Groundwater Flow Modeling in the Shallow Aquifer of Buffalo Creek, Greensboro

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Abstract U.S. Environmental Protection Agency categorized Buffalo Creek as one of the impaired waters in Cape Fear River Basin, North Carolina, due to high concentrations of metals and pathogens. These contaminants originate from effluents discharged from industries and agricultural activities. This study used a numerical groundwater flow modeling approach to investigate the surface and groundwater interaction in the Buffalo Creek watershed for the fate and transport of contaminants. The movement of groundwater flow was simulated using MODFLOW while the particle tracking was analyzed by the MT3D model. MODFLOW solves groundwater flow equation using the finite-difference approximation. The flow region which covers both North and South Buffalo Creek was subdivided into blocks or cells in which the medium properties were assumed to be uniform. The cells are made from a grid of mutually perpendicular lines that are variably spaced depending upon the location. Spatial locations and distributions of stream networks, elevations, boundary conditions (no flow and constant, variable head zones), existing well locations, and industrial as well as wastewater effluent discharge locations were developed within ArcGIS environment. The modeling tasks of this study are domain characterization (database for surface elevation and stream network), modeling setup, and calibration and validation of the model using observed data. The observed data for baseflow was obtained using the baseflow filter algorithm, which basically separates baseflow from streamflow based on nature of the hydrograph. The modeling setup and initial calibration results for the steady-state simulation are presented in this chapter.

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Introduction

Due to its more complex nature, the movement of particles and their effects in groundwater system cannot be traced and detected easily. Because of this, much of resources required to study and mitigation measures are skewed towards other water resources (surface water) sectors. Timeframes between an original pollution event, percolation through the unsaturated zone, transport in groundwater, and eventual baseflow discharge to a receiving river may be years to decades and depend upon the pathways and distances involved, groundwater velocities and capacity for natural attenuation of a pollutant in the subsurface. On the contrary, the effect of contaminated surface waters (streams, rivers, lakes and ponds) can easily be detected through their direct symptoms like aquatic life deterioration, human health changes and others, attracting the attention of experts, managers and politicians. The development of human activities expanded in cities, agricultural lands and in large settlements. Groundwater contamination by number of metallic elements and organics is nearly always the result of human activities such as hazards which pose health risks to human.

In almost all of the previous studies and assessments, much attention was given only to surface waters where immediate effects can be observed. Due to the critical role of groundwater in the hydrologic cycle and ecosystem, funding decisions to prevent adverse effects to the resources will more fully recognize groundwater's role. Unfortunately, the complex nature of groundwater movement and its interaction with surfaces waters (lakes, streams, rivers and recharge) may be one of the reasons why much was not done in this area. The amount of groundwater available from the regolith-fractured crystalline rock aquifers system in Guilford county, North Carolina, is largely unknown. To begin to address pollution prevention or remediation, we must understand how groundwater and surface water interrelate. These are interconnected and can be fully understood and intelligently managed if only when the fact is acknowledged. The need to understand groundwater system and its interaction with surface water and stressors (contaminants) is one of the areas where recent studies give attention due to its paramount need. Planners and Managers benefit from additional knowledge of groundwater resources.

This study attempts to build a calibrated steady-state flow of groundwater in the regolith aquifer of Buffalo Creek Watershed, Guilford County. A three-dimensional steady-state model MODFLOW (PMWIN 5.3.1) was constructed to simulate shallow aquifer of groundwater flow. ArcGIS was used for geographic data development, management, integration, and analysis. Using tools of ArcGIS such as ArcMap, Arc Catalogue, and ArcTools, surface elevations, streamflow networks, flow directions, flow lengths, basin boundaries, and slopes are created, analyzed, and used for MODFLOW inputs. Based upon the limitations of PMWIN to process the input, ArcGIS tool provides flexibility in setting up the appropriate spatial allocations and merging of the default raster data through resampling and extraction of DEM data. MODFLOW is used to numerically solve the three-dimensional groundwater flow equation using the finite-difference method (Harbaugh

et al. 2000). The groundwater flow equation is solved using the finite-difference approximation method. The flow region is considered to be subdivided into blocks in which the medium properties are assumed to be uniform. The plan view rectangular discretization results from a grid of mutually perpendicular lines that may be variably spaced.

Site Description

This study was conducted on 88.5 mile^2 of Buffalo Creek watershed in Guilford County, North Carolina. Guilford County consists of approximately 658 mile^2 in the central part of the Piedmont province. The watershed is located in the upper Cape Fear River basin that includes most parts of Greensboro city, characterized by shallow unconfined regolith aquifer. The topography of the area consists of low rounded hill and long, northeast-southwest trending ridges with up to few hundred feet of local relief. The Climate of Guilford County is typed as humid-subtropical with mean minimum January temperatures range from 31 to 33 °F whereas mean maximum July temperature range from 87 to 89 °F. Annual precipitation varies across the county from 43 to 48 in. (Kopec and Clay 1975). The lowest rainfall occurs in the southern and south western parts of the county; the highest rainfall occurs in the southern and southeastern parts of the county (HERA Team 2007).

Geologically, Guilford County lies within the Charlotte Slate Belt. Metamorphic and Igneous crystalline rocks are mantled by varying thickness of regolith (HERA Team 2007). Daniel and Harned (1998) in their idealized sketch of groundwater system, categorized the regolith aquifer geological setting of the Guilford County as: (1) the unsaturated zone in the regolith, which generally contains the organic layer of the surface soil, (2) the saturated zone in the regolith, (3) the lower regolith which contains the transition zone between saprolite and bedrock, and (4) the fractured crystalline bed rock system.

Methodology

ArcGIS 10.0 tools (ArcMap, ArcCatalogue, and ArcTools) were used to manage and transform spatial distribution of geospatial parameters. First, from a USGS developed earth explorer interface, data of Shuttle Radar Topographic Mission (SRTM) 2000, an approximated geospatial area of the watershed is sited and delineated to be downloaded as a rectangular area (79–80° W and 35–36° N). The approximated region of interest was tiled into two subsets for downloading and later exporting to GIS.

In ArcGIS, the two subset data tiles were imported as mosaic data and retiled as a single data using data management tools. Depending upon the PMWIN limitations in data inputs (maximum cell size of 250,000), raster data of DTED resampled
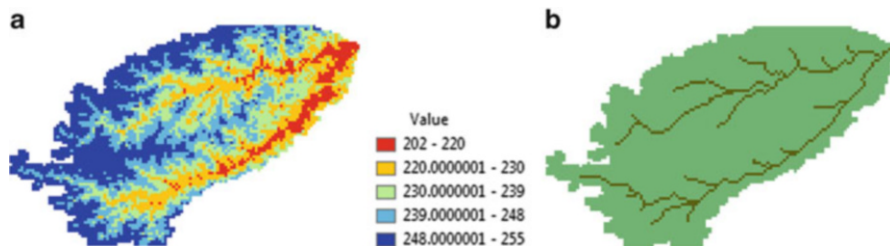
Fig. 1 (**a**) Delineated Buffalo Creek Watershed and (**b**) stream network and distribution

multiple times until maximum allowed or less number of cell sizes and appropriate cell dimensions are met. After filling the raster data set for any sink, a cell with defined drainage direction, flow directions were developed for major and tributary streams using hydrology tools. While establishing the stream network, output cells with high flow accumulation are only used to identify streams. For the size of cells we have already set, high flow accumulation is considered for cells receiving flow from more than 100 output cells. That means cells with flow accumulation receiving from zero output raster are categorized as highs or peaks that also indicates the boundary of the watershed. Consecutively, cells receiving flow from 0 up to 99 numbers are categorized as undefined direction flow cells. The final feature of the stream channel and links are constructed by thresholding the results of the flow accumulated raster and using GIS conversion tools (Fig. 1b). While delineating the targeted basin, the analysis extent is narrowed and widened from the original coordinate until the outlet from the basin in question is delineated and visible (Fig. 1a).

PMWIN is one of the most complete groundwater simulation systems in the world developed by Chiang and Kinzelbach (2001). It includes all the supporting models (MODFLOW, MT3D, MT3DMS, MOC3D, PMPATH) for Windows, PEST2000, and UCODE. MODFLOW is a simulation system for modeling groundwater flow with the modular three-dimensional finite-difference groundwater model developed by the U.S. Geological Survey (McDonald and Harbaugh 1988). At present, PMWIN supports seven additional packages which are integrated in the original MODFLOW. One of these packages is the streamflow-Routing package (STR1). This particular package (Prudic 1989) is designed to account for the amount of flow in streams and to simulate the interaction between surface streams and groundwater.

MODFLOW is a computer program that simulates one-, two-, or three-dimensional groundwater flow using a finite-difference solution of the model formulation. The partial differential equation for transient three-dimensional groundwater flow in heterogeneous and anisotropic medium, for confined or unconfined aquifer is expressed as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_{s}\frac{\partial h}{\partial t} \qquad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivity along the x, y, and z coordinate axes parallel to the major axes of hydraulic conductivities; h is the potentiometric head; W is the volumetric flux per unit volume representing source; S_s is the specific storage of the porous medium; and t is time. MODFLOW is designated to simulate groundwater flow system in the aquifers in which (a) saturated flow condition exists, (b) Darcy's Law applies, (c) the density of groundwater is constant, and (d) the principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system. The groundwater flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium of properties are assumed to be uniform.

For Buffalo Creek watershed, a two-dimensional steady-state MODFLOW model was constructed to simulate groundwater flow for the shallow regolith unconfined aquifer. The model requires the use of Streamflow routing package and Recharge package. The discretization package also sets the spatial and temporal dimensions. In the basic packages boundary conditions (weather flow in the cell is constant, variable/calculated or no flow) and initial hydraulic heads values defined. Values of hydraulic conductivity and the wetting capability are defined in the block-centered flow package. For all MODFLOW/PMWIN packages, an ASCII input was defined with strict format. From ArcGIS output we finally selected a horizontal grid dimension of 200 m × 200 m size organized along rows and columns. The total grid is divided into 128 columns and 82 rows.

Results and Discussion

Groundwater flow system needs to be simulated and calibrated before determining the fate of contaminants in the regolith aquifer system. Groundwater flow has been simulated and calibrated for steady-state case of the aquifer. The trial and error modeling effort for assumed horizontal hydraulic conductivity, evapotranspiration, recharge flux, and initial hydraulic heads were not succeeded. Parameter values continue to be very sensitive, particularly for horizontal hydraulic conductivity and evapotranspiration rates without giving some convergence trend neither to the volumetric water budget balance nor to the representative hydraulic head. For any change to the order of 10^{-14}, the net volumetric water budget (inflow–outflow) changes to nearly 62 %. Similarly, steady-state head also changes with change in horizontal hydraulic conductivity. For any slight changes like, 10^{-08} in hydraulic conductivity value, calculated hydraulic head values goes to the extent where, in some cells beyond the land surface while in others the cells dry out. PEST, parameter estimation tool included in PMWIN which in fact runs outside of the

MODFLOW PMWIN domain was also tried to calculate model parameters. This inverse modeling approach configured to estimate horizontal hydraulic conductivity, evapotranspiration, and recharge rate. Unfortunately, none of the monitoring wells those intended to provide measurement data for inverse modeling were found in the Buffalo Watershed. The nearest available wells from neighboring watersheds are: Gibsonville monitoring well (G 50W2), an active monitoring well located at the real-world coordinates 36.088262 (x) and 79.547915 (y) located at about 10 km away from the exit point of Buffalo watershed. The other monitoring well, inactive well is Yow 2, is located at about 5 km away from the southern water divide line at coordinates 35.958388 and 79.838645, x and y, respectively. Using the parameter estimation tool, PEST provided in the PWMIN, the coordinates were changed systematically to be located within the watershed boundary region, in such a way that their locations are transformed to the nearest coordinate and also similar ground surface elevation and/or assumed hydraulic head. This approach also fails without arriving at some result to model the aquifer parameters. We conclude that, PEST cannot run (inverse run) for observation wells not only located outside the watershed boundary region, it also not considers even if these wells are not active.

Back to the trial and error procedure, we decided to reduce (with justifiable reason) the number of parameters for estimation. Accordingly, the previous recharge flux that includes the component of evapotranspiration is removed from the input data. While doing so, the annual net groundwater recharge amount is estimated from previous study sources (Daniel and Harned 1998). For this particular case, the seasonal variations of groundwater depth in Guilford County and adjacent Counties were also reviewed to estimate the annual recharge flux for the watershed. The annual average amount of recharge flux can be estimated from the annual average baseflow that groundwater contributes to the stream. It is estimated that baseflow from the catchment has no any other source than areal recharge, which is the percolated part of rainfall.

Baseflow Filter Program was used to separate the annual average amount of discharge from groundwater. The model separates the baseflow from its direct input, streamflow records. This recursive digital filter method described by Nathan and McMahon (1990) was originally used in signal analysis and processing (Lyne and Hollick 1979). Filtering surface runoff (high frequency signal) from baseflow (low frequency signals) is analogous to the filtering of high frequency signals in signal analysis and processing (Arnold and Allen 1999). The stream record data passed over the filter three times (forward, backward, and again forward). Each pass will result in less baseflow as a percentage of total flow. Accordingly, the user gets some added flexibility to adjust the separation to more approximate site conditions. The equation for the filter is:

$$q_t = \beta \ q_{t-1} + (1+\beta)/2^*(Q_t - Q_{t-1}) \tag{2}$$

where q_t is the filtered surface runoff (quick response) at the t time step, Q_t is the original streamflow, and β is the filter parameter. Baseflow, b_t is calculated with the equation

$$b_t = Q_t - q_t \tag{3}$$

From USGS daily stream discharge data (1998–2013) for Buffalo Creek stream, records were downloaded and exported to the Filter program. The filter program outputs the calculated baseflow for the three round run in addition to the measured input discharge. From the separated baseflow of 15 years discharge measurement for Buffalo Creek Watershed at Oak Ridge, the average baseflow is calculated as 55 ft^3/s. This value includes the discharge released to the stream from the two sewage treatment plants: T.Z. Osborne Plant and the North Buffalo Facility. The treatment plants permitted to process about 40 million gallons and 16 million gallons of sewage per day for both T.Z. Osborne and North Buffalo, respectively. The discharge estimated from the plant is assumed to be nearly equal to the total water supply required/supplied for Greensboro City. Nearly, all the sewage or wastewater that is generated by customers flows by gravity through sewers that range from 6 to 72 in. in diameter (City of Greensboro 2011). The total daily treated sewage released to Buffalo Stream is estimated to the average collected sewage from the city. Every day, an average of 26 million gallons of sewage generated in our homes and industries that must be collected, transported, and treated to very stringent standards before it is released back into our environment, our streams. The daily demand of water supply for Greensboro City grows from 12 million gallons in 1960 to 33.4 million gallons in 2013. Considering the average sewage disposed to the stream, it is assumed that a 27 millions of gallons of treated sewage is released to Buffalo Stream daily, the amount that matches closely with the city's daily water supply demand. Finally, this amount is subtracted from the calculated total baseflow from the stream to arrive at an estimated actual baseflow from Buffalo Creek with a discharge rate of 13.23 cubic feet per second. This amount when compared to report by City of Greensboro looks bit higher. The City in its report of Sewage Collection and Reclamation Plant Report for 2011 mentioned that our discharge flow constitutes over 97 % of the stream below our discharge points at the lowest streamflows. This report did not mention how and which time of the month or year this estimation was done, since there are large discrepancies of flow happens over seasons of the year. Moreover, the comparison did not mention
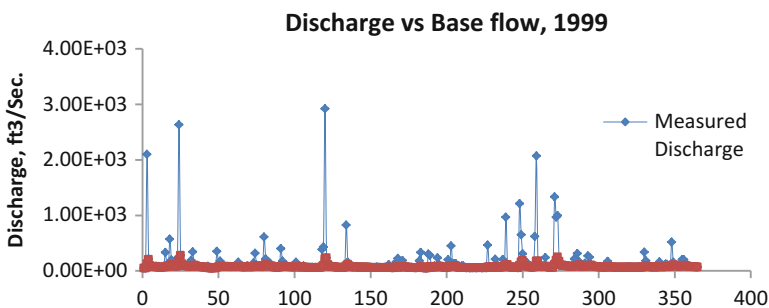

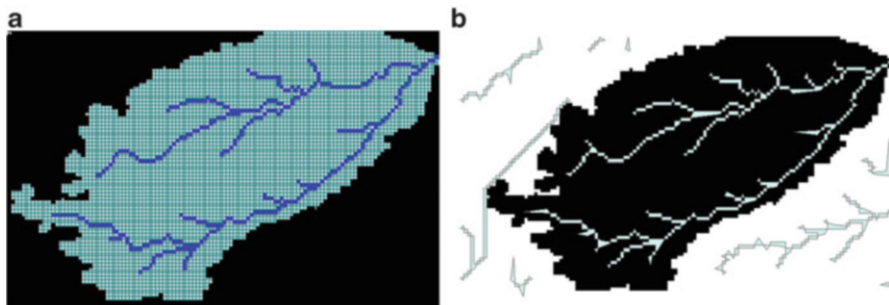Fig. 2 Streamflow vs. baseflow, typical 1999 yearly average

Fig. 3 Geometry of stream network developed by (**a**) MODFLOW-PMWIN and (**b**) GIS
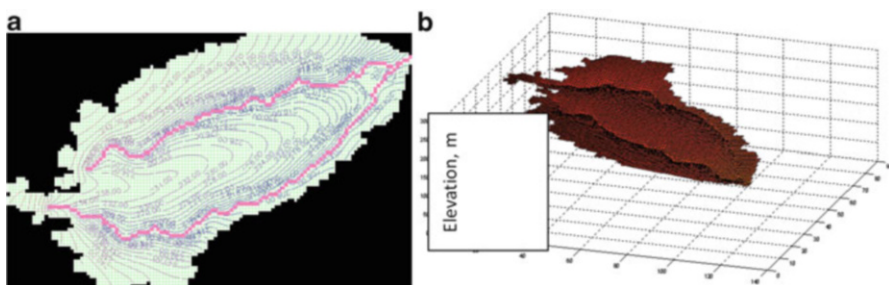

Fig. 4 Steady-state simulated hydraulic heads (**a**) contour and (**b**) 3-D view

weather it is daily, monthly, or annual based or certain period's volumetric estimation. In other words, the assumption/measurement may also be during peak discharging time. Both the true baseflow and discharge from the treatment plants vary significantly over months of the year, but the report does not support its assumption in neither of the cases. In our case, the percentage of actual estimated baseflow to total baseflow (including sewage from treatment plant) estimated to be 21 % (Fig. 2).

To estimate the areal recharge for MODFLOW input, the total volume of the true estimated baseflow amount is distributed over the watershed area. An estimated areal recharge flux of 2×10^{-09} m/s is used as an input recharge rate for the model as an initial input value. After all the required data and parameters input (basic package, discretization package, streamflow routing package, block-centered flow packages, recharge package, porosity) to MODFLOW-PMWIN, the stream network geometry is compared with the natural trend of stream network developed from ArcGIS (Fig. 3).

PMWIN has some limitations on the number of stream networks. The maximum allowed stream segment is twenty-five, and the total number of tributary streams to a segment of stream is ten. Taking into account this limitation, only two small tributary streams on North Buffalo Creek, near where it joins South Buffalo Creek have been omitted. In regard to the number of tributary stream to a segment of

stream, we have had only a maximum of three tributary streams that release to a segment, which is less than ten (Fig. 4).

Accounting for the large amount of flow coming from the sewage treatment plant in PMWIN-MODFLOW environment was one of the challenges we faced to run the MODFLOW in arriving at true/representative parameters. Different approaches: (a) distributing the total annual flow as a recharge flux, (b) considering the equivalent discharge as recharging well, by activating well package, and (c) creating an arbitrary river channel by activating river package with equivalent discharge rate as if the river is crossing Buffalo watershed. For the first case, even though the model was able to run properly, the results obtained were at the expense of horizontal hydraulic conductivity values. Conductivity values were increased to the order of 10^2, which are not representative of the watershed's hydraulic conductivity values. For the second case, we tried to recharge the aquifer at the bottom end of one of the top layer cells, but this still leads to accept the recharge as groundwater and influences parameters of the aquifer, nonrepresentative result. Similarly, the river package input was also unable to give a representative water budget values. Fortunately, the last option (option iv) that assumes the treatment plant's discharge as a specified constant head pool in the main stream channels, over the modeling period was able to model groundwater flow effectively. Accordingly, the two main stream channels (North and South Buffalo streams) were considered as constant head cells with varying depth throughout their length.

The distributions of the calibrated hydraulic heads are compared and verified with the available information and previous studies. Within the water shed, a study conducted on Functional Assessment for a Proposed Floodplain Storm Water Treatment Wetland (Kimberly 2002) indicates that groundwater fluctuates between 0.5 and 3 m below ground surface. Even though this study was limited to specific area of the watershed (in regard to groundwater study), it highlights the depth at which groundwater is found in flood plain of South Buffalo sub-watershed. The simulated result of hydraulic heads in flood plain region varies from some few centimeters above ground surface to 5 m below. The variation is acknowledged as the study of groundwater was only confined to an area of one cell width (200 m) of MODFLOW. Daniel and Harned (1998) also mentioned that the seasonal variation of depth of saturated aquifer in piedmont region varies between 4 and 12 ft. They also validated their assumptions from study conducted by on Groundwater Observation Wells in Orange County that this depth of aquifer variation is within 42–46 ft. below the ground surface. The calculated hydraulic heads in our case, although falls within this range, shallower and deeper groundwater depths are also observed. Basically, water wells are selected and located in areas where groundwater can easily be found (technical, economical, and natural reasons). Similarly, it is obvious to assume the locations of these observation wells in relatively less elevated locations indicating that in relatively high elevated nearby locations, the depth of ground water also increases from its reference, ground surface.

Groundwater depth data of relatively nearby observation wells found in adjacent watersheds Gibsonville and Yow 2 were also considered as one of validating parameters. Yow 2 is about 5.3 km south of Buffalo Watershed boundary.
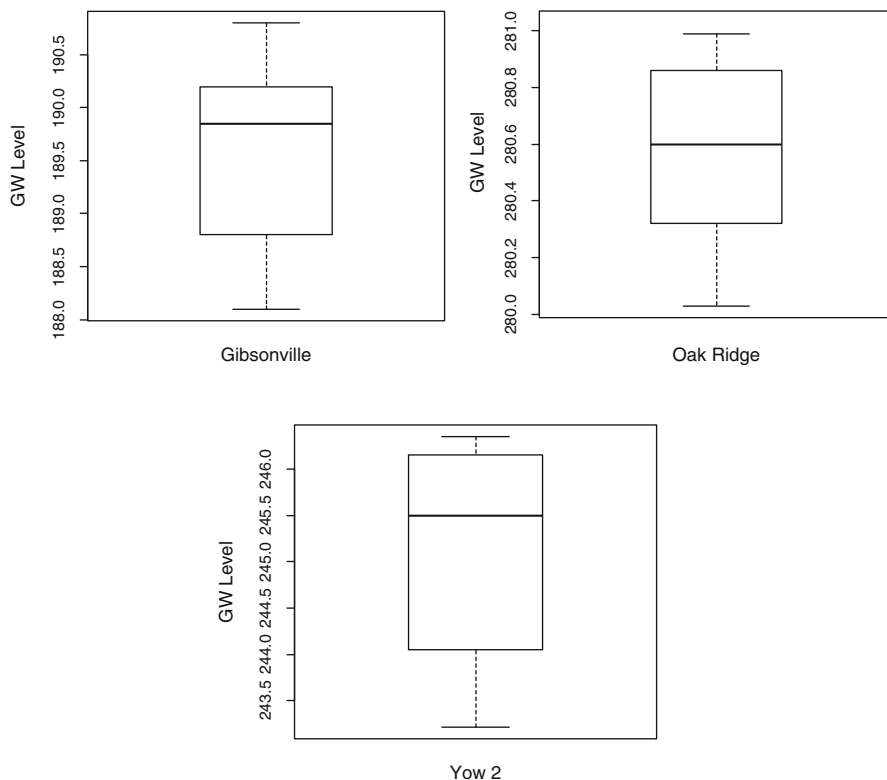
Fig. 5 Box plot, annual groundwater depth fluctuations statistics for Gibsonville, Oak Ridge, and Yow 2 Observation wells

Watershed divide line passes between Yow 2 observation well and similar elevation surface within Buffalo Creek watershed. The distance of this comparison point is nearly 5 km from its watershed divide line. This shows a similar surface slope in either side of the watershed divide line. Gibsonville, the second nearby and only active well located at about 10 km downstream of Buffalo Creek watershed. Available groundwater depth data for Yow 2 (2001–2003) and Gibsonville (2000–2013) is downloaded from USGS/NCWRD website for statistical analysis. Both wells are located at ground surface elevation of 246.88 and 197.5 m for Yow 2 and Gibsonville, respectively. Annual average of groundwater depth is estimated from Box plot of Fig. 5. The similarity of simulated hydraulic head for Yow 2 has been discussed above.

For Gibsonville, the average maximum and minimum data were evaluated and its average annual groundwater depth was estimated to be 189.5731 m. As the topography of the surface between the exit point of Buffalo Creek and the observation well is flat, a constant slope is estimated from distance and altitude, 0.055 %. The gradient of hydraulic head is also assumed to be parallel to ground surface slope. Calculated hydraulic head at exit point of Buffalo Creek is 194.3351 m. This

comes out to be about 0.0476 % hydraulic head gradient which is in agreement with ground surface slope. This difference is considered as acceptable; the $200\,\text{m} \times 200\,\text{m}$ cell size ground surface elevation value is considered by GIS to be a surrogate elevation for the entire cell. Another output result by MODFLOW is the annual volumetric water budget balance, (input–output). This percentage difference is 0 %, indicating good result. Volumetric water budget output by MODFLOW is also compared and verified with the separated (baseflow separation model) and calculated value of baseflow. MODFLOW calculates 3.4 % by volume less than the calculated water balance.

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