Impact of Storm Water Recharge Practices on Boston Groundwater Elevations

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Abstract: 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 storm water recharge practices for any activity that triggers the zoning bylaw. In Boston, recharge to the water table results from the infiltration of rainfall and snowmelt, leakage from water mains, and recharge from artificial 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 artificial systems, including pump and infiltrate systems and storm water recharge best management practices (BMPs). The primary objective of this research was to exploit existing information on groundwater elevations and recharge practices to quantify the effect of the required recharge BMPs on the behavior of groundwater elevations in the Back Bay region of Boston. Regional multivariate regression models were developed to determine the potential effects of recharge BMPs on observed groundwater elevations. The literature review revealed several analogous multivariate linear regression studies, none which focused on behavior of stormwater BMPs. The model reveals that the installation of recharge BMPs has a small but highly statistically significant positive effect 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 model can be used to predict the effect 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. **DOI:** 10.1061/(ASCE)HE.1943-5584.0000534. © *2012 American Society of Civil Engineers.*

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Introduction

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

The effect 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 because of leakage from water and sewer systems (Foster et al. 1999; Lerner 1990). Changes in urban groundwater elevations that result from anthropogenic alterations can result in expensive consequences. For instance, declining groundwater elevations can cause land subsidence, building damage, and ecological habitat deterioration in groundwater-fed streams and wetlands. Likewise, rising groundwater elevations can cause increased infiltration into sewer and storm water 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 artificial systems (Aldrich and Lambrechts 1986). Otto et al. (2002) estimate lost groundwater infiltration within Boston of 166.2—388 million cubic meters annually because of increased impervious areas. Overall, the Back Bay region of Boston has experienced periodic declines in groundwater elevations potentially caused by a combination of decreased infiltration because of increased impervious area and active mitigation management for both water and sewer leaks. In the Back Bay region of Boston (Fig. 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.

In an effort to mitigate the anthropogenic effects 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 storm

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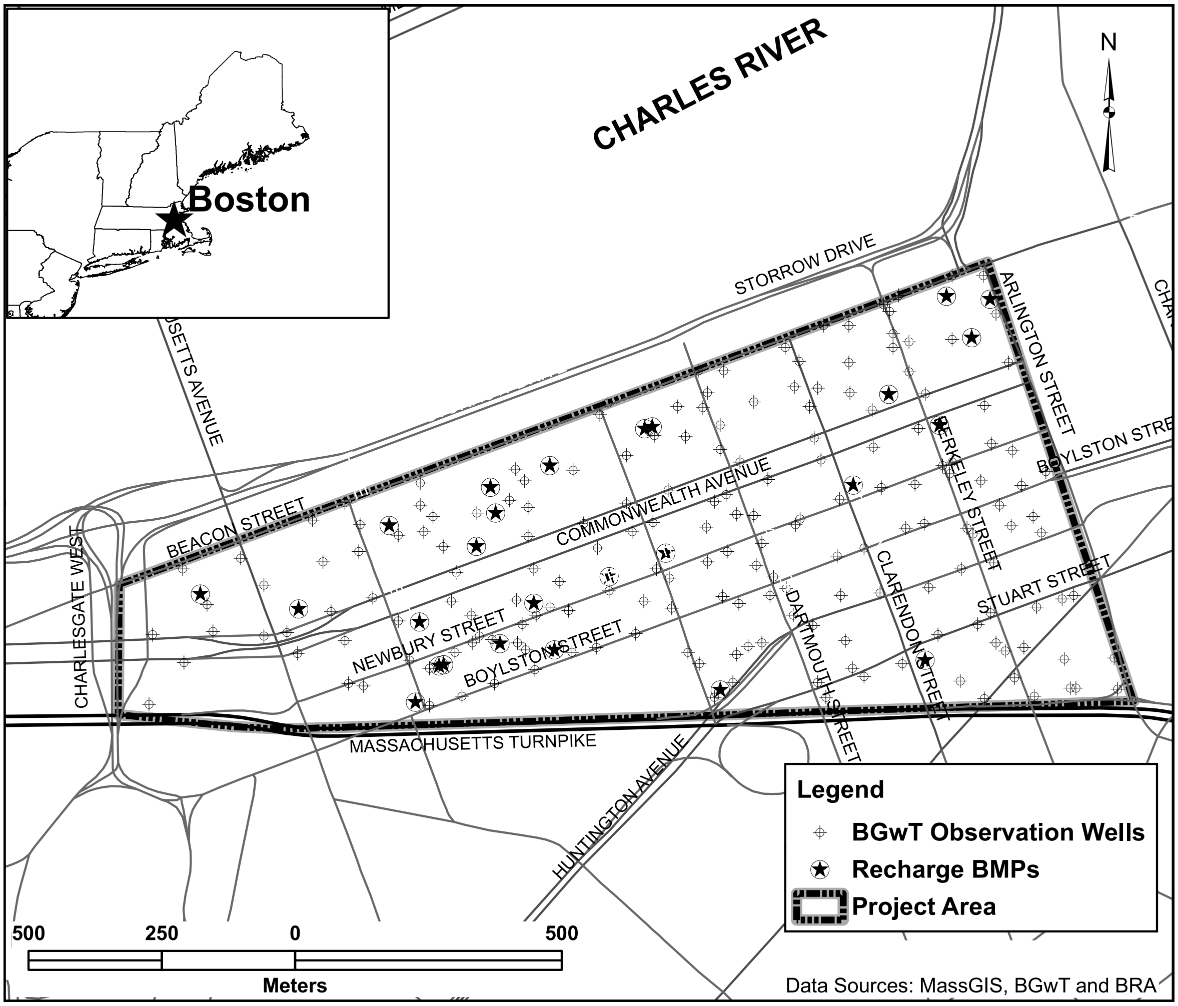

Fig. 1. Boston Back Bay model domain

water 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 up to the first 25.4 cm of precipitation depth from the portion of the project triggering the zoning article. Excess rainfall overflows from the recharge systems are directed to the city storm water system. From 2006 to 2010, a total of 79 recharge BMPs had been installed throughout Boston. This potential recharge capacity of the installed recharge BMPs totaled 1,188 m^3 of recharge. Of these, 24 recharge BMPs have been installed within the study area in the Back Bay region of Boston (Fig. 1), totaling an estimated potential recharge of 256 m^3, which averages to 0.25 mm of precipitation being directly recharged to the subsurface over the Back Bay area for each storm event.

Storm water management using infiltration strategies has been shown to reduce storm water 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's County 1999; USEPA 2002). To date, few studies have investigated the temporal and spatial effects of such storm water management practices. Recently, studies have investigated changes to peak-flow discharges in urban environments using infiltration-based strategies (Holman-Dodds et al. 2003; Perez-Pedini et al. 2005), which indicated sensitivity of mitigation benefits because of the location of infiltration sites. Similarly, Gilroy and McCuen (2009) found that reported storm water benefits would be minimal if detention basins were not placed properly to mitigate storm water runoff. Spatial storm water management strategies have been evaluated for their ability to affect 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 because of spatial arrangements of bioretention basins. Likewise, Machusick et al. (2011) found that BMP design mitigated groundwater mounding and the effectiveness of groundwater observations in design of recharge systems. Understanding the effect of storm water mitigation strategies such as recharge BMPs on urban groundwater systems is difficult because of 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 is a unique urban environment because groundwater elevations have been recorded regularly at observation wells to monitor the potential effect of changes in groundwater levels on wood piles that support the buildings. Therefore, a large spatial and temporal data set 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 effect of recently introduced storm water recharge BMPs on the behavior of groundwater elevations in Boston. A mathematical model is needed that is able to sort out the complex interactions among all the factors that control groundwater elevations in an urban environment. Any previous studies that developed modeling methods that could be readily applied to evaluate the effect of BMPs on average groundwater elevations on a regional basis were not found. Groundwater elevations are affected by the heterogeneous subsurface environment and by leaks in the storm water, 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 that accounts for all of these factors. For example, Carneiro and Carvalho (2010) report the difficulty in groundwater model implementation in an urban environment at a similar scale (approximately1 km^2). The authors report that the greatest difficulty in model calibration was spatial recharge and argued for the need of future research; this paper presents an alternative method employing multivariate linear regression to detect the effect of recharge BMPs to groundwater elevations.

Previous investigations that have attempted to model groundwater elevation changes because of storm water management (Endreny and Collins 2009; Gobel et al. 2004) have used site-specific groundwater flow models to determine groundwater effects from infiltration. The difficulty in creating a model of an urban groundwater environment arises from the heterogeneity of the system because of both variability in hydrogeologic conditions and urban infrastructure (Carneiro and Carvalho 2010). A transient groundwater model becomes even more difficult to calibrate, validate, and simulate scenarios because of 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 because of recharge practices are statistically significant. Other methods may be available for evaluating such changes, for example perturbation modeling or stochastic groundwater modeling approaches (Li et al. 2003; Yi and Lee 2004); however, such approaches are far more complex to apply than the approach described in this paper.

Because a very large database of groundwater elevations is available from 234 observation wells throughout the study area over the period 1999–2010, a hybrid multivariate statistical/physical modeling approach, which is able to exploit all available well data combined with climatic, land-use data, BMP location, and capacity data, was taken. The approach was to develop a spatial multivariate statistical model that accounts for the primary determinants of changes in groundwater elevations in an urban environment. Such a regional statistical approach is useful because it enables the making of quantitative and rigorous statements regarding the significance of the various factors that govern groundwater elevations in an urban environment including recently introduced recharge BMPs.

A second goal of the study was to identify the regional average effect of all the currently installed recharge BMPs on groundwater elevations under historical conditions and a variety of future storm water recharge BMP planning scenarios. Although the model described in this paper was developed for the case study of Boston, the modeling approach taken and its application for evaluating future storm water BMP policies could be applied to any urban environment with necessary adaptations where appropriate, such as groundwater extractions, leaking water mains, and groundwater gradients. The results document the effect of the transient recharge caused by the installation of recharge BMPs to average long-term groundwater elevations throughout the Back Bay region of Boston.

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 using

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

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

In summary, several previous studies used MLR to estimate groundwater elevations on the basis of 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 on groundwater systems that could be used to predict groundwater elevations. The study extends these previous studies to include the effect of storm water recharge BMPs on groundwater elevations.

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 artificial recharge systems. Although pumping activities are known to exist near the study area because of 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 Eq. (1) to account for their potential effect on groundwater elevations. For example, the distance between a recharge BMP and an observation well and the capacity of the BMP should affect observed groundwater elevations. This paper shows an attempt to fit multivariate statistical models that predict the groundwater elevation at a particular location and time period as a function of numerous potential explanatory variables, including previous groundwater elevation, precipitation, and potential evapotranspiration, and the distance and capacity of recharge BMPs and several other explanatory variables described subsequently.

The study area shown in Fig. 1 is the Back Bay region of Boston, an area of the city created by the filling of the Charles River estuary beginning in the 1840s. The study area is underlain by an unconfined aquifer system composed of a mixture of sand and gravel and urban fill deposited on silt and clay. The eastern and southern boundary of the study area represents the extent of filled land. The northern boundary running along Beacon Street represents a no-flow condition because of the presence of the Old Mill Dam, constructed in 1829, which remains under the street. To the west, the boundary represents a variable head boundary, Muddy Brook, which flows into the Charles River. A total of 24 recharge BMPs and 234 observation wells are located within the study area with 8,014 groundwater elevation observations. Because the study area is made up of several hundred individual well locations, the model is referred to as a "regional" model.

Data

The data necessary for the proposed models include time series of daily precipitation, climatic effects, historic groundwater elevations, recharge BMP capacity, and locations of all recharge BMPs and observation wells within the model domain. A summary of potential explanatory variables is shown in Table 1.

Groundwater elevations: Groundwater elevations have been collected by the Boston Groundwater Trust (BGWT) since 1999 throughout the study area at geospatially referenced observation wells. In addition, new observation wells are installed annually, resulting in varying record lengths of groundwater observations. Because groundwater elevations were collected spatially on a predefined grid within the study area, there did not exist a particular day at which all groundwater elevation readings were completed. Hence, resulting groundwater elevation data are unequally spaced. Given the urban location of the observation wells, it was sometimes difficult to locate and measure groundwater elevations during winter months because of snow and ice cover. This variability in data collection resulted in an average time between groundwater measurements of 56 days with a standard deviation of 23 days, indicating high variability in the timing of groundwater observations. Given that the largest spatial data set of groundwater elevations are manually collected observations, a timelag, k, in days between observations at each individual well site was used to account for the irregular time intervals between observations.

Climate: Daily weather observation data were 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. Because of the variability in the elapsed time between observations (k), various precipitation terms were tested as explanatory variables. The following precipitation variables in meters 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_k).

Potential evapotranspiration: Hodgson (1978) suggested that transpiration can affect an observed groundwater elevation at time t [see Eq. (1)]. To mimic the effect of variations in transpiration, daily potential evapotranspiration (PET) was estimated using the Hargreaves method (Shuttleworth 1993) given by

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

where PET = daily potential evapotranspiration in mm/day; S_O = extraterrestrial radiation measured in water equivalent in mm/day; T = average daily temperature in degrees Celsius; and δ_T = difference between daily maximum and daily minimum temperatures in degrees Celsius. The PET variables were adjusted to meters per day for inclusion in the model. The Hargreaves method was the highest ranked temperature-based method for computing PET reported in comparisons reported in the ASCE *Manual of Practice No. 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 5 days or longer without significant error. Among all temperature-based methods, the Hargreaves method is the only one recommended by Shuttleworth (1993).

Daily potential evapotranspiration 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 and was used as a proxy for actual evapotranspiration. In this paper, PET represents the transient relationship between the groundwater elevations and both vegetative and atmospheric interactions. Initial evaluations considered use of individual tree locations mapped as part of the Greater Boston Urban Forest Inventory as input to the model. Experiments showed that inclusion of PET produced models with better goodness of fit measures than those which used individual tree locations. Future studies should consider regional calibration of any temperature-based estimates of PET using the more advanced and accurate Penman-Monteith approach (see Fennessey and Vogel 1996).

Capacity of recharge BMP: 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 256 m^3.

Table 1. Potential Explanatory Variables

Variable name	Description	Units	Data source
k	Time elapsed in days between observed groundwater elevations	Days	BGWT
	Ground water observations		
GW_t	Observed groundwater elevation at time t; 234 wells	m	BGWT
GW_{t-k}	Previous recorded groundwater elevation k days before GW_t	m	BGWT
	Climate variables		
P_{day}, P_1, P_7, P_k	Precipitation obtained from KBOS	m	NCDC
PET_{day}, PET_1, PET_7, PET	Potential evapotranspiration [Eq. (2)]	m/day	BGWT/NCDC
	Storm water recharge BMPs		
$\sum \text{BMP}$ with $q = 1$ or 2	Recharge BMP terms [Eq. (5)]	m^3/m^q	BGWT/GIS
$\sum \text{BMP} * P$ with $q = 1$ or 2	Recharge BMP interaction terms with precipitation interaction	$\text{m}^3/\text{m}^{q*}\text{m}$	BGWT/NCDC

Note: BGWT = Boston Groundwater Trust; GIS = geographic information system; KBOS = Boston Logan International Airport; NCDC = National Climatic Data Center.

The Boston Redevelopment Authority (BRA) completes site reviews for requirements under Article 80 of the Boston code for any proposed new development or redevelopment within the city. Site plans submitted to the BRA document recharge BMP designs to meet city requirements under both Article 80 and Article 32 in addition to state regulations for storm water (310 CMR 10.00 and 314 CMR 9.00). The BRA maintains a database of impervious areas that contribute storm water flow to on-site recharge BMPs, thereby reducing directly connected impervious area within the study area. The location, capacity, and date of installation of all operational recharge BMPs were obtained from the BGWT. From these data, distances between each observation well and recharge BMP were obtained using a geographic information system (GIS).

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:

$$\mathrm{GW}_t = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon_t \tag{3}$$

where GW_t = groundwater elevation at time t; $X_1, \ldots, X_n$ = observable physical explanatory variables; $\beta_0, \ldots, \beta_n$ = model coefficients; and ε_t = normally distributed model errors with 0 mean and constant variance σ_ε^2. 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; and rainfall events and previous groundwater elevations are expected.

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

$$\mathrm{BMP}_i = \frac{Y_{i,t} \times \mathrm{CAP}_i}{D_{i,j}^q} \tag{4}$$

where $Y_{i,t}$ = indicator variable that takes the value of 1 if the BMP is installed at site i at time t and 0 otherwise CAP_i = capacity of the BMP at site i in cubic meters; and $D_{i,j}$ = distance in meters from the BMP_i to the well of interest, j. The variable q, the power on the variable $D_{i,j}$, was tested at $q = 1$ and $q = 2$ as shown in Table 1.

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

$$\sum \mathrm{BMP} = \sum_{i=1}^{n} \mathrm{BMP}_i = \sum_{i=1}^{n} \frac{Y_{i,t} \times \mathrm{CAP}_i}{D_{i,j}^q} \tag{5}$$

where i = specific recharge BMP; $D_{i,j}$ = distance between BMP i and observation well j; and n = total number of BMPs in the region. The assumption inherent in Eq. (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 Strack (1989). As described by Strack (1989), the solution considering unconfined groundwater flow with rainfall and radial flow toward a well can be solved assuming superposition. For this evaluation, the well represents the recharge BMP with a negative discharge, and hence radial flow away from the well must be assumed. Explicit assumptions for the principle of superposition to solve radial flow from a well 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 (Seasholes 2003), 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) because 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 and historic documentation of filling of the study area (Seasholes 2003; Newman and Holton 2006). Such variability leads to violation of the assumption of uniform hydraulic conductivity. However, for the purpose of this study, it is assumed that Eq. (5) represents a superposition approach to physically describe the effect of the recharge BMPs on observed groundwater elevations.

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 using Minitab 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 (Helsel and Hirsch 2002). 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. The prediction sum of squares represents the regression residual computed by deleting the ith 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 exhibited unrealistic influence on regression model parameter estimates. Another attractive metric of the overall goodness of fit is NSE (Nash and Sutcliffe 1970). 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 affected by both cross correlation and bias between the observations and predictions.

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

$$\mathrm{GW}_t = \beta_0 + \beta_1 \mathrm{GW}_{t-k} + \beta_2 P_k + \beta_3 k + \beta_4 \mathrm{PET}_1 + \beta_5 \sum \mathrm{BMP} + \varepsilon_t \tag{6}$$

A summary of the model coefficients for the multivariate model given in Eq. (6) 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 of Table 2 is recommended for use in practice because it exhibits the lowest PRESS and the highest prediction R^2; both validation type statistics 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.

Table 2. Summary of Regional Groundwater Model Results

Model	Constant (β_0)	GW_{t-1} (β_1)	P_k (β_2)	K (β_3)	PET_1 (β_4)	$\sum$BMP (β_5)	Adjusted − R^2	Predicted − R^2	NSE	SE	PRESS
1	−0.11 (16.6)	0.93 (234.3)					87.5	87.5	0.88	0.16	2,151
2	−0.05 (−7.33)	0.94 (273.5)	0.83 (48.4)				90.6	90.6	0.91	0.14	1,683
3	0.04 (5.23)	0.94 (281.8)	1.19 (52.9)	−0.002 (−25.4)			91.2	91.2	0.92	0.14	1,591
4	0.09 (11.9)	0.95 (303.6)	1.24 (59.5)	−0.003 (−31.1)	−9.87 (−21.7)		92.4	92.4	0.92	0.13	1,345
5	**0.07** (10.5)	**0.95** (324.5)	**1.25** (64.0)	**−0.003** (−31.7)	**−10.19** (−24.0)	**0.052** (5.85)	93.4	93.4	0.92	0.13	1,091

Note: The table reports model coefficients (β's in Eq. (3)) along with their t-ratios in parentheses, adjusted and prediction R^2, NSE, SE in meters for each model, and PRESS; all coefficients were significant at the 1% level.

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Goodness of Fit

Table 2 documents that for the 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. Because the prediction R^2 is a validation type statistic, similar goodness of fit when the model is employed in prediction mode is expected. The NSE value is 0.92, with average prediction error (SE) of 0.11 m and root-mean square of the residuals (RMS) of 0.13 m. Fig. 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 Fig. 2 indicate that the regional groundwater model reproduces the observed groundwater elevations with a relatively high level of confidence and little or no bias.

Discussion

It is important to emphasize 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 conditioned on the various values of the explanatory variables. Thus, the 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 effects of the location and capacity of various installed BMPs. The final regional model given as model 5 in Table 2 can be summarized as

$$GW_t = 0.07 + 0.95GW_{t-k} + 1.25P_k - 0.003k - 10.19PET_1 + 0.052\sum BMP \quad (7)$$

The regional regression model documents that the recharge BMPs have a statistically significant positive effect on average groundwater elevations. The model coefficient for the $\sum$BMP term was found to be 0.052 with a t-ratio of 5.85. This implies that the model coefficient has a standard deviation of only 0.009; thus, there is extreme confidence for the value of this coefficient. The $\sum$BMP coefficient 0.052 represents the positive change in predicted groundwater elevation on average that would occur by holding all other explanatory variables constant. For example, a 1-m^3 recharge BMP installed 1 m from an observation well would, on average, increase the observed groundwater elevation by 0.052 m. Likewise, a 10-m^3 recharge BMP installed 100 m from an observation well would increase the average observed groundwater elevation by only 0.0052 m. This result illustrates the small yet statistically significant effect of the recharge BMPs on groundwater elevations. It would be very difficult to isolate this observed effect using advanced groundwater modeling methods (Yao et al. 2010; Li et al. 2003) given the very slight influence that each BMP has on local groundwater elevations.

The coefficient $\beta_5 = 0.052$ represents the conditional average increase in groundwater elevations to be expected across the region; this assumption is important given that conditions at specific well locations will display either more or less of an increase in groundwater elevations. For example, groundwater gradients and local groundwater flow directions may greatly affect observed changes in groundwater elevations as a result of recharge BMPs. Overall, across the Back Bay region of Boston, the coefficient provides an average effect that is likely to occur at any specific location.

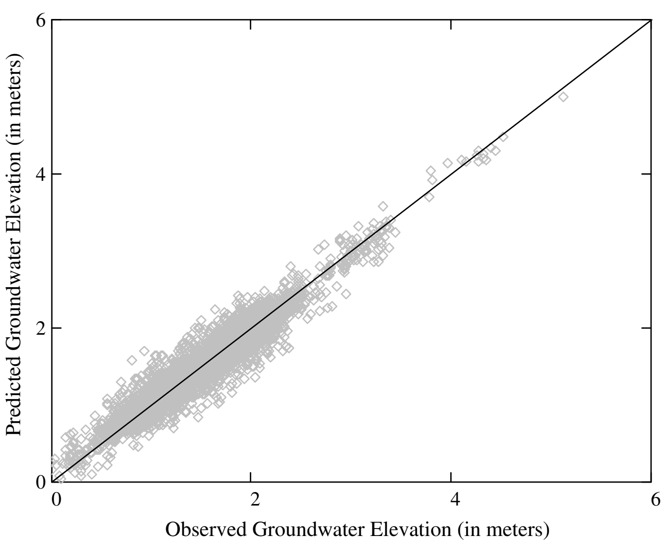

Fig. 2. Comparison of predicted versus observed groundwater elevation; data set includes observed groundwater elevations from June 1999 to September 2009

Model Validation

Cross-validation methods were conducted to evaluate the application of the model to situations not considered when fitting the model summarized in Table 2. Cross-validation was conducted using a standard method of blind testing or validating the model with data not used during model calibration. Additionally, repeated random subsampling was employed in which the calibration data were 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 subsampling procedure was repeated 100,000 times to increase the probability that observations were

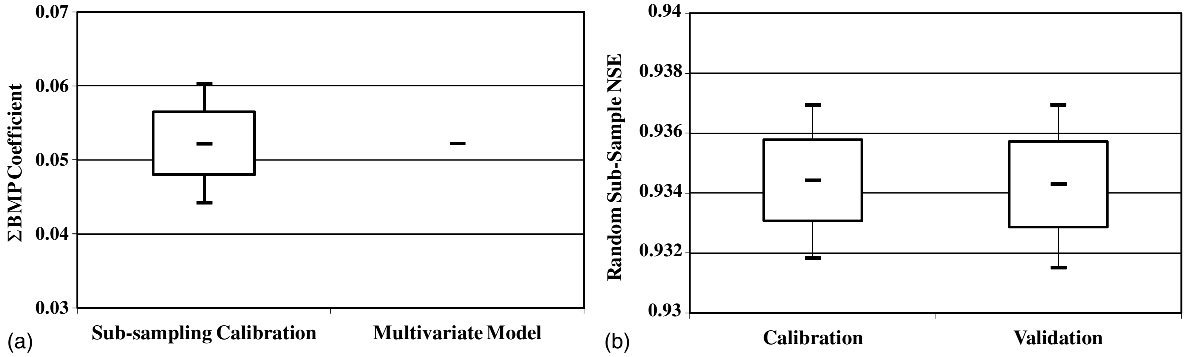

Fig. 3. Groundwater model coefficient cross-validation results: (a) $\sum$BMP coefficient; (b) calibration and validation NSE

selected for both the calibration and validation data sets during the validation procedure.

Fig. 3(a) illustrates box plots for estimates of the model coefficient associated with the variable $\sum$BMP obtained in the random subsampling validation compared with the multivariate model results included in Table 2. Fig. 3(a) illustrates that the variability in the $\sum$BMP term coefficient is small and averages to the value summarized in Table 2. 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 effect of recharge BMPs on observed groundwater elevations with a relatively high degree of precision. Also reported in Fig. 3(b) is the variability in the NSE for the validation and training sets. The variability in NSE values was quite similar for both the calibration and validation data sets.

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 previously. The blind-sample validation data set included two additional recharge BMP installations that were approved and activated after October 2009. Model performance was tested by comparing observed data to predicted groundwater elevations as illustrated in Fig. 4. Results indicate, once again, that the model in Eq. (7) was able to accurately reproduce groundwater elevations with a NSE of 0.87 and a RMS of 0.17 m.

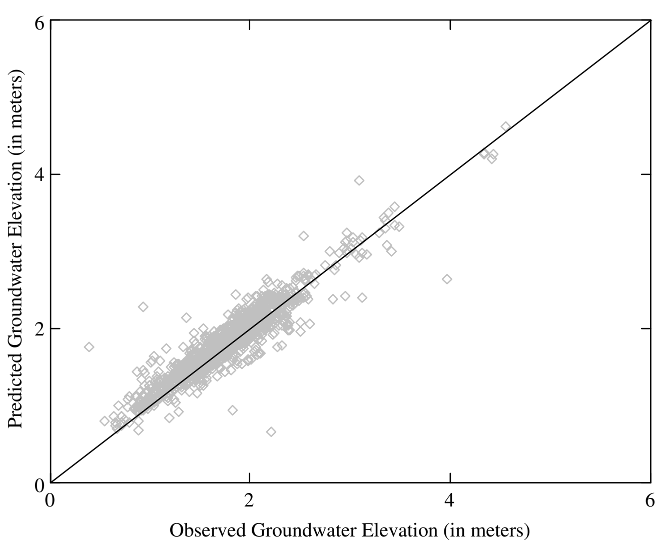

Fig. 4. Blind-sample model validation; data set includes observed groundwater elevations from October 2009 to June 2010

Overall, the 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 that explore the effect of future storm water BMP recharge facilities in the Back Bay on groundwater elevations. The RMS is reported to be 0.13 m for the calibration data set and 0.17 m for the validation data set, which are both better fits than reported for similar scale (approximately 1 km^2) urban groundwater models (Carneiro and Carvalho 2010).

Application of Regional Groundwater Model

Effect of Individual Recharge BMP

The model coefficient for the $\sum$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 $\sum$BMP term, the effect of a particular recharge BMP can be represented graphically as illustrated in Fig. 5. Fig. 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, Fig. 5 illustrates that a recharge BMP of 50-m^3 capacity placed 500 m from an observation well would on average increase groundwater elevations by 0.0052 m.

Fig. 6 also illustrates how the $\sum$BMP model coefficient can be used for urban storm water planning. For example, if an increase in groundwater elevation of 0.01 m was desired, with a recharge BMP storage capacity of 20 m^3, the recharge BMP should be placed approximately 105 m from the groundwater observation well.

The two graphical summaries shown in Figs. 5 and 6 illustrate the predictive power of the model in Eq. (7). Figs. 5 and 6 provide guidance on how to interpret the implications of the model for use in future storm water recharge BMP planning or urban streamflow restoration that may benefit from additional groundwater discharge to surface flows.

The results in Figs. 5 and 6 are on the basis of the model summarized in Eq. (7) 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

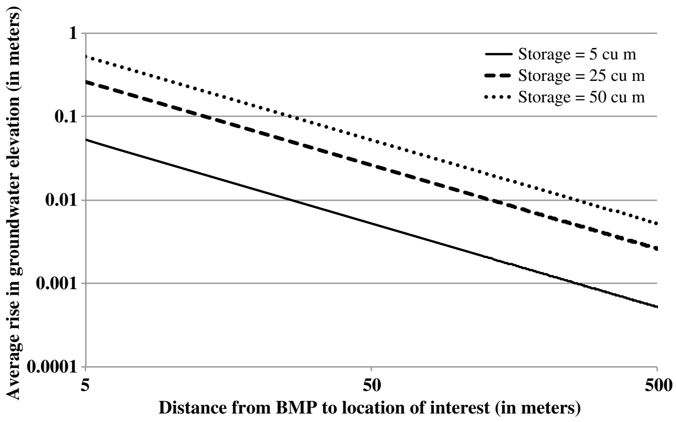

Fig. 5. Relationship between average rise in groundwater elevations and distance from BMP to location of interest

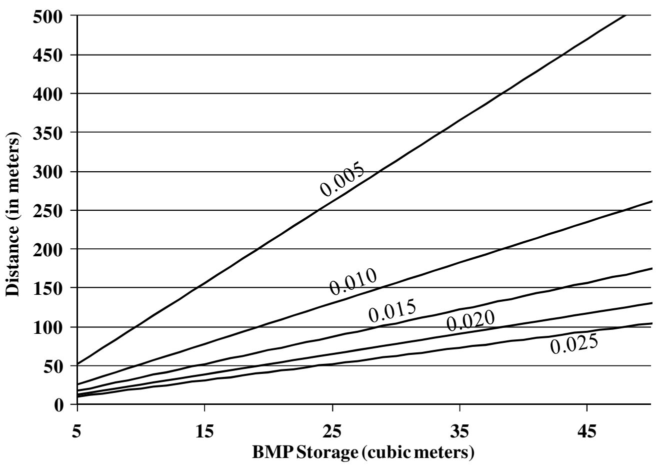

Fig. 6. Average rise in groundwater elevation in meters resulting from recharge BMP of particular capacity located a distance from a particular location of interest

Figs. 5 and 6 may change and may need to be updated. However, the validation experiments reported previously indicate rather robust results, regardless of the number of well observations considered in the development of the model.

Effect of System of Recharge BMPs

The BMP groundwater model given in Eq. (7) can also be used to evaluate the effect of an installed system of future recharge BMPs. For illustrative purposes, three recharge BMP scenarios were developed to illustrate the application of Eq. (7) for stormwater planning. The following three scenarios are considered:

- Scenario 1: Single recharge BMP per block, located centrally, with a 7.93-m^3 capacity;
- Scenario 2: BMPs placed at approximately every tenth building, with approximately six BMPs per block and a 7.93-m^3 capacity; and
- Scenario 3: Remove all existing BMPs.

For each of the preceding scenarios, the $\sum$BMP term given in Eq. (7) is estimated using assumed location and average regional BMP capacities for each scenario, and the results of the analysis are illustrated in Fig. 7. Scenario 1 resulted in an average groundwater elevation increase of 0.037 m, with local areas experiencing an increase of up to 0.08 m [Fig. 7(a)]. Scenario 2 increased average groundwater elevations by 0.226 m, with areas installing multiple recharge BMPs experiencing up to a 0.29-m increase in groundwater elevations [Fig. 7(b)].

In addition, Scenario 3 considered the removal of all existing recharge BMPs from the Back Bay region. This was accomplished by simply setting the $\sum$BMP term in the model to 0 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 -0.03 m; however, reductions ranged from -0.012 to -0.10 m when the existing recharge BMPs were artificially removed from the Back Bay region. These results indicate that the regional BMP groundwater model can be used to assess the potential average groundwater increase across Back Bay resulting from various installed BMP recharge facilities.

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. The 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. The regional model indicates that well elevations are most affected by previous well elevations and the recharge that results from the precipitation that occurred since those previous well elevations were observed. It is also shown 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.

Although the approach is primarily on the basis of the theory of statistics, it is also on the basis of on the physical water balance given by Hodgson (1978), which is similar to Scanlon et al. (2002). The regression constant and the timelag 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.

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 was examined. The model validations illustrated in Fig. 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 in this paper can be used to predict the effect of future BMP installations on groundwater elevations because the model relates the average increase in groundwater elevations at a particular location to the capacity, time of installation,

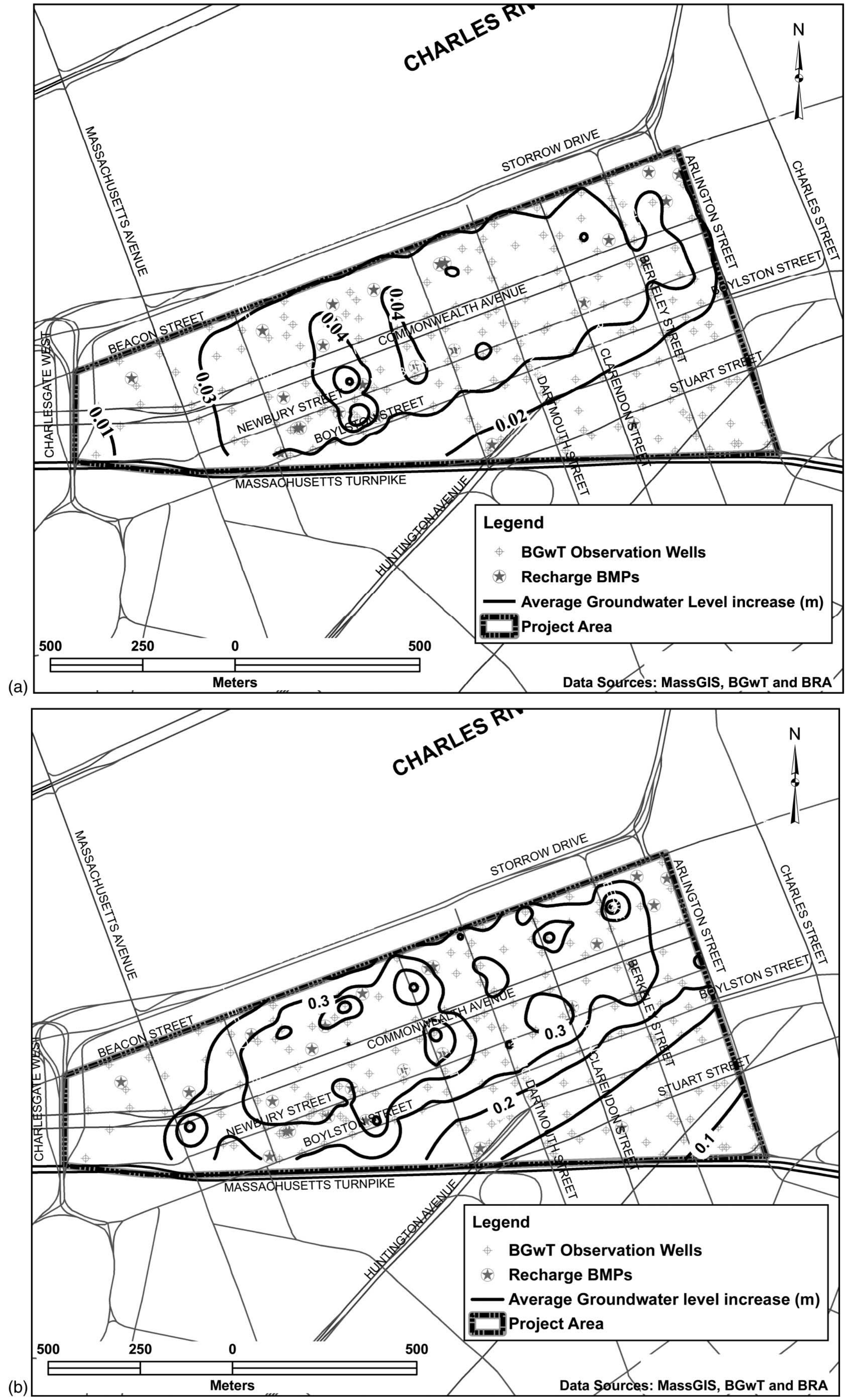

Fig. 7. Results from (a) Scenario 1 and (b) Scenario 2 documenting average effect of recharge BMPs to groundwater elevations within Back Bay

and location of a particular recharge BMP or a set of such BMPs. The results of the various case studies document that groundwater elevations generally are not drastically increased over the region until multiple recharge BMPs are placed throughout the study area given the small but significant effect of the recharge BMPs to observed groundwater elevations.

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