(23.9)	(1227)	(231)	(-112)							
4	0.29	0.95	1.25	-0.01	-398.2		93.0%	93.0%	0.93	0.39	22796
	(55.4)	(1376)	(272)	(-146)	(-100)						
5	0.26	0.95	1.25	-0.01	-401.7	0.088	93.5%	93.5%	0.93	0.38	20696
	(51.8)	(1419)	(279)	(-147)	(-105)	(12.5)					

Goodness of fit

Table A.1 documents that for our recommended mode in row 5; the prediction R^2 value was 93.5%, indicating that the model explains approximately 94% of the variability in groundwater observations within Back Bay. Since the prediction R^2 is a validation type statistic, we expect similar goodness of fit when the model is employed in prediction mode. NSE values were 0.93, with average prediction error (SE) being 0.38 feet. Figure A.1 illustrates the model goodness of fit by comparing the calibration results with actual observed values. The calibration data included all observations collected from June, 1999, to September, 2009. Results in Figure A.1 indicate that the regional groundwater models can predict observed groundwater elevations with a relatively high level of confidence and no bias.

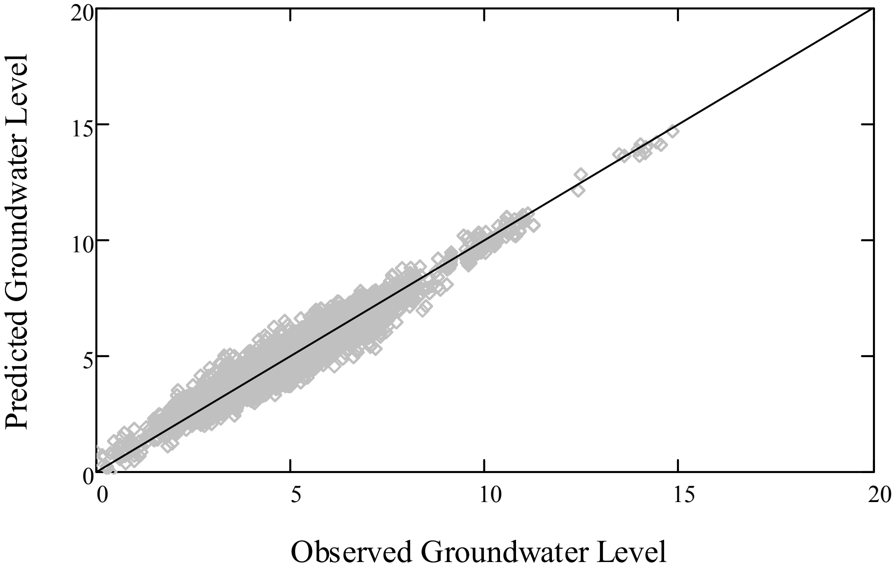

Figure A.8: Comparison of Predicted and Observed Groundwater Elevations Corresponding to Model Calibration

Discussion The final regional model given as model 5 in Table A.1 can be summarized as

$$GW_t = 0.24 + 0.95GW_{t-k} + 1.25P - 0.01k - 401.7PET_1 + 0.088BMP_i \quad \text{(A.2)}$$

The regional regression model documents that individual recharge BMPs have a statistically significant impact on average groundwater elevations. The model coefficient for the BMP term was found to be 0.088 with a t-ratio of 12.5. This implies that the model coefficient has a standard deviation of only 0.007; thus, we are quite confident of the value of this coefficient. The BMP model coefficient represents the change in predicted groundwater elevation, on average, that would occur by holding all other explanatory variables constant. For example, a 1 ft^3 recharge BMP installed 1 foot from an observation well would, on average, increase the observed groundwater elevation by 0.088 feet. It is important to note that this coefficient represents the average expected increase in groundwater elevation at a well j caused by an individual recharge BMP at site i; this assumption is important given that possible conditions at specific well locations will display either more or less of an increase in observed groundwater elevations. It is also important to note that this model does not include the regional impact of all the recharge BMP's installed in the Back Bay region, which is why the predicted increase is quite different than for the previous model described in the main text. This single BMP model described in this appendix documents the average impact of a single BMP on nearby groundwater elevations and is not as accurate the model described in the main text which includes the impact of all recharge BMP's within the region.

Model validation A secondary data set of observed groundwater elevations from October 2009 to June 2010 was obtained from BGwT to conduct blind-sample model validation. Model performance was tested by comparing observed data to predicted values as illustrated in Figure A.2. Results indicate that the model in equation (A.2) was able to accurately reproduce observed values with a NSE of 0.87.

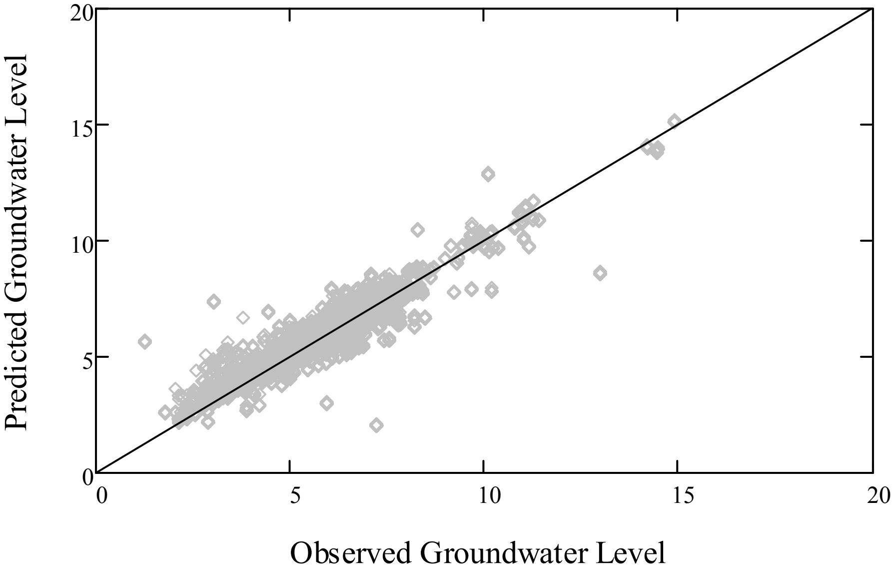

Figure A.9: Blind Sample Model Validation

Overall, our validation results indicate a high degree of stability in model parameter estimates and model performance. These results indicate that the model coefficients are stable and within a reliable range to conduct additional modeling which explore the impact of future additions of stormwater BMP recharge facilities in the Back Bay.

Appendix B – Validation of Regression Model Coefficients

In this section we illustrate boxplots for other model coefficients than the BMP term considered in the main text. Figure B.1 illustrates boxplots of the model coefficients which were obtained from random sub-sampling validation experiments. Those boxplots are compared to the model coefficients reported in Table 2 (labeled as Multivariate Model).