State of Ohio
Environmental Protection Agency

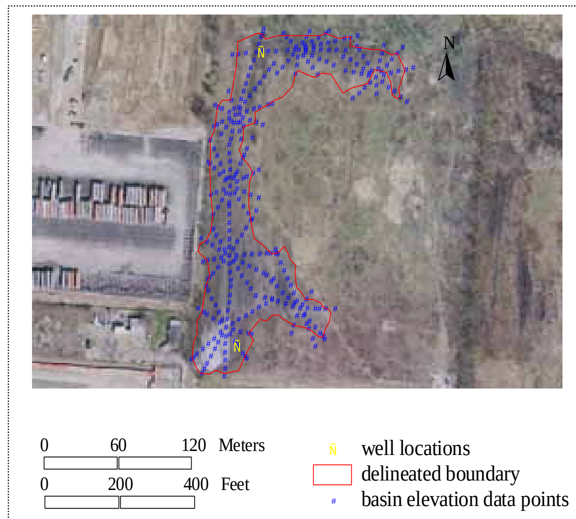
Wetland Ecology Group
Division of Surface Water

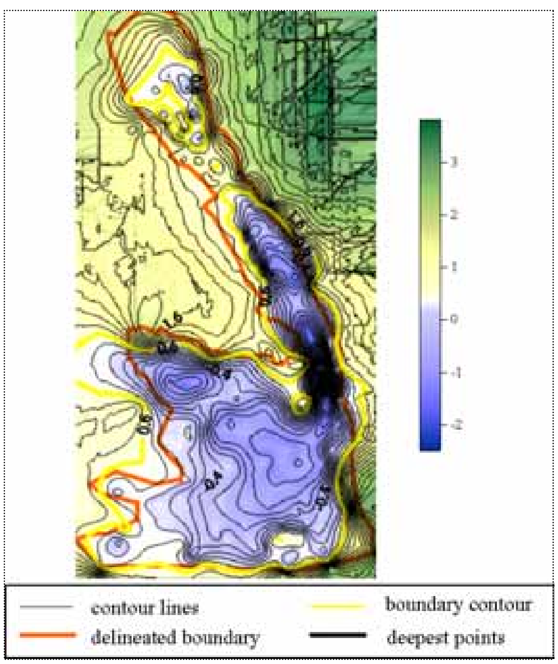
AN ECOLOGICAL AND FUNCTIONAL ASSESSMENT OF URBAN WETLANDS

VOLUME 2

MORPHOMETRIC SURVEYS, DEPTH-AREA-VOLUME RELATIONSHIPS AND FLOOD STORAGE FUNCTION OF URBAN WETLANDS IN CENTRAL OHIO

Ohio EPA Technical Report WET/2007-3B





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AN ECOLOGICAL AND FUNCTIONAL ASSESSMENT OF URBAN WETLANDS IN CENTRAL OHIO

VOLUME 2: MORPHOMETRIC SURVEYS, DEPTH-AREA-VOLUME RELATIONSHIPS, AND FLOOD STORAGE FUNCTION

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ABSTRACT

Water storage in wetlands reduces the severity of floods by lowering flood elevations and delaying stormwater runoff. Riverine urban wetlands release stored floodwaters gradually to urban rivers and streams, diminishing peak storm flows and recharging groundwater. Depressional urban wetlands capture and retain water entering them and release it to the atmosphere through evapo-transpiration. Functional data on wetland morphometry, perimeter, area and hydroperiod were collected at 22 urban wetland sites to understand the influence of basin morphology and water depth on area and volume of water. For each wetland, the jurisdictional boundary was delineated and georeferenced in order to map the wetland perimeter and determine wetland area. Basin morphometric data were collected using a laser level and stadia rod. GPS and manual triangulation were used to obtain coordinates where elevation measurements were taken. Wetland elevations were referenced to water elevations in a shallow groundwater well installed in each wetland. The *Surfer* 8.05 (Golden Software) program was used to create 3-D models of basin morphometry for each of the wetlands surveyed. Using *Surfer*, wetland water volumes and areas were calculated at a series of water depths. Area and volume were graphed as a function of water depth, and equations were fitted to the trendlines of the data. Groundwater well data collected at each site were used in these equations to calculate water volume stored over time. Simple equations for depressional and riverine wetlands were generated relating water volume, when wetland was inundated to its boundary, to surface area and maximum depth. Volume was better correlated with the product of wetland area and maximum depth than with just wetland area, alone. Depressional wetlands were half as deep and held half the volume of riverine wetlands but were more efficient at capturing and retaining the water entering them. On average, a one-acre depressional wetland stored 0.4 acre-feet of water when inundated just to its boundary, while a one-acre riverine wetland stored 0.8 acre-feet. However when comparing annual precipitation falling on the delineated footprint, on average depressions captured 11 times more than the maximum basin volume, while riverine wetlands captured less than 7 times their maximum basin volume. At their maximum water heights, depressional wetlands stored an average of 0.7 acre-feet of water per acre while riverine wetlands stored 1.2 acre-feet per acre, with an average for all wetlands of 0.9 acre-feet per acre.

INTRODUCTION

Urbanization results in decreased retention of water in watersheds. Water is quickly routed downstream, where it increases the frequency and intensity of floods, reduces stream baseflow during dry periods, and causes bank erosion and channel widening (Poff et al. 1997). In cities with combined sewer overflows, higher peak flows increase the overflow of mixed stormwater and untreated sewage. One of the services that wetlands provide is to capture and store stormwater, reducing peak flows (Mitsch and Gosselink 2000). Because flood and stream damage is usually caused by peak flows, wetlands can reduce the risk of floods (Novitizki 1979, Verry and Boelter 1979) and stream bank erosion (Azous and Horner 2000). Urban wetlands can be particularly valuable, reducing the increased rate and volume of surface-water runoff from pavement and buildings (USEPA 1995). In Boston, the U.S. Army Corps of Engineers (USACOE 1972) estimated that if the 8400 acres (3400 hectares) of wetlands in the Charles River Basin were drained and leveed off from the river, flood damages would increase $17 million per year (USACOE 1972). A 1981 study estimated the water supply value of wetlands in this basin to be over $100,000 per acre (Thibodeau and Ostro 1981).

In addition to preserving natural wetlands to provide flood storage, wetlands can be constructed to manage urban stormwater and be sustainable (Wong et al. 1998). The area, vegetation, slope, location of the wetland in the flood path and the saturation of soils before flooding all determine the effectiveness of wetlands in reducing flood damage (USEPA 2006). How much of the stormflow will be introduced into a wetland is defined by the interaction of the detention period, inflow characteristics and storage volume (Wong et. al 1998). Depressional wetlands are often considered to have no or much less flood storage functionality than riverine wetlands (Zedler 2003).

Wetlands are well known for their "kidney-on-the-landscape" value. However, these services are rarely assessed quantitatively and usually not in urban contexts (But see USACOE 1972; Thibodeau and Ostro 1981). The export of wetland functions from urban impact areas to rural mitigation sites is a well known problem to wetland regulators and is recently gaining attention (e.g. Ruhl and Salzman 2006). Volume 1 of this report explored questions regarding the attainable biological expectations of these wetlands in urban contexts. Even very degraded wetlands may still be providing ecological services like flood storage or water quality improvement. In the State of Ohio's wetland categorization system, a wetland only needs to be doing one thing at moderate or superior levels in order to be protected as a Category 2 or 3 wetland, respectively (Ohio Administrative Code Rule 3745-1-54). So even an urban wetland that is highly degraded ecologically may still be providing a residual ecological service like flood storage or water quality improvement at moderate or greater levels. We evaluated the flood storage function of urban wetlands by developing morphometric models to determine the relationship between a wetland depth (stage), area of inundation and stored water volume (Haag et al. 2005). In order to quantify water stored in urban wetlands and to predict how much water a certain size wetland may store, we 1) mapped the basin morphometry of 22 urban wetland sites and created 3-Dimensional models for each site; 2) used the model to predict water volume and area that was inundated at increasing stage heights, and developed equations relating stage to volume and area for each site; 3) used water level data collected from shallow groundwater wells at each site in the volume equation to calculate daily water volume storage; 4) determined the relationships between volume, wetland area, and maximum depth; and 5) developed a regression equations for predicting volume based on area and perimeter length. Finally, we compared our estimated storage volumes to the volume of precipitation falling on the delineated footprint of the site and to daily, maximum, and annual flows of several typical central Ohio streams.

METHODS

Site Selection

All of the wetland study sites were located in Franklin County, Ohio (Figure 1). Much of Franklin County is developed and includes the City of Columbus and its surrounding suburbs. However outlying areas of the county, particularly to the south and west are still predominately agricultural. The sample for this study was generally theboun-dary of the Interstate 270 outerbelt to exclude wetlands not located in urbanized locations. All wetlands (PEM, PFO, PSS excluding PUBs) mapped by the National Wetland Inventory and significant pixel agglomerations of the Ohio Wetland Inventory that were not mapped by the NWI (predominately woods on hydric soils) were numbered (total = 649) and a simple random sample of 100 wetlands was obtained using the random sample feature of Minitab v. 12.0. Recent (2006) aerial photography was inspected to determine whether the wetland could still be found near that location (e.g. the site was not developed or the wetland obviously destroyed) and the first 22 sites where a wetland was present based on a site visit, and access to sample the wetland was obtained, were included in this study. Site characteristics are summarized in Table 1. As discussed in Volume 1 of this report, three of the sites were subsequently divided into 2 assessment units for the purposes of assessment using the Ohio Rapid Assessment for Wetlands and the Vegetation Index of Biotic Integrity: The Quarry was determined after vegetation sampling to be divisible into two Hydrogeomorphic classes (slope and fringing/riverine); Ridenour Rd was determined to be an impoundment/riverine and a slope/riverine; and Alum Creek Drive was divided into north and south areas to compartmentalize a large stormwater input that was mostly impacting the northern part.

Collection of hydrology data

Shallow ground water level monitoring wells were installed at each site (Ecotone or WM models, Remote Data Systems, Inc.). Twenty-two wells were installed in April and early May 2006 and operated until March 22, 2007. Extra wells were installed in August 2006 at the Ridenour Road, Sunbury Road and Watkins Road sites because survey work indicated that these sites appeared to have north and south areas that were hydrologically distinct. Spring and early summer hydrologic records at the Hills and Worthington Park sites were lost due to well vandalism and at Big Walnut Park due to a defective battery. The water level recorders have a built-in data logger attached to a 115.5 cm (45.5 in) long copper wire that is inserted into a slotted well screen (4 in of this wire is above the calibration point (0.0 in) of the well). Water level in the well is measured by sending a small electrical pulse down the copper wire. The data logger records the level of water around the wire. Wells were usually placed just up gradient of the areas of standing water at the edge of the wetland in locations where inundation of the data logger was unlikely and away from public view to avoid vandalism.

Wells were installed by auguring a hole with a posthole digger, backfilling the hole with a few inches of sand, inserting the well into the hole, backfilling the borehole with sand, and grouting the top of the hole with bentonite. After installation, the distance between ground surface and the calibration point was measured. Wells were not usually installed as far as the calibration point. Well holes were excavated until an impermeable clay layer was reached in the B or C-horizons. Wells were programmed with the Meazura handheld with a Palm™

operating system (Remote Data Systems, Inc.) to record ground water readings every 12 hours (8 am and 8 pm). Data was downloaded periodically and transferred into Microsoft Excel™. Hydrographs were constructed for each site.

Collection of morphometric data

Each wetland in the study was mapped using the delineation procedures in the 1987 Federal Wetland Delineation Manual (Environmental Laboratory 1987). The perimeter of the wetland was flagged and mapped using Trimble GeoExplorer 3 GPS unit. Initial plans were to map the wetland basins by moving through the wetland using a laser detecting stadia rod and a GPS unit to record the position of each elevation. However, trial sessions demonstrated that our GPS unit was not able to consistently ensure sub-meter accuracy of the position readings, which was our aim. Instead, the GPS unit (a Trimble GeoExplorer 3) was used to record just the location of the shallow groundwater well(s) installed earlier in each wetland. With a few exceptions, a minimum of 100 readings were taken at each well in order to maximize groundwater well position accuracy.

The morphometric data were collected using transects radiating out from a rotating laser (EAGL Model 1000 electronic rotating laser level) position at approximately 30° from each other. The laser level was set up on a tripod in an area with good lines of site to collect elevation readings. Manual triangulation was used to determine the position of the laser relative to the groundwater well. This was accomplished with a Lensatic military compass and 200 ft. measuring tape to determine the compass bearing and measure the distance of the laser to the groundwater well, respectively. Compass bearings were recorded in mils to increase precision. Elevations readings at the base of the groundwater well were taken using a laser detecting stadia rod. The height from the base of the groundwater well to the zero calibration mark on the groundwater well was also recorded. Compass bearings for each transect were recorded. At 20 ft. intervals along each transect, depth readings and distances from the laser unit were recorded. Transects helped to ensure compass bearings were maintained so measurement errors were minimized. Additional basin elevation readings were taken at shorter intervals if noticeable changes in elevation occurred. The upland morphometry was also mapped by extending the transects 20 ft., if practicable, outside the wetland boundaries, and taking elevation readings there. At sites where the upland area was steeply sloped, readings were recorded as far up the slope as they could be safely taken. At two sites, Three Creeks oxbow and Ridenour Road, the wetland maximum depth is an underestimation, because they had small but very deep depressions which were too deep to measure safely.

If one laser position did not adequately cover the wetland, the laser was moved to collect additional elevation readings, referencing the new laser location back to a known position. Before going into the field, aerial photos of the wetlands were opened in Arcview GIS to estimate how many laser positions would be needed. The exact number and location of laser positions needed to effectively map the basin elevations was determined in the field. Some smaller wetlands required only one laser position, while larger wetlands required up to nine laser positions. Occasionally, less than 12 transects at each laser position were used, e.g. at a laser position in a corner of a wetland. If needed, a transect bearing was moved slightly from 30° relative to other transects to ensure a good line of sight for the laser.

Data analysis

Statistical Analysis. Data were analyzed using ANOVA and simple linear regression (Minitab Version 12.0). Data were log-transformed first to meet the assumption of normality requirement for ANOVA. All tests of significance were made at $p = 0.05$.

Morphometric data processing. The wetland's groundwater well location was entered by importing the groundwater well's GPS file and differentially correcting the data in Pathfinder Office™. After differential correction, outlier readings for each groundwater well were deleted based on the spread of the points and horizontal precision. To enter the initial laser position, a new feature was created in Pathfinder Office and offset from the groundwater well location point using the compass bearing and distance from groundwater well recorded in the field. Compass bearing units in mils were converted in Excel to degrees, minutes and seconds units, as Pathfinder Office did not recognize mils. Elevations along each transect were entered by creating a new feature for each reading, entering its elevation and offsetting its location from the laser location using the compass bearing and distance from the laser recorded in the field.

The elevation data with position information (Easting, Northing) were then exported into Arcview GIS v. 3.2 as a shapefile over a color orthophoto where it was visually inspected for accuracy. The wetland area and perimeter were calculated from the area of the polygon and the length of the line, respectively, formed by the wetland boundaries in Arcview GIS. Elevation data was exported from Arcview GIS as a delimited text file with northing, easting and elevation columns. The delimited text file was imported into Excel and the elevations were referenced to the ground level at the base of the groundwater well by subtracting the laser reading taken at the groundwater well. The adjusted elevation data file was then was imported into Surfer v. 8.05 (Golden Software, Inc.), saved as a Surfer data file and gridded (radial basis function) with a maximum grid spacing of 3 ft. by 3 ft. (evenly spaced grid), with a multiquadric basic function. A 3-D contour map was created in Surfer from the grid. The radial basis method of interpolation provided the most accurate representation of basin topography in our judgment. Elevation data collected outside of the wetland boundary ensured part of the upland was mapped which was recommended in the Surfer program documentation.

The Surfer program was then used to calculate the volume of water stored in the basin and the surface area covered by the water based on increasing water levels (the upper surface of the grid equaling the water level). The script file "contarea.bas" was downloaded from the website of the Golden Software, Inc. (ftp://ftp.goldensoftware.ws/ public/ scripts/ surfer8/) and used to calculate the area and volume for each wetland at increasing 0.1 ft contour intervals, ranging from the lowest contour to the highest contour in each model. The volume was the average of three different volume functions: the Trapezoidal Rule, the Simpson's Rule and the Simpson's 3/8 rules.

Stage:area/stage:volume equations. The volumes and areas generated from the model were plotted with stage levels to give stage:volume and stage:area curves. Trendlines were fitted to these curves (4^{th} order polynomial). A 4^{th} order polynomial trendline was used because it gave the closest match to the data, and increased the accuracy of predicting volume. However, these equations should not be used to extrapolate volume or area outside the stage ranges used to generate these equations as

4th order polynomials may give unpredictable results when these polynomials oscillate.

Generating volume over time in each wetland using equations. Since the range of stages in our groundwater well data were covered by the ranges of stages used to generate each equation, we used these equations to predict volume in each wetland based on its groundwater well data. The daily groundwater well data from each site were used in developing the stage volume trendline equation. Volumes in acre-feet were converted to gallons and plotted over time. A decision was made to report results in English units to increase understanding of the results to persons outside of the scientific community. To sum the volume over the reporting period, the trapezoidal method was used to give a better approximation.

Wetlands with 2 groundwater wells. The Ridenour Road, Sunbury Road and Watkins Road wetlands had 2 groundwater wells installed. The Ridenour Road wetland was bisected by a berm to detain stormwater from a housing development. Wells were installed to monitor water levels in the impounded portion and un-impounded portion. The Sunbury Road and Watkins Road were divided into north and south areas and additional wells were installed to be able to monitor hydrology separately in these zones. At these sites, the wetland data were divided into two sections, one for each groundwater well. Three models were generated: one for each groundwater well and a combined model in which the data were joined. In order to give a reasonable and conservative estimate of volume, all the combined volumes were calculated by adding together the volume from their respective sections.

Generalized equation of depth-area-volume for depressional and riverine wetlands. The contour elevation from the model that most closely matched the wetland's delineated boundary was used to determine water storage volume of the wetland when the wetland was inundated to its boundary. These volumes were plotted against wetland area or against area x depth to generate generalized equations that could estimate volume based on the wetland area and/or area x depth for depressional and riverine wetlands. To illustrate the non-circular shape of natural wetlands, the relationship between area and perimeter-to-area for the study wetlands was compared with that of a perfect circle.

RESULTS

Perimeter, area and maximum depth

The 22 sites ranged in size from 0.1 to 8.9 acres with an average size of 1.9 ± 0.5 acres (Table 1). Wetland perimeters ranged from 296 to 4,206 feet, averaging 1,624 ± 267 feet. The average depressional wetland was half as small as a riverine wetland, averaging 1.1 ± 0.4 acres to the riverine's average of 2.5 ± 0.8 acres, while the average depressional perimeter was 1144 ± 265 feet compared to the riverine perimeter average of 2023 ± 411 feet, although the difference was not significant for either the area (ANOVA, $p = 0.30$) or perimeter (ANOVA, $p = 0.18$). The average number of elevation points collected per acre was 205 ± 53. Smaller wetlands tended to be over sampled due to our sampling method.

The maximum depth of the wetlands ranged from 0.5 feet to 5.8 feet, averaging 2.0 ± 0.3 feet. The riverine wetlands were significantly deeper (ANOVA, $p = 0.04$) than depressional wetlands, being twice as deep at 2.6 feet vs. 1.3 feet. Seventeen out of the twenty-two wetlands were shallow with a maximum depth < 3 feet. The five wetlands that had a maximum depth greater than 3 feet were riverine and over 1.5 acres in size. Two of the riverine wetlands, Ridenour Road and Three Creeks oxbow, had deep depressions that could not be measured safely, so their maximum depth is an underestimation. The deepest depressions at these sites were associated with man-made alterations and may not reflect natural wetland depths. Superimposed on an aerial photo of each wetland (Figures 2A-23A) are the groundwater well location, the elevation points and the delineated boundary. Some of the aerial photos show how close development is to these study wetlands.

3-D Models

Three-dimensional models of the basin morphometry are shown in Figures 2B-23B, with an orange line indicating the delineated boundary line taken by GPS. For comparison, highlighted in yellow is the model contour line that most closely matched the delineated boundary. Although there was generally a good match between the delineated boundary and the model boundary, it was never perfect. This may be due to human or instrumental errors in mapping the boundary, not collecting enough elevation readings at the wetland edge, or the conservative nature of the three parameter approach in the Corps delineation manual (Environmental Laboratory 1987) where a point may be within the inundatable boundary of the wetland but lacking in a dominance of hydrophytic vegetation or hydric soils. At some sites, deeper points were just off the boundary indicating a transition to a deeper ditch, stream or river that was not wetland.

The deepest point in each wetland is indicated on the model by a thick black contour line. Contour intervals are indicated in the figure legends. The maximum depth areas were relatively small compared to the size of the wetlands. The color scale to the right of each model indicates elevation range by color. The elevations were referenced to the ground level at the base of the groundwater well in each wetland. Therefore, ground level at the groundwater well is 0 feet in elevation. Elevations above this point are positive and below this point are negative. If there were two groundwater wells in the wetland, elevations were referenced to the groundwater well location indicated in the figure legend.

Stage:area and stage:volume relationships

The volume of water stored by the wetland and the area covered by the water depend on the wetland's stage height (i.e. depth of water). Area and volume were plotted with stage height to give stage:area and stage:volume relationships for each wetland (Figures 2C-23C). For the area curves, at lower stages a small increase in stage rapidly increases area as many of the wetlands have relatively flat bottoms, while there is a slower increase in volume. At higher stages, the opposite occurs as large increases in volume produce smaller increases in surface area.

Water volume stored in wetland

The ground water well data were used in the stage:volume trendline equation to calculate twice a day the water volume stored in each wetland (Figures 2D-23D). Zero values indicate no surface water was in the wetland (wetland dry). Red lines indicate when the groundwater monitoring wells were not operational.

Two sites, Easton and Hills, had groundwater wells that could not measure the lowest water elevations in these wetlands because of their groundwater well locations and the deepness of their pools. When the water levels fell below the bottom of these groundwater wells, surface water may have been in the wetlands, but the groundwater wells could not record it. In these graphs, a blue line indicates the period when the water level fell below the base of the groundwater well. During these periods, these wetlands may have held some water volume but it could not be calculated, so the sum total volume may be an underestimate for these wetlands.

The area under the curve in Figures 2D-23D (total volume over the reporting period) was calculated and summarized for depressional, riverine and all wetlands (Table 2). Four of the depressional wetlands and two of the riverine wetlands were excluded from the sum total calculations, as their groundwater wells were operational less than 75% of the study period. Summing the maximum values for the remaining wetlands shows 6 depressional wetlands stored 2,890,386 gallons total at their maximum (Table 2). The ten riverine wetlands stored 15,810,105 gallons total at their maximum. All the depressional wetlands had a minimum value of 0 indicating these wetlands dried out during the study period (Table 2), while 7 out of the 12 riverine wetlands dried out. During the summer and early fall (July 7th to October 6th), 9 out of the 10 depressional wetlands had a median value of zero and half were totally dry during this period while none of the riverine wetlands were dry.

The maximum volumes usually occurred after a heavy rain (Figure 24). The maximum volume and sum total volume in Table 2 were standardized to volume per maximum area (maximum area was the surface area covered by water at the maximum groundwater well height, calculated using the *Surfer* model) (Figure 25A). The riverine wetlands achieved a maximum volume per acre about 170% of the maximum in the depressional wetlands within the study period (Figure 25A). At their maximum water heights, a one-acre depressional wetland stored an average of 221305 ± 31014 gallons, or 0.7 ± 0.1 acre-feet, while a one-acre riverine wetland stored an average of 381832 ± 54192 gallons or 1.2 ± 0.2 acre-feet, which was significantly different ($p = 0.02$). The average maximum volume for all wetlands was 0.9 ± 0.1 acre-feet per acre. Seasonally, the maximum volume/acre was significantly higher in riverine wetlands as compared to depressional wetlands in the summer (July 6 through October 5) ($p = 0.03$) and in the winter (January 6 to March 21) ($p = 0.03$).

Comparisons within HGM classes show for the depressional wetlands maximum volume/acre was significantly lower during the summer (July 6 to October 5) ($p < 0.001$) as compared to the other seasons as all of these wetlands dried out during the summer.. There was no significant difference seasonally between the riverine wetlands in maximum volume per acre.

Summing daily volumes over the study period, the depressional wetlands (Figure 25B) stored significantly less water than the riverine wetlands, 7,565,575 ± 1,999,130gallons per acre as compared to 30,980,747 ± 7,906,424 gallons per acre for riverine wetlands,($p = 0.005$). Seasonally, except for the period from April 6 to July 5, there were significant differences between the depressional and riverine wetlands volumes per acre (July 6 to October 5, ANOVA, $p < 0.001$), (October 6 to January 5, ANOVA, $p = 0.049$). (January 6 to March 21, 2007, ANOVA, $p = 0.002$).

Comparisons within HGM classes seasonally, the depressional wetlands had a significantly lower sum volume/acre during the summer (July 6 to October 5) ($p < 0.001$) as compared to the other seasons. There was no significant difference seasonally between the riverine wetlands in sum total volume per acre.

Water storage volumes when wetlands were just inundated to their boundaries are given in Table 3. The water storage of depressional wetlands was significantly less per acre when inundated to their boundary than for riverine wetlands (ANOVA, $p = 0.03$), averaging 141,021 gallons per acre to 246,472 gallons per acre, respectively. Total volume divided by total area (Table 3) can give an estimate of mean depth (Haag et al. 2005). The depressional wetlands mean depth of 0.4 ± 0.1 ft. was half the riverines' mean depth of 0.8 ± 0.1 ft., which was significantly different (ANOVA, $p = 0.02$), while the average mean depth for all the wetlands was 0.6 ± 0.1 ft.

The volumes and areas in Table 3 were plotted to find area:volume relationships for depressional (Figure 26A) and for riverine wetlands (Figure 26B) and equations generated from the trendlines for each. The equation relating area to volume:

Depression:

$$\text{volume} = 0.3557 * \text{area}^{0.8045} \qquad \text{Eqn. 1}$$

Riverine:

$$\text{volume} = 0.6468 * \text{area}^{\cdot 1.0992} \qquad \text{Eqn. 2}$$

where, area = area of wetland in acres and volume = acre-feet of water. Since maximum depth was known (Table 1), the relationship between volume and maximum depth x area was determined for depressional wetlands (Figure 27A) and riverine wetlands (Figure 27B). The equation relating the product of area and maximum depth to volume:

Depression:

$$\text{volume} = 0.3219*\text{area} * \text{max depth} \qquad \text{Eqn. 3}$$

Riverine:

$$\text{volume} = 0.2546*\text{area} * \text{max depth} \qquad \text{Eqn. 4}$$

where area = area of wetland in acres, max depth = maximum depth of the wetland in feet, and volume = acre-feet of water. There was a greater correlation between maximum depth x area-to-volume than with just area-to-volume, which is reflected in the higher R^2 values in Figure 27 than in Figure 26. The Quarry site is an outlier in Figure 26B. As this was the largest site, this equation may only be good for wetlands ≤ 7 acres. However, when depth was added to the relationship (Figure 27B), the Quarry site falls in line with the other wetlands.

Brooks and Hayashi (2002) developed a formula for calculating volume of vernal pools based on area and depth. Volumes for the study wetlands were calculated using Brook and Hayashi's equation 3,

$$V_{max=}\ A_{max} \times d_{max} - 1 + 2/p$$

where A_{max} = area of water surface corresponding to the maximum depth, $d_{max,}$ and assuming p (the basin profile coefficient) = 1. Comparison of the volumes when the wetlands were inundated to their boundary from the Brooks and Hayashi (B&H) equation to this study's 3-D model output shows that for depressional wetlands, the B&H equation and the Surfer model gave like averages (Table 4); while for the riverine wetlands, the B&H equation gave a higher volume average. The average riverine wetland volume calculated using the Surfer model was 2.3 acre-feet while using the B&H equation it was 3.0 acre-feet, a 30% difference. The equations relating volume to area x max depth derived from this study's wetlands gave the closest match to the Surfer models volumes, being less than 5% different. The area x volume equation gave similar results as the Surfer model for depressional wetlands, but underestimated volume for riverine wetlands by almost 20%.

Soil water storage capacity

Though soil water absorption was not measured during this study, the depressional wetlands' ability to absorb rainwater is illustrated in their wetland hydrographs. An example of this is seen in the Towne Center groundwater well hydrograph (Figure 28). Overlaying the groundwater well hydrograph with precipitation data shows in the summer when the wetland is dry, the wetland absorbs repeated rainfall events without it translating into increased water levels.

Shape of wetlands

The perimeter-to-area ratios decreased as the area of the wetland increased (Figure 29). The perimeter-to-area ratios were larger for the study wetlands than would be predicted if the wetlands were perfectly circular. The delineated wetland boundaries (red lines on the aerial photos in Figures 2A to 23A) show most of the wetlands have an irregular and more elliptical shape than a circle.

Improvements to methods

While our method of surveying the morphometry of the wetlands gave good results, it was time consuming and could be improved. Recommendations to save time in future studies include using a Total Station that could electronically measure distance and angle. A GPS receiver with sub-meter accuracy would enable one to take elevation readings outside the transects and to take more elevations readings on the wetland's boundary to produce a better map. Haag et al. (2005) found that adding elevation points collected just below the boundary contour considerably improved the accuracy of their maps as compared to just using a low density of transect points alone. Care should be taken to not extend the transect length too much in large wetlands because at the end of a 100 foot transect, transects were over 50' apart, while at the end of a 200' transect they were over 100 feet apart. The wetland areas nearest the laser level location were over sampled compared to other areas as the sampling transects all originated at the laser. Fewer elevation readings could be taken from 0-40 feet out, perhaps alternating distances every transect, and still maintain the accuracy of the model.

DISCUSSION

Overview

Wetland protection is a preventative measure to reduce or prevent flood damage (Association of State Floodplain Managers 1996). The flood retention function of wetlands is at its greatest worth in urban areas where they can reduce flood damage to properties (Boyer and Polasky 2004). In addition to flood mitigation, wetlands provide other functions such as supporting plant and animal diversity, improving water quality, and maintaining stream flow as well as providing opportunities for recreation and aesthetic appreciation (Ehrenfeld 2004, Mitsch and Gosselink 2000). This study documents the flood storage capacity of urban wetlands in Central Ohio. To the extent that Columbus, Ohio is typical of other urban areas in Ohio and surrounding states, these results can be extended to wetlands located elsewhere.

The urban wetlands maximum volume occurred after heavy rains demonstrating that these wetlands store stormwater and help to reduce peak flows. The hydrographs give evidence of the wetlands storing and releasing water over time. When filled to their maximum, twelve riverine wetlands stored over 15 million gallons of water while ten depressional wetlands stored almost 3 million. On average, a one-acre depressional wetland can store about 0.4 acre-feet of water when inundated to its boundary, while a one-acre riverine wetland can store about 0.8 acre-feet of water. At their maximum heights, a one-acre depressional wetland stored an average of 0.7 acre-feet while a riverine wetland stored 1.2 acre-feet.

Although depressional wetlands store less surface water than riverine wetlands, depressional wetlands have great water storage capacity in their soils. Though soil water storage was not included in our models, it can be inferred in the groundwater well hydrographs. In the summer when the wetlands were dry, rainfall events did not result in increased water levels in the wetlands. During dry periods, it seems there is enough soil pore space to absorb the rainfall volume. In the fall, with decreased evapotranspiration, the available soil pore space becomes used up and the wetland fills (Harrold et al. 1963). Wetland soils generally have high water storage capacity. They are either mineral or organic soils. The upper layer of wetland soils is often organic peat made up of decaying plant material. Peat soils have at least 80% total pore space while mineral soils generally range from 45-55 %. Therefore, organic soils have a higher water-storage capacity than mineral soils (Mitsch and Gosselink 2000). Depressional wetlands generally release stormwater more slowly than riverine wetlands, by temporarily or permanently diverting the precipitation that would flow into streams if the wetlands were not present. Two measures of the effectiveness of a wetland in flood mitigation are its capacity to store additional water and whether it has non-saturated soils (McAllister et al. 2000). The dry down of depressional wetlands in summer results in these wetland having non-saturated soils and increases their ability to store additional water, enhancing their flood storage capacity. Prairie potholes have been found to decrease flooding more than riverine wetlands. (SAST 1994). Riverine wetlands had a significantly deeper maximum depth, mean depth, maximum volume and sum total volume over the study period than depressional wetlands. On average, depressional wetlands were half as deep and held about half the volume per acre at their maximum as riverine wetlands. Riverine wetlands stored significantly more water during all periods except from April 6 to

July 5. Previous data suggests riverine wetlands are especially valuable in their ability to absorb stormwater and slow the discharge of stormwater downstream (Krieger 2001). Seasonally, the depressional wetland's maximum volume and sum total volume was significantly less during the period from July 6 to October 5 than during the other periods.

Relative storage efficiency of depressional and riverine wetlands

Annual hydrographs for every site are provided in the Appendix. Riverine and depressional wetlands had distinctly different hydrologic signatures. Depressional wetlands had a strong seasonal signature with a marked summer drawdown (Figure 30). Some riverine wetland hydrographs also showed a season signature but also had strong flood pulses even during the driest periods. Other riverine sites had large pulses of floodwater throughout the year and did not evince any seasonal drawdown, although an increasing or decreasing baseline of inundation is still discernible (Figure 31). Notable in many depressions is the nearly complete drawdown of these sites by early summer, despite regular and sometimes large precipitation events throughout this period (See e.g. hydrographs for Bolton Field, Easton, Hills, ISG151, Somerset Park, Watkins Road, Wilson Road in the Appendix. Hydrograph for Cherry Bottom, technically a riverine site but one that only occasional receives overbank flooding, also shows a very strong seasonal signature). The hydrographs of the groundwater wells at depressions during this period were largely nonresponsive to these precipitation events. Depressions appeared to be extremely efficient at capturing and removing precipitation from the local hydrologic system. In fact, the hydrographs developed here strongly suggest transpiration is the clear hydrologic driver in this process. We observed an abrupt reinundation of most depressional sites in just 1-3 rain events October/November 2006 just as vegetation becomes dormant for the year (Figure 32).

In contrast, while evapotranspiration is clearly removing water from riverine systems also, very large amounts of their annual volume is only temporarily stored. We compared the basin (mapped) volume, the volume of precipitation falling on the delineated footprint, and the summed daily morphometric volume estimate (from Table 2), to evaluate the flood storage efficiency of depression and riverine wetlands in this study (Table 5). On average, the total precipitation falling on the delineated footprint was 11.1 times the basin volume for depressions and 6.8 times the basin volume of riverine wetlands (Table 5). This means that while basin volume of depressions was, on average, approximately half that of the riverine sites (0.4 acre-feet per acre to 0.8 acre-feet per acre; see Table 3), depressions were capturing and removing from the hydrologic system nearly 2 times more precipitation than riverine sites. The difference is due to the fact that a large proportion of the precipitation that falls on riverine wetlands flows out of the site back into streams. The large disparity in average summed daily volumes (~10 million to ~100 million gallons) is largely attributable to the flood desynchronization (versus flood storage) services of riverine and depressional wetlands. On average, the summed morphometric volume estimate was 2632% greater than estimated precipitation volume falling on the delineated footprint of riverine wetlands; for depressions the summed morphometric volume estimate was only 943% greater on average (Table 5).

In effect, the data collected here shows that, acre for acre, depressions are more efficient than riverine wetlands at capturing and removing water from the local hydrologic cycle;

in contrast, riverine wetlands are clearly better at desynchronizing stream flood events. This result has significant policy implications given the recent U.S. Supreme Court decision in *Rapanos/Carabell* regarding the scope of Clean Water Act regulation of wetlands *vis-a-vis* the determination if a wetland is a "water of the United States" and what constitutes a sufficient significant nexus to assert geographic jurisdiction over more "isolated" wetlands. The act of filling depression wetlands in urban contexts typically also involves hardening the land surface and routing stormwater to engineered temporary detention basins (i.e. "desynchronization" basins) which release the flows to the local hydrologic network. These unvegetated basins do not function equivalently to the destroyed depressional wetland as transpiration is absent, which is the hydrologic driver of the relative storage efficiency of depressions. Basically, the act of destroying an "isolated" depression creates a "significant nexus" where none existed previously since the depressions can capture and remove precipitation reaching them from the hydrologic system.

Based on this data, we would conclude that a complex of 100 one-acre "isolated" depressions would provide a greater flood storage service than an equivalent acreage of riverine wetlands. The question, in the usually highly fragmented urban context, becomes, when does this same conclusion could apply to a complex of 5 or 10 one-acre depressions, or even a single one-acre depression? The Section 401/404 permit programs, in practice, consider wetlands individually (although both have authority to consider cumulative, secondary, and/or indirect impacts, these provisions are usually not invoked because of pragmatic and evidentiary difficulties in permit appeals). But, flood storage services (in the case of depressions) or flood desynchronization services (in the case of riverine wetlands) usually become manifest in a watershed in the context of populations of wetlands. We obtained USGS stream gauge data for a large (Olentangy River), medium (Big Walnut Creek) and small (Hellbranch Run) stream for April 1, 2006 to April 1, 2007 (the period we had wells deployed) and calculated the annual, average daily, maximum daily, and minimum daily flow (gallons per day) in these streams (Table 6). We divided the total daily flow for each stream by the average storage capacity of depressions (141,021 gal/ac), riverine (246,472 gal/ac), and all wetlands (198,539 gal/ac) in this study to obtain an estimate of the number of acres of wetland necessary to hold that volume of water and the percentage of the watershed acreage that represented (Table 6). Finally, we estimated the total storage capacity of the 649 mapped urban wetlands (649 times average storage capacity) and the percentage of the annual flow of each stream they could store (Table 6). We realize that there are many assumptions built into these estimates but our purpose was to obtain a relative perspective on flood storage capacity of different sized streams and the total flows moving through their respective hydrologic networks, and not an absolute estimate.

Considering just the "all wetlands" estimate, approximately 2300, 900, and 70 acres of wetlands in the Olentangy, Big Walnut, and Hellbranch watersheds could store the average daily flow in these streams (which is about 1%, 0.5% and 0.5% of the acreage of these watersheds); for maximum daily flows, the acreages are substantially higher (23000, 21000, and 1800 acres, respectively) which represents about 6.5%, 10%, and 7.4% of the acreage of these watersheds, respectively (Table 6). Considering just the acreage of Franklin County, to capture the average daily flow would need 1%, 0.3%, and 0.03% of the land in Franklin County of for the Olentangy, Big Walnut, and

Hellbranch, respectively; maximum daily flows would need 6.6%, 6.2% and 0.5%, respectively (Table 6). Finally, considering the estimated storage capacity of the 649 mapped urban wetlands in this study, they could store about 0.75%, 2% and 43% of the average daily flow of the Olentangy, Big Walnut and Hellbranch, respectively (Table 6).

There is clearly a dose of unreality about these figures since we just pointed out that the depressional wetlands are not in landscape position to store any of the water actually moving through these streams. In fact, from a "depressional wetland flood storage" perspective, once the water is flowing in the stream the battle is already over; depressions can keep water from getting to the stream but not remove it once it is there (this is where riverine wetland desynchronization can play its part). Although so frequently said that it is nearly a truism, clearly what is needed is a watershed-scale appreciation of the hydrologic volumes moving through the system and how best to apportion storage and removal (depressions) and storage/desynchronization (riverine) in the system to ensure a hydrologic balance that maintains various uses (e.g. water supply, recreation) and stream ecosystem health (the goal of the Clean Water Act to protect, restore and maintain the biological, chemical, and physical integrity of the nation's waters). Our general conclusion, given that ~650 mapped urban wetlands in Franklin County could store ~1-2% of the average daily flow of larger streams and ~40% of a small stream, is that the extant population of urban wetlands in Franklin County, Ohio is providing a substantial flood storage service.

Although this study focused on "urban" wetlands, we believe the results obtained here are not inapplicable to depressional and riverine wetlands throughout Ohio and the midwest. The depressional wetlands assessed had largely intact, precipitation-driven hydrologies, similar to what would occur in "reference" depressional systems. Similarly, the riverine wetlands assessed did not appear to be atypical in their hydrology from other riverine mainstem systems in Ohio. The results obtained are clearly applicable to other urban centers and there appears to be no reason not to use them throughout Ohio.

"Rapidly" assessing water storage capacity of depressional and riverine wetlands

Although considered the primary forcing factor in wetland ecosystems (Mitsch and Gosselink 2000), quantitative hydrologic assessments are undertaken much less frequently than floral or faunal surveys and are uncommon in data collected in regulatory permit programs. Of the published, HGM guidebooks which all include hydrologic "functions" in their models, virtually none were developed based on quantitative reference hydrology data: Lin (2006) (depressional wetlands in the upper Des Plains river basin); Aisnlie et al. (2004) (low gradient riverine wetlands in western Kentucky); Klimas et al. (2004) (forested wetlands in the delta region of Arkansas); Klimas et al. (2004) (forested wetlands in the West Gulf Coastal Plain region of Arkansas); Noble et al. 2004 (depressional wetlands in peninsular Florida); Stutheit et al. 2004 (rainwater depressional wetlands in Nebraska); Uranowski et al. (2003) (low-gradient blackwater riverine in peninsular Florida); Hauer et al. 2002 (Intermontane pothole wetlands in the Northern Rocky Mountains); Hauer et al. (2002) (riverine floodplains in the northern Rocky Mountains); (Rheinhardt et al. 2002) (wet pine flats on mineral soils in the Atlantic and Gulf Coastal Plains); Shafer et al. (2002) (northwest Gulf of Mexico tidal fringe wetlands); Smith and Klimas (2002) (selected region subclasses of wetlands in the Yazoo Basin lower Mississippi River);

Wilder and Roberts (2002) (low-gradient riverine wetlands in western Tennessee).

While producing 3-dimensional basin maps was a pain-staking process, the data collected here has allowed the derivation of highly correlated regression models using wetland area and/or maximum depth to estimate water storage capacity (Equations 1-4; Figures 26-27). Wetland area is routinely collected as part of every wetland permit and Eqns. 1 and 2 are "rapid" wetland storage volume estimators. We conclude that these equations work, as well as they do, because for practical purposes, the sites in this study were flat, with an average relief of ~ 2 ft.

The 4th order polynomial trendline fitted to each wetland's stage-volume relationship gave a close fit to the data, although data cannot be extrapolated outside the stage levels used to generate these equations or beyond the wetland sizes in this study (~10 acres), although we expect the relationships to hold above these limits). The stage:area trendlines fit less well than the stage:volume trendlines to the data. Haag et al. (2005) also found that the "S"-shaped curved generated by the stage:area relationship could not be represented over its entire range by the power function or higher-order polynomials. The equations generated from the stage:volume trendline gave us the opportunity to calculate daily surface water volume based on groundwater well data at the site.

Being able to predict volume based on the size and depth of natural wetlands can help managers by providing a simple procedure for determining flood storage of wetlands proposed for impacts or to design wetlands that have the capacity to mitigate flood damage, while providing other functions such as quality habitat. This study generated equations to predict volume based on area and based on area x maximum depth for both riverine and depressional wetlands. The equation based on area x maximum depth gave a better correlation. The Brooks and Hayashi (2002) equation also gave a good match to the 3-D model output for the depressional wetlands.

The equations give insight into the relationships between area, depth and volume in natural wetlands. Constructed wetlands are often made deeper than natural wetlands with steeper slopes to ensure the wetland meets the hydrology criteria and area requirements for mitigation, but they function more as ponds and fail as wetlands (Mack and Micacchion 2006, Kettlewell 2005, Porej 2003). Comparison of wetland depths is complicated by small but deep depressions in wetlands. To overcome this, Haag et al. (2005) compared mean depths and found 4 marshes and cypress wetlands in Florida with an average mean depth of 1.16 and 0.69 feet, respectively. The mean depths found in this study were shallower for depressional wetland at 0.4 feet while the riverine wetlands had a mean depth of 0.8 feet. Less than a quarter of the study wetlands had a maximum depth greater than 3 feet and these were all riverine wetlands. Constructed wetland should be patterned after natural wetlands to ensure functionality.

The study wetlands had a higher perimeter-to-area ratio than would be predicted if they had the shape of a circle. Shape as well as the area of a wetland varies the perimeter to area ratio (Brooks and Hayashi 2002). Brooks and Hayashi (2002) found the relationship between perimeter-to-area ratios and surface areas of vernal pools to be similar but slightly higher than the relationship for an ellipse because the wetlands had a more complicated perimeter shape than an ellipse. Although not calculated in this study, the flooded areas in a wetland based on stage can be determined from the 3-D model output and can be used to determine duration of inundation.

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Table 1. Size of sample wetlands (area, delineated perimeter and maximum depth) and density of sample points.

site #	site name	wetland description	HGM class	area (acres)	area (ha)	perimeter (ft)	perimeter (m)	maximum depth from boundary contour (ft)	maximum depth from boundary contour (m)	# data points	# points per acre	# points per ha
44	Airport Plaza	degraded forested wetland	dep	1.66	0.67	1253	382	1.14	0.35	119	72	177
142	Watkins Rd. combined	degraded ash swamp	dep	3.46	1.40	3154	961	0.91	0.28	335	97	239
151	ISG	oak swamp	dep	0.95	0.39	1265	386	0.87	0.27	108	113	280
268	Towne Center Apts	vernal pool	dep	0.24	0.10	486	148	0.59	0.18	61	257	636
274	Somerset Park	emergent depression	dep	0.13	0.05	381	116	0.93	0.28	55	411	1015
281	Golf Course	headwater depression	dep	0.25	0.10	642	196	2.01	0.61	78	309	763
286	Hills	vernal pool	dep	0.27	0.11	425	129	2.92	0.89	60	226	559
308	Easton	vernal pool	dep	0.87	0.35	1224	373	2.33	0.71	160	184	456
409	Wilson Road	small cattail marsh	dep	0.64	0.26	863	263	0.85	0.26	96	150	372
492	Bolton Field	red maple swamp	dep	2.70	1.09	1745	532	0.73	0.22	155	57	142
19	Ridenour Rd. combined	riverine wetland	riv	2.50	1.01	2644	806	3.72	1.13	289	116	286
76	Big Walnut Park	riverine swamp forest	riv	1.27	0.51	1920	585	1.54	0.47	155	123	303
82	ATV	small depression in floodplain	riv	0.06	0.03	296	90	1.66	0.50	78	1238	3059
201	3 Creeks Oxbow	oxbow wetland	riv	1.56	0.63	2290	698	5.78	1.76	321	205	507
204	Alum Creek Dr	riverine swamp forest	riv	4.54	1.84	4037	1230	1.51	0.46	490	108	267
242	Sunbury Rd. combined	riverine wetland	riv	7.00	2.83	4206	1282	3.08	0.94	334	48	118
351	Worthington HS	small depression in floodplain	riv	0.28	0.11	561	171	2.63	0.80	64	228	563
352	Worthington Park	small depression in floodplain	riv	0.49	0.20	713	217	0.48	0.15	60	122	303
354	Antrim Park	riverine channel swamp	riv	2.01	0.81	1979	603	3.26	0.99	189	94	232
358	Graceland	riverine wetland	riv	0.44	0.18	621	189	1.25	0.38	64	146	360
464	Quarry	riverine wetland	riv	8.88	3.59	3877	1182	5.58	1.70	482	54	134
529	Cherry Bottom Park	wet woods on floodplain	riv	0.96	0.39	1135	346	1.24	0.38	143	149	368
		Average depressional (± s.e.)		1.1 ± 0.4	0.5 ± 0.1	1144 ± 265	349 ± 81	1.3 ± 0.3	0.4 ± 0.1	123 ± 26	188 ± 36	464 ± 89
		Average riverine (± s.e.)		2.5 ± 0.8	1 ± 0.3	2023 ± 411	617 ± 125	2.6 ± 0.5	0.8 ± 0.2	222 ± 46	219 ± 94	542 ± 232
		Average all (± s.e.)		1.9 ± 0.5	0.8 ± 0.2	1624 ± 267	495 ± 81	2 ± 0.3	0.6 ± 0.1	177 ± 29	205 ± 53	506 ± 130
		Range all		0.1 - 8.9	0.03 - 3.6	296 - 4206	90 - 1282	0.5 - 5.8	0.1 - 1.8	55 - 490	48 - 1238	118 - 3059

Table 2 Volume summary (gallons) for entire study period (April 6 to March 21), Spring/Early Summer (April 6 to July 5), Summer/Early Fall (July 6 to October 5), Fall/Early Winter (October 6, 2006 to January 5, 2007), Winter/Early Spring (January 6 to March 21); "% time" is fraction of study period well was operational. Blank values (other than zero) indicate well was not operational during period. Zero values indicate wetland was dry (no water). Date Max indicates date when maximum volume was achieved. "Sum" column is sum of daily values over period using trapezoidal method. Sites marked with an "*" were excluded from calculations as those wetlands' wells were operational less than 75% of period.

		Entire Period April 6 to March 21, 2007							Spring/Early Summer April 6 to July 5, 2006					Summer/Early Fall July 6 to October 5, 2006					Fall/Early Winter October 6 to January 5, 2007					Winter/Early Spring Jan 6 to March 21, 2007				
HGM class	Site Name	Mean	Min	Median	Max	Date Max	Sum	% time	Mean	Min	Median	Max	Sum	Mean	Min	Median	Max	Sum	Mean	Min	Median	Max	Sum	Mean	Min	Median	Max	Sum
dep	Airport Plaza*	35,739	0	21,186	680,029	6/1/07	8,919,466	72	18,472	0	657	680,029	1,265,315	21,461	0	0	665,308	1,659,022	59,930	14,308	51,802	539,244	4,451,218	52,497	0	43,648	593,803	1,543,910
dep	Bolton Field	86,150	0	0	607,949	1/15/07	26,118,504	87	92,288	0	2,945	467,758	6,947,892	0	0	0	0	0	72,500	0	0	441,824	4,283,294	223,122	0	258,082	607,949	14,887,318
dep	Bridgeview*	32,762	0	29,641	83,954	10/4/07	7,438,636	65	20,946	0	11,426	76,894	1,424,071	20,150	0	51	83,954	1,851,238	62,101	34,669	63,076	82,156	3,786,668	62,777	56,410	62,313	69,379	376,660
dep	Easton	9,831	0	0	148,126	3/2/07	2,591,665	76	7,069	0	5,797	18,421	531,216	0	0	0	0	0	554	0	0	10,682	40,821	87,081	5,279	109,982	148,126	2,019,628
dep	Hills*	29,870	0	36,995	61,406	3/14/07	6,033,381	58	no data	no data	no data	no data	no data	2,058	0	1,891	6,255	132,064	28,841	1,785	37,392	60,279	2,220,939	60,837	60,279	60,841	61,406	3,680,378
dep	ISG	13,670	0	0	131,533	1/15/07	3,603,946	77	6,940	0	0	118,140	308,825	0	0	0	0	0	9,081	0	0	99,918	746,876	50,875	0	54,253	131,533	2,548,245
dep	Somerset Park	12,605	0	10,609	58,561	3/12/07	3,707,147	85	9,151	300	10,882	21,191	632,035	94	0	0	505	8,774	20,314	0	24,414	56,699	1,674,244	27,123	11,727	26,110	58,561	1,392,094
dep	Towne Centre*	7,626	0	0	71,495	3/15/07	1,914,517	73	2,971	0	0	15,506	222,212	0	0	0	0	0	14,683	0	11,332	48,036	988,335	34,309	15,506	32,980	71,495	1,392,094
dep	Watkins Rd	96,313	0	0	516,254	1/15/07	34,109,485	76	47,435	0	0	409,771	3,579,415	0	0	0	0	0	182,170	0	188,693	398,849	18,352,966	229,777	0	224,545	516,254	12,177,103
dep	Wilson Road	38,534	0	11,638	531,080	3/15/07	10,644,750	80	32,422	0	13,500	228,528	2,433,466	63	0	0	11,622	5,811	63,817	0	64,727	159,585	4,513,860	92,535	0	81,481	531,080	3,691,613
	Mean Depressional	36,310	0	11,007	289,039		13,462,583		23,769	30	4,521	226,249	2,405,475	4,383	0	194	76,765	2,431	51,399	5,076	44,144	189,727	4,935,343	92,093	14,920	95,424	278,958	6,119,334
	± s.e. Depressional	9,856	0	4,388	81,906		5,492,253		9,022	32	1,757	80,067	1,049,863	2,746	0	189	65,906	1,822	16,696	3,578	17,979	61,154	2,785,497	23,289	7,450	25,584	78,099	2,390,084
	Total of maximum values for depressional wetlands				2,890,386							2,036,239					767,646					1,897,271					2,789,584	
riv	Alum Creek	206,251	0	219,255	1,074,674	6/1/07	71,950,255	100	212,683	0	170,799	1,074,674	19,258,958	72,159	0	2,417	601,910	6,554,526	339,284	39,098	329,180	768,080	31,217,611	199,744	0	228,828	641,239	14,919,159
riv	Antrim Park	99,028	24,420	27,828	1,098,071	7/17/06	34,090,731	99	47,759	24,420	26,664	538,875	4,127,727	64,229	24,423	24,913	1,098,071	5,912,804	82,702	24,423	50,498	711,661	7,581,195	222,517	24,450	105,626	1,098,071	16,469,006
riv	ATV	8,245	0	3,108	58,796	1/15/07	2,606,090	91	3,468	0	954	44,731	202,728	187	0	0	4,497	16,404	7,366	153	4,464	31,916	674,614	23,035	11,532	18,310	58,796	1,712,345
riv	Big Walnut Park*	28,725	0	0	1,093,933	3/2/07	6,384,538	64	no data	no data	no data	no data	no data	189	0	0	21,409	10,705	4,728	0	0	46,009	423,514	80,000	0	13,236	1,093,933	5,950,320
riv	Cherry Bottom	94,474	0	103,126	243,129	3/1/07	28,761,193	87	77,174	0	53,847	217,196	5,786,471	4,069	0	0	229,999	386,905	161,849	0	186,633	236,524	13,682,577	167,668	0	180,771	243,129	8,905,241
riv	Graceland	20,439	0	0	256,273	3/15/07	7,003,405	99	84	0	0	8,423	7,290	2,103	0	0	141,325	189,810	11,804	0	0	170,894	1,087,300	77,380	0	18,628	256,273	5,719,006
riv	Quarry	1,510,914	244,251	1,001,781	6,264,108	12/3/07	478,565,534	91	1,224,160	460,966	968,989	5,424,704	71,478,146	881,721	244,251	783,749	3,145,681	81,105,123	1,821,806	753,510	1,139,433	6,264,108	167,249,421	2,129,154	567,079	1,079,167	6,264,108	158,732,844
riv	Ridenour Rd	448,884	282,602	453,775	1,107,079	1/15/07	156,417,497	100	374,936	282,849	343,785	599,205	33,728,810	407,409	282,602	396,370	668,259	37,465,514	534,544	369,228	546,473	656,063	49,161,997	483,652	302,042	492,492	1,107,079	36,061,176
riv	Sunbury Rd	1,104,723	0	1,088,339	3,045,973	3/15/07	334,894,019	87	753,371	0	752,126	1,884,416	67,925,579	760,113	45,002	694,071	2,445,475	69,645,898	1,484,213	826,864	1,379,092	2,423,804	121,670,414	1,924,553	851,473	1,889,280	3,045,973	75,652,128
riv	Three Creeks	366,837	163,412	328,248	1,299,314	10/17/06	99,273,891	78	347,538	230,523	313,351	1,105,635	27,296,894	245,402	172,199	223,559	1,299,314	19,616,777	409,016	267,216	387,160	1,299,314	24,947,710	534,931	163,412	441,514	1,299,314	27,412,511
riv	Worthington HS	15,400	0	2,140	158,081	1/15/07	5,278,635	99	1,338	0	0	13,045	115,643	1,802	0	17	34,480	165,328	5,206	567	2,601	29,899	478,179	61,416	1,920	31,488	158,081	4,519,485
riv	Worthington Park*	37,701	0	16,572	110,675	1/13/07	5,964,390	46	no data	no data	no data	no data	no data	384	0	0	25,001	24,272	52,446	0	51,237	110,675	3,755,652	95,871	3,420	110,675	110,675	2,184,465
	Mean Riverine	328,468	59,557	270,348	1,317,509		121,884,125		253,543	83,230	219,210	1,091,090	22,992,825	203,314	64,040	177,091	809,618	22,105,909	409,580	190,088	339,731	1,062,412	41,775,102	499,994	160,444	384,168	1,281,389	35,010,290
	± s.e. Riverine	140,585	30,681	112,964	509,930		51,011,245		116,082	47,772	99,155	518,007	8,654,187	91,068	30,474	83,819	298,835	10,630,333	176,519	88,238	135,180	514,087	18,130,652	211,430	80,545	163,084	512,765	15,399,563
	Total of Maximum values for Riverine wetlands				15,810,105							10,910,903					9,715,420					12,748,946					15,376,670	
	Mean all wetlands	195,669	32,486	152,465	850,022		61,411,187		149,100	45,412	121,624	681,429	11,437,362	112,891	34,931	96,684	476,503	9,871,477	246,771	105,992	205,373	665,737	21,608,091	314,584	94,297	252,920	825,739	18,494,257
	± s.e. all wetland	81,692	17,631	66,661	296,798		35,033,544		67,932	27,233	58,978	286,919	5,962,728	53,275	17,713	48,752	180,837	7,328,000	102,330	51,295	79,470	291,942	12,416,639	121,829	45,983	93,332	296,942	10,518,555
	Total of maximum values for all wetlands				18,700,491							12,947,142					10,483,066					14,646,217					18,166,254	

Table 3 Volume (gallons and acre-feet) when wetland inundated to perimeter and volume per area (gallons/acre and acre-feet/acre)

name	Volume (gallons) at boundary contour	Volume (acre-feet) at boundary contour	Area (acre) from delineation	Volume per area (gallons per acre)	Volume per area (acre-feet per acre) (Mean Depth)
Airport Plaza	228003	0.70	1.7	137475	0.42
Watkins Road combined	351428	1.08	3.5	101580	0.31
ISG	103614	0.32	1.0	108781	0.33
Towne Center Apts	18807	0.06	0.2	79394	0.24
Somerset Park	17453	0.05	0.1	130348	0.40
Golf Course	51117	0.16	0.3	203975	0.63
Hills	89066	0.27	0.3	335846	1.03
Easton	123834	0.38	0.9	135086	0.41
Wilson Road	60435	0.19	0.6	94741	0.29
Bolton Field	224316	0.69	2.7	82982	0.25
Ridenour Rd. combined	511585	1.57	2.5	204993	0.63
Big Walnut Park	216532	0.66	1.3	171131	0.53
ATV	15407	0.05	0.1	244560	0.75
3 creeks oxbow	852672	2.62	1.6	545535	1.67
Alum Creek Dr	639457	1.96	4.5	140992	0.43
Sunbury Rd combined	1770953	5.43	7.0	253084	0.78
Worthington HS	75667	0.23	0.3	269564	0.83
Worthington Park	29854	0.09	0.5	60940	0.19
Antrim Park	516584	1.59	2.0	257071	0.79
Graceland	79480	0.24	0.4	181089	0.56
Quarry	4140530	12.71	8.9	466260	1.43
Cherry Bottom	156105	0.48	1.0	162439	0.50
Mean depressional, ± s.e.	126807 ± 34308	0.4 ± 0.1	1.1 ± 0.4	141021 ± 24491	0.4 ± 0.1
Mean riverine, ± s.e.	750402 ± 340142	2.3 ± 1	2.5 ± 0.8	246472 ±39189	0.8 ± 0.1
Mean all, ± s.e.	466950 ± 194619	1.4 ± 0.6	1.9 ± 0.5	198539 ±26209	0.6 ± 0.1

Table 4 Volume when wetland inundated to boundary from 3-D Surfer model output compared to a) volume based on Brooks and Hayashi (B&H) (2002) equation 3; b) volume based on this study's area x max depth equation; and c) volume from this study's area equation. Volumes are ± s.e.

Wetland name	HGM	Volume from Surfer model (acre-feet)	Volume using Brooks and Hayashi equation (acre-feet)	% Difference between Surfer and B&H equation	Volume using area x max depth equation (acre-feet)	% Difference between Surfer and area x max depth equation	Volume using area equation (acre-feet)	% Difference between Surfer and area equation
Airport Plaza	dep	0.70	0.63	9.6	0.61	12.7	0.53	23.6
Watkins Rd	dep	1.08	1.05	2.2	1.02	5.5	0.97	10.5
ISG	dep	0.32	0.28	13.2	0.27	16.2	0.34	-7.6
Towne Center	dep	0.06	0.05	18.9	0.05	21.6	0.11	-93.5
Somerset Park	dep	0.05	0.04	22.2	0.04	24.9	0.07	-31.7
Golf Course	dep	0.16	0.17	-7.0	0.16	-4.1	0.12	25.0
Hills	dep	0.38	0.26	32.1	0.25	34.4	0.12	67.8
Easton	dep	0.38	0.67	-77.3	0.65	-71.2	0.32	16.5
Wilson Road	dep	0.19	0.18	2.9	0.17	6.2	0.25	-33.6
Bolton Field	dep	0.69	0.66	4.6	0.63	7.9	0.79	-15.0
Ridenour Rd	riv	1.57	3.09	-97.1	2.36	-50.6	1.77	-12.6
Big Walnut Park	riv	0.66	0.65	2.2	0.50	25.3	0.84	-26.1
ATV	riv	0.05	0.03	26.5	0.03	43.8	0.03	34.5
3 Creeks Oxbow	riv	2.62	3.01	-15.1	2.30	12.1	1.06	59.6
Alum Creek Dr	riv	1.96	2.29	-16.5	1.75	11.0	3.41	-73.7
Sunbury Rd	riv	5.43	7.20	-32.4	5.50	-1.1	5.49	-1.0
Worthington HS	riv	0.23	0.25	-6.0	0.19	19.1	0.16	31.1
Worthington Park	riv	0.09	0.08	14.5	0.06	34.7	0.30	-222.2
Antrim Park	riv	1.59	2.18	-37.7	1.67	-5.2	1.39	12.1
Graceland	riv	0.24	0.18	25.3	0.14	42.9	0.26	-7.3
Quarry	riv	12.71	16.53	-30.1	12.62	0.7	7.13	43.9
Cherry Bottom	riv	0.48	0.40	16.8	0.30	36.4	0.62	-29.2
Average depressional		0.4 ± 0.1	0.4 ± 0.1	0%	0.4 ± 0.1	4%	0.4 ± 0.1	9%
Average riverine		2.3 ± 1	3 ± 1.4	-30%	2.3 ± 1	1%	1.9 ± 0.7	19%
Average all		1.4 ± 0.6	1.8 ± 0.8	-26%	1.4 ± 0.6	1%	1.2 ± 0.4	18%

Table 5. Summary of mapped, precipitation, and morphometric volume estimates for urban wetlands in this study.

HGM class	site	mapped volume (gal)	total precip (gal) on jurisdictional footprint	times total precip > mapped volume	total vol (gal) based on morphometric estimate	% morphometric estimate > than precip	avg precip (gal) on jurisdictional footprint	max precip (gal) on jurisdictional footprint
dep	Airport Plaza	228,003	2,090,910	9.2	8,919,466	427%	5,991	84,195
riv	Alum Cr	639,457	5,718,063	8.9	71,950,255	1258%	16,384	230,249
riv	Antrim Park	516,584	2,533,398	4.9	34,090,731	1346%	7,259	102,012
riv	ATV	15,407	77,903	5.1	2,606,090	3345%	223	3,137
riv	Big Walnut Park	216,532	1,595,449	7.4	6,384,538	400%	4,571	64,244
dep	Bolton Field	224,316	3,409,025	15.2	26,118,504	766%	9,768	137,271
riv	Bridgeview	51,117	317,843	6.2	7,438,636	2340%	911	12,799
riv	Cherry Bottom	156,105	1,212,167	7.8	28,761,193	2373%	3,473	48,810
dep	Easton	123,834	1,093,755	8.8	2,591,665	237%	3,134	44,042
riv	Graceland	79,480	554,668	7.0	7,003,405	1263%	1,589	22,335
dep	Hills	89,066	333,424	3.7	6,033,382	1810%	955	13,426
dep	ISG151	103,614	1,199,703	11.6	3,603,946	300%	3,438	48,308
riv	Ridenour Md	511,585	3,147,272	6.2	156,417,497	4970%	9,018	126,731
dep	Somerset Park	17,453	168,270	9.6	3,707,147	2203%	482	6,776
riv	Sunbury Rd N	1,770,953	8,824,825	5.0	334,894,019	3795%	25,286	355,349
riv	The Quarry	4,140,530	11,199,302	2.7	478,565,534	4273%	32,090	450,962
riv	Three Creeks	852,672	1,972,498	2.3	99,273,891	5033%	5,652	79,427
dep	Towne Centre	18,807	299,147	15.9	1,914,517	640%	857	12,046
dep	Watkins Rd	351,428	4,362,555	12.4	34,109,485	782%	12,500	175,667
dep	Wilson Rd	60,435	803,957	13.3	10,664,750	1327%	2,304	32,373
riv	Worthington HS	75,667	355,237	4.7	5,278,635	1486%	1,018	14,304
riv	Worthington Park	29,854	616,990	20.7	5,964,390	967%	1,768	24,844
	total	10,272,899	51,886,359	5.1	1,336,291,676	2575%	---	---
	total depressions	1,216,956	13,760,745	11.3	97,662,862	710%	---	---
	total riverine	8,839,411	37,570,947	4.3	1,231,625,409	3278%	---	---
	average	466,950	2,358,471	8.6	60,740,531	1879%	---	---
	average depressions	---	1,528,972	11.1	10,851,429	943%	---	---
	average riverine	---	3,130,912	6.8	102,635,451	2632%	---	---

Table 5. Comparison of storage capacity of urban wetlands to flow from Olentangy River, Big Walnut Creek, and Hellbranch Run.

OLENTANGY R. at Worthington		acres of depressional wetlands to capture flow	acres of riverine wetlands to capture flow	acres of wetlands to capture flow	BIG WALNUT CR. at Central College	acres of depressional wetlands to capture flow	acres of riverine wetlands to capture flow	acres of wetlands to capture flow	HELLBRANCH RUN at mouth	acres of depressional wetlands to capture flow	acres of riverine wetlands to capture flow	acres of wetlands to capture flow
Watershed size (ac)	347,519				215,056				24,128			
Annual flow (gal)	165,716,284,503				62,898,908,708				2,909,181,978			
Average daily flow (gal)	461,605,249	3,273	1,873	2,325	173,275,231	1,229	703	873	240,231,012	113	58	73
Max daily flow (gal)	3,199,268,366	22,686	12,980	16,114	3,018,299,650	21,403	12,246	15,203	250,770,935	1,778	1,017	1,263
Min daily flow (gal)	16,157,921	115	66	81	68,509,585	486	278	345	25,853	0.18	0.10	0.13
% of watershed in wetlands to capture average daily flow		0.94%	0.54%	0.67%		0.57%	0.33%	0.41%		0.47%	0.24%	0.30%
% of watershed in wetlands to capture maximum daily flow		6.53%	3.74%	4.64%		9.95%	5.69%	7.07%		7.37%	4.22%	5.23%
% of Franklin County Land Area in wetlands to capture average daily flow		0.95%	0.54%	0.67%		0.36%	0.20%	0.25%		0.03%	0.02%	0.02%
% of Franklin County Land Area in wetlands to capture maximum daily flow		6.57%	3.76%	4.66%		6.19%	3.54%	4.40%		0.51%	0.29%	0.37%
% of annual flow captured by average depressional capacity of urban wetlands	0.45%				1.18%				25.58%			
% of annual flow captured by average riverine capacity of urban wetlands	0.31%				0.81%				17.46%			
% of average daily flow captured by average capacity of urban wetlands	0.76%				1.99%				43.04%			

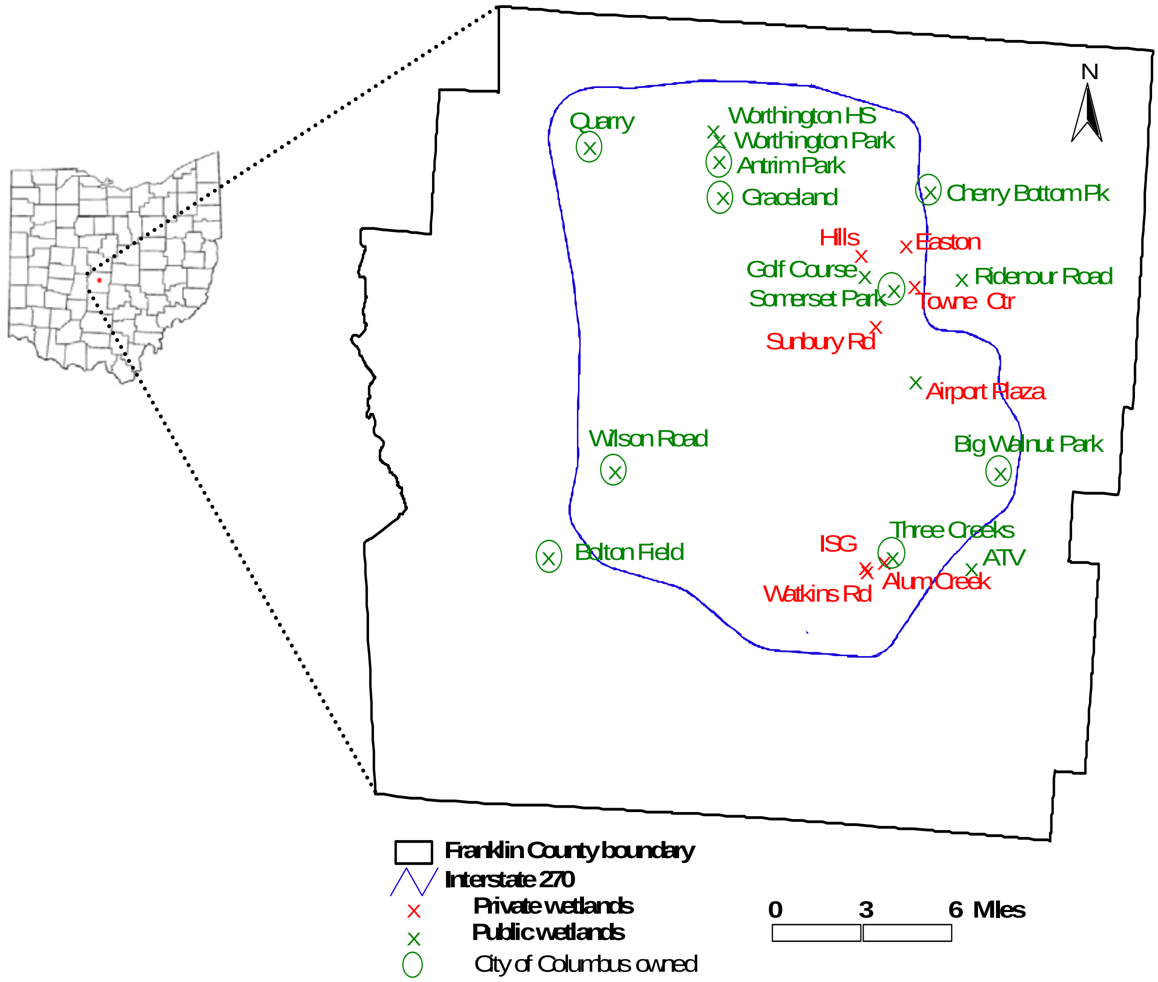

Figure 1 Franklin County in Ohio. Interstate 270 (blue line) and sites (red and green stars) shown. Public wetland sites have green stars (City of Columbus owned sites circled) while private sites are indicated with red stars.

Airport Plaza, #44

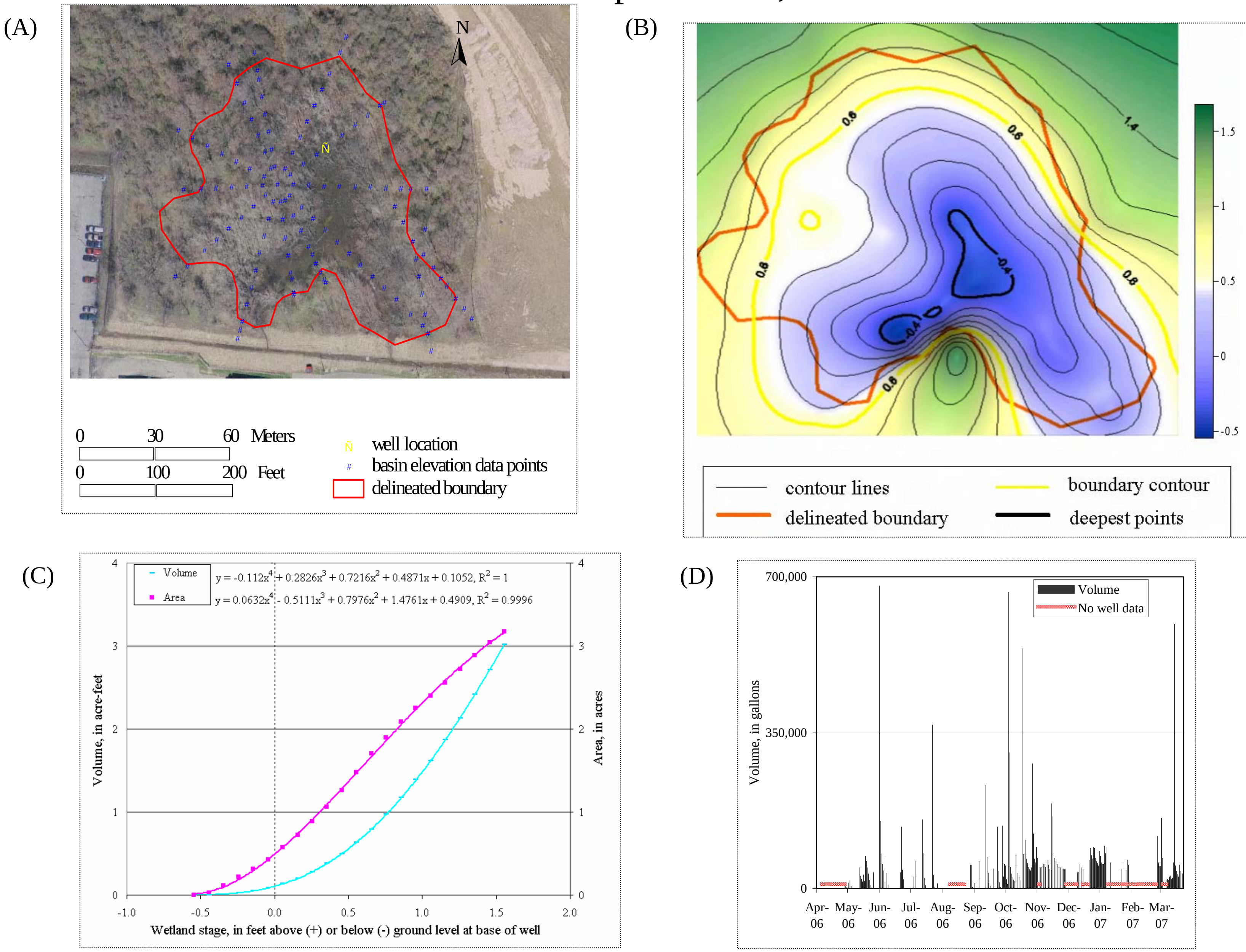

Figure 2 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Watkins Road, #142

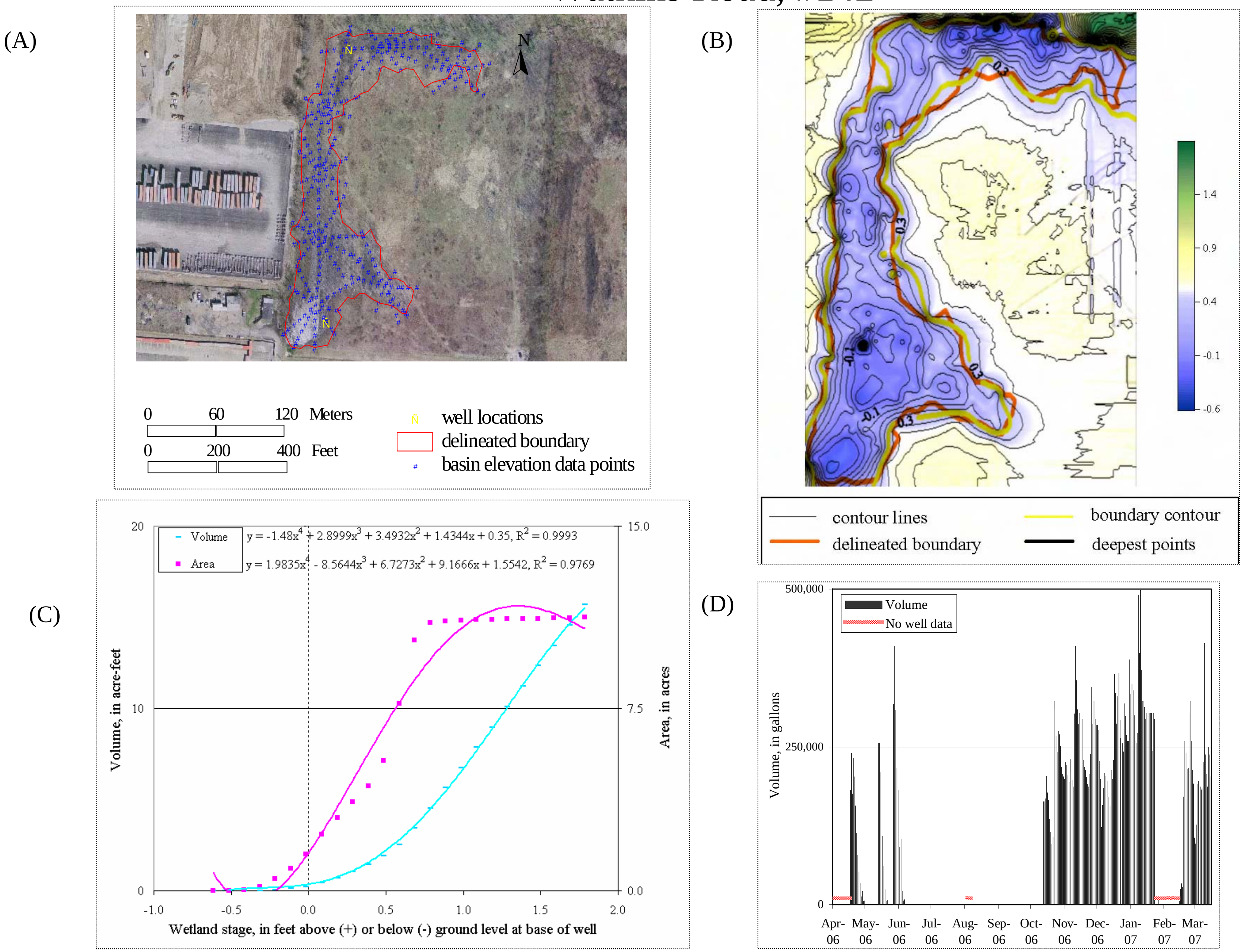

Figure 3 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft. contour interval referenced to ground level at base south well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time based on both wells' data.

ISG, #151

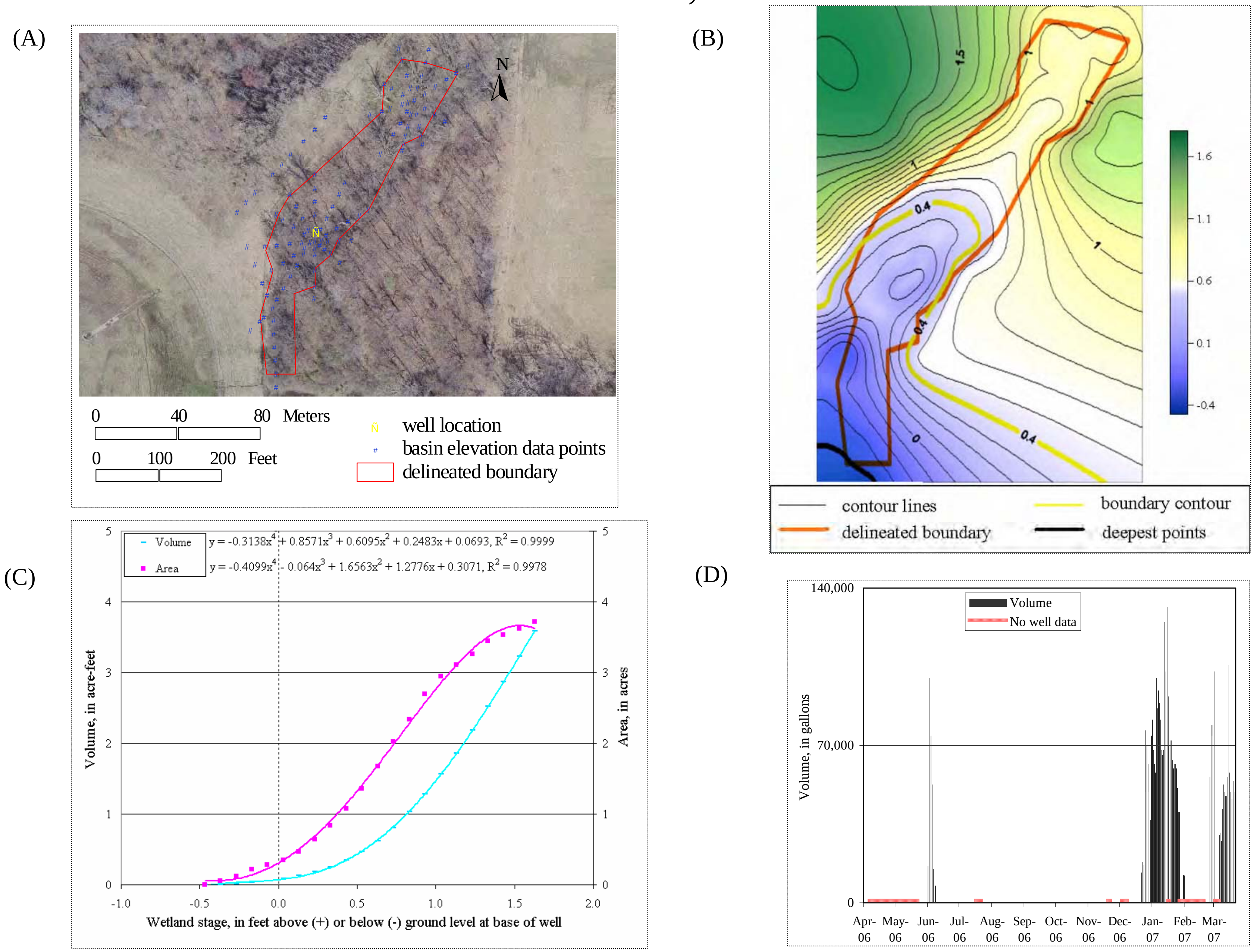

Figure 4 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Towne Center, #268

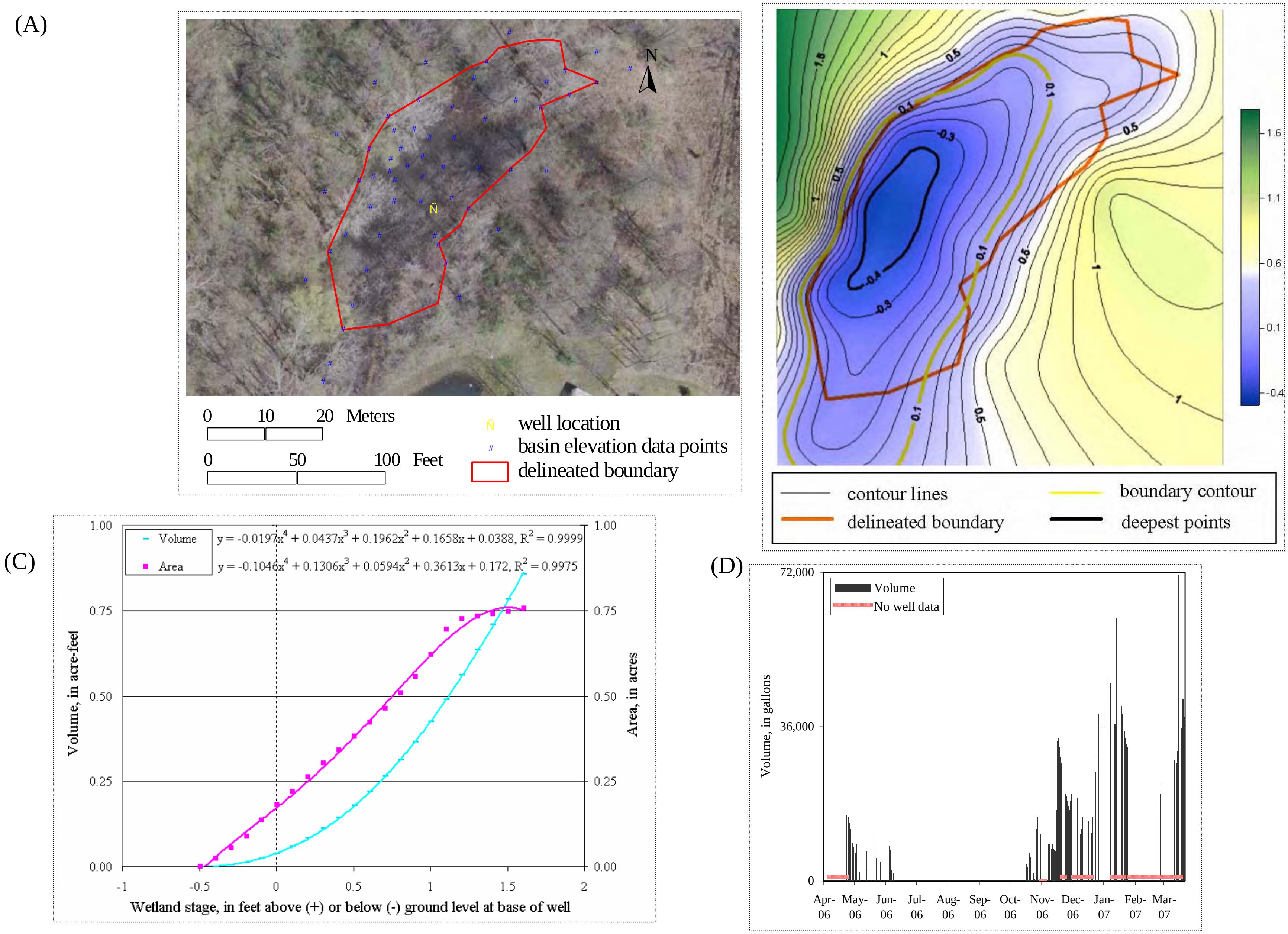

Figure 5 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Somerset Park, #274

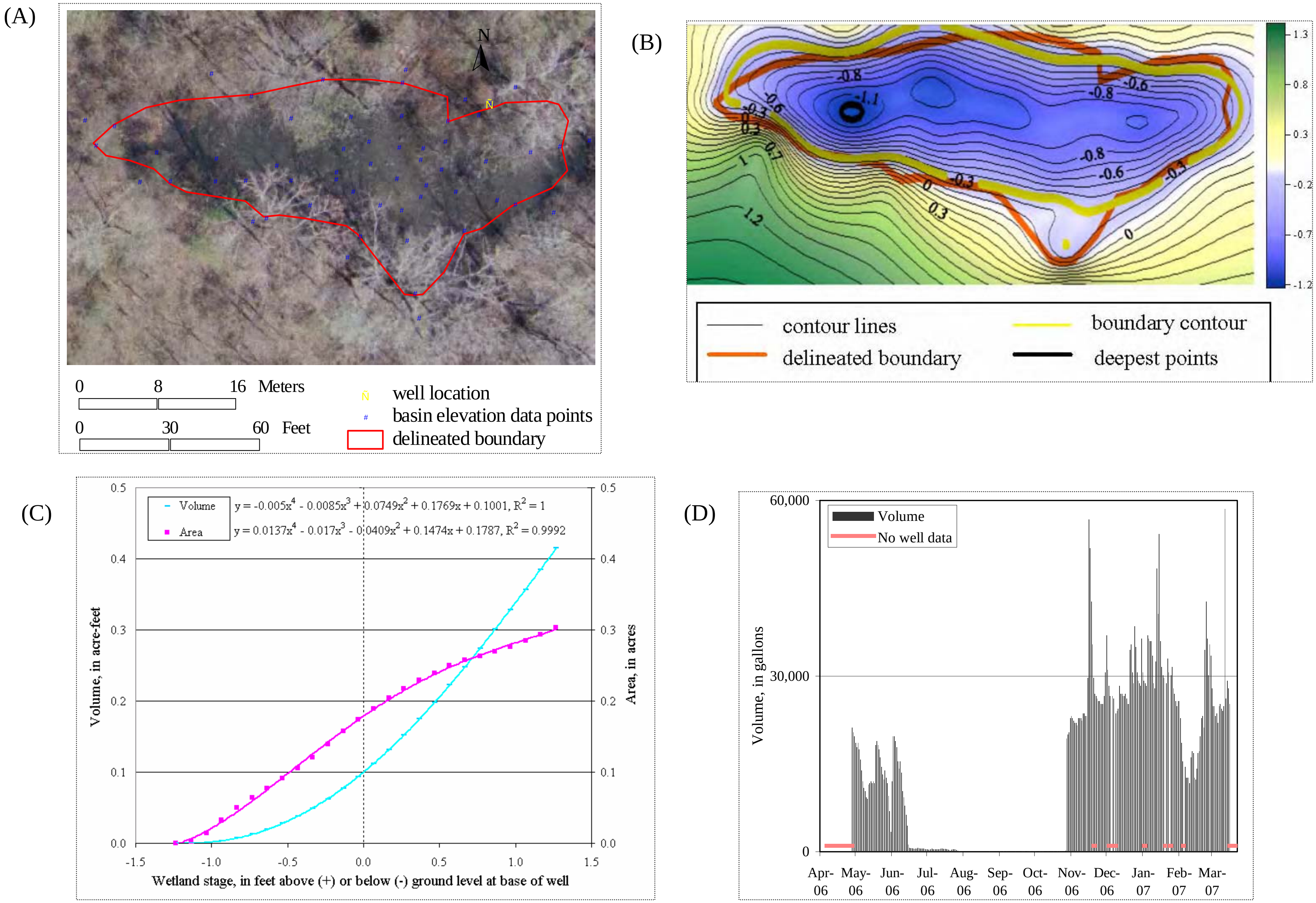

Figure 6 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Bridgeview (Golf Course), #281

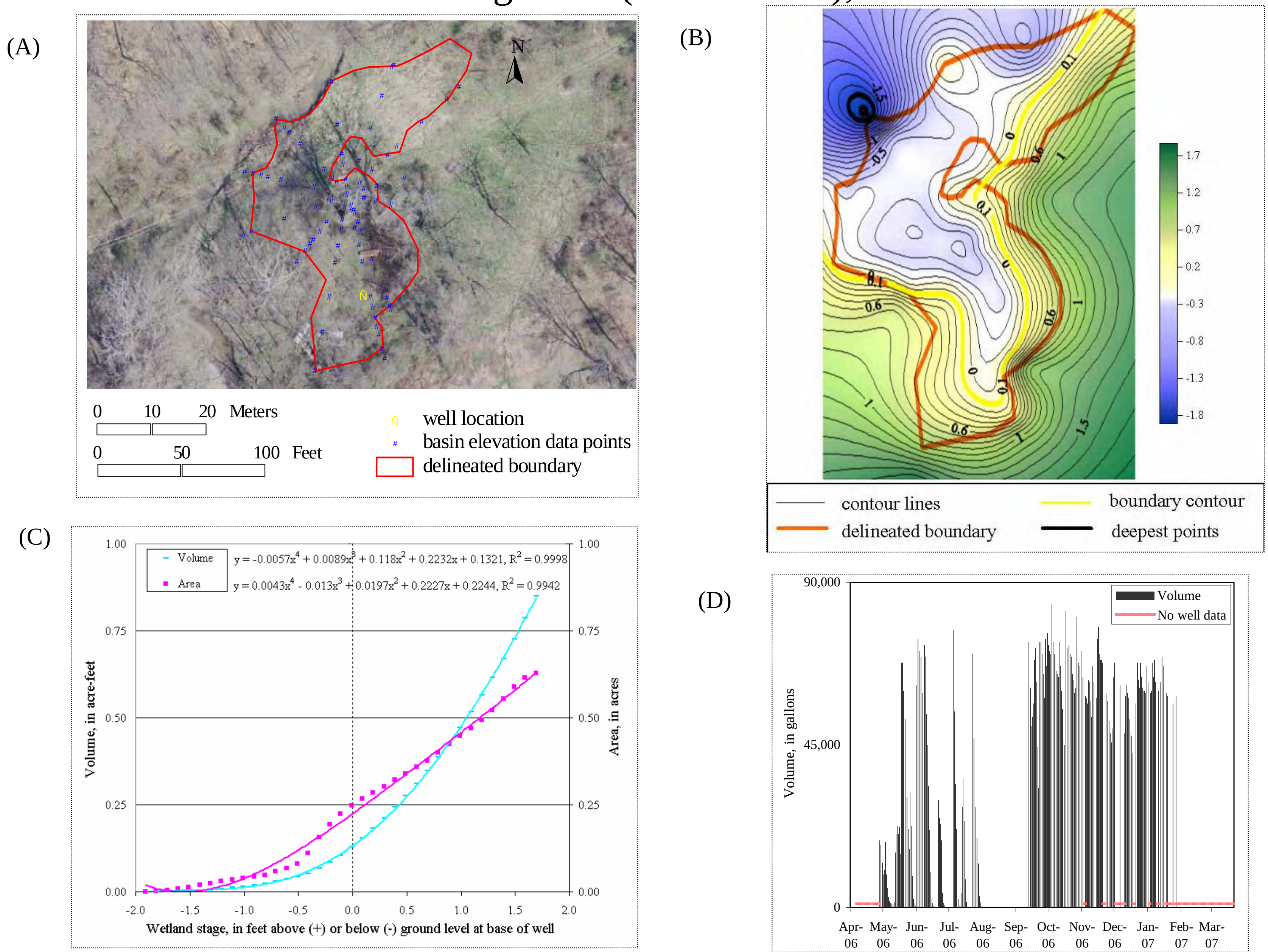

Figure 7 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Hills, #286

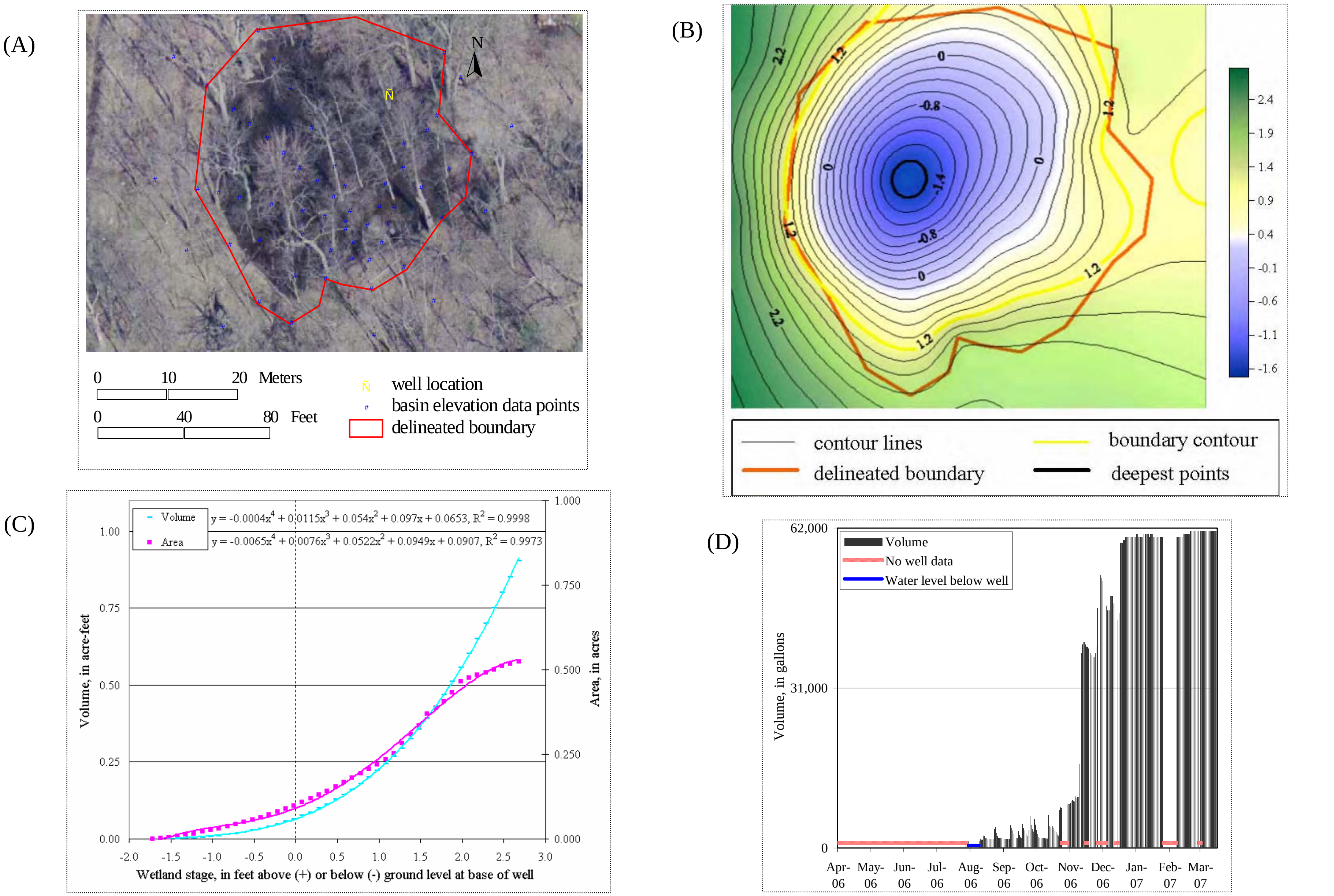

Figure 8 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Easton, #308

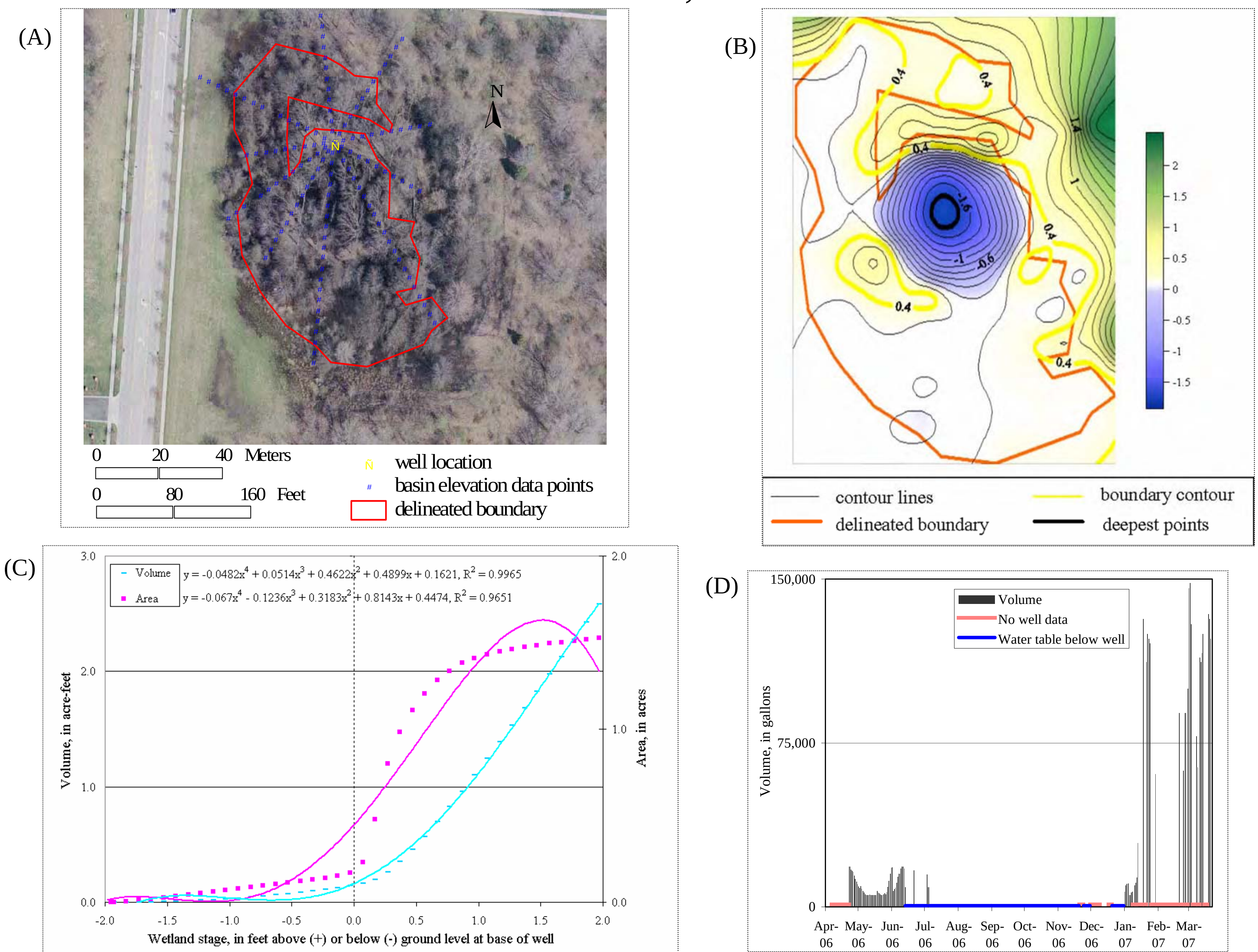

Figure 9 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft contour interval referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Wilson Rd, #409

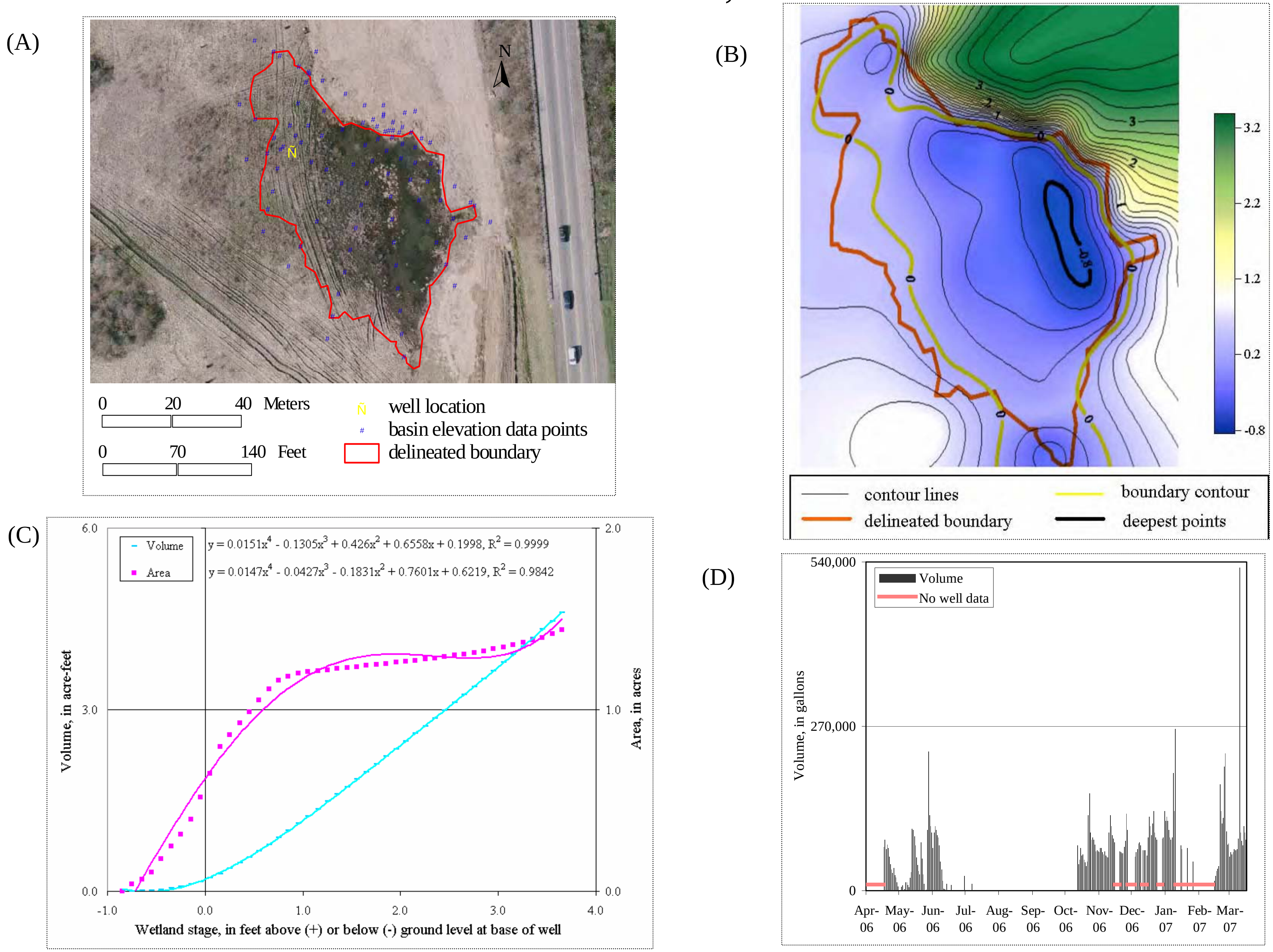

Figure 10 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Bolton Field, #492

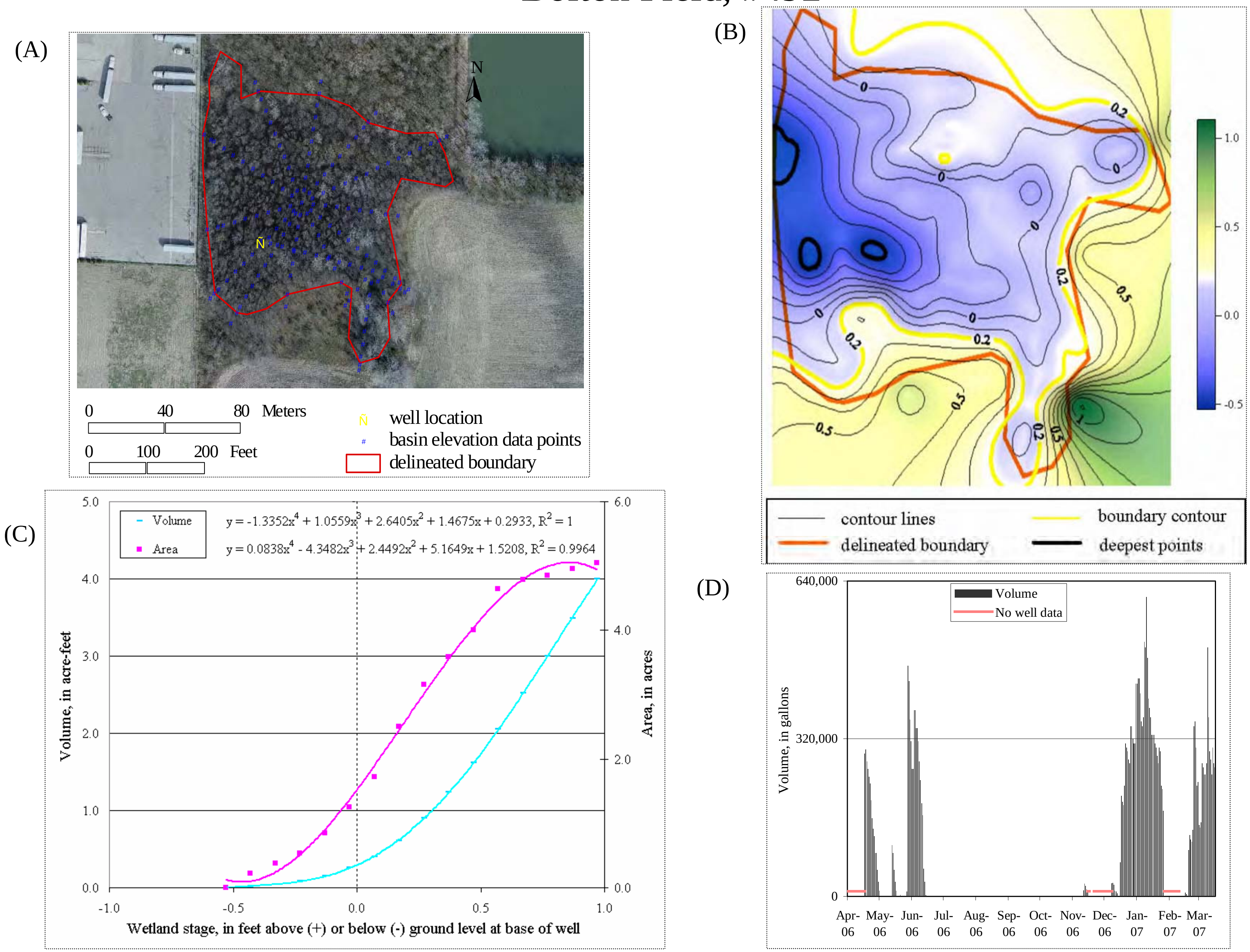

Figure 11 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.1 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Ridenour Rd., #19

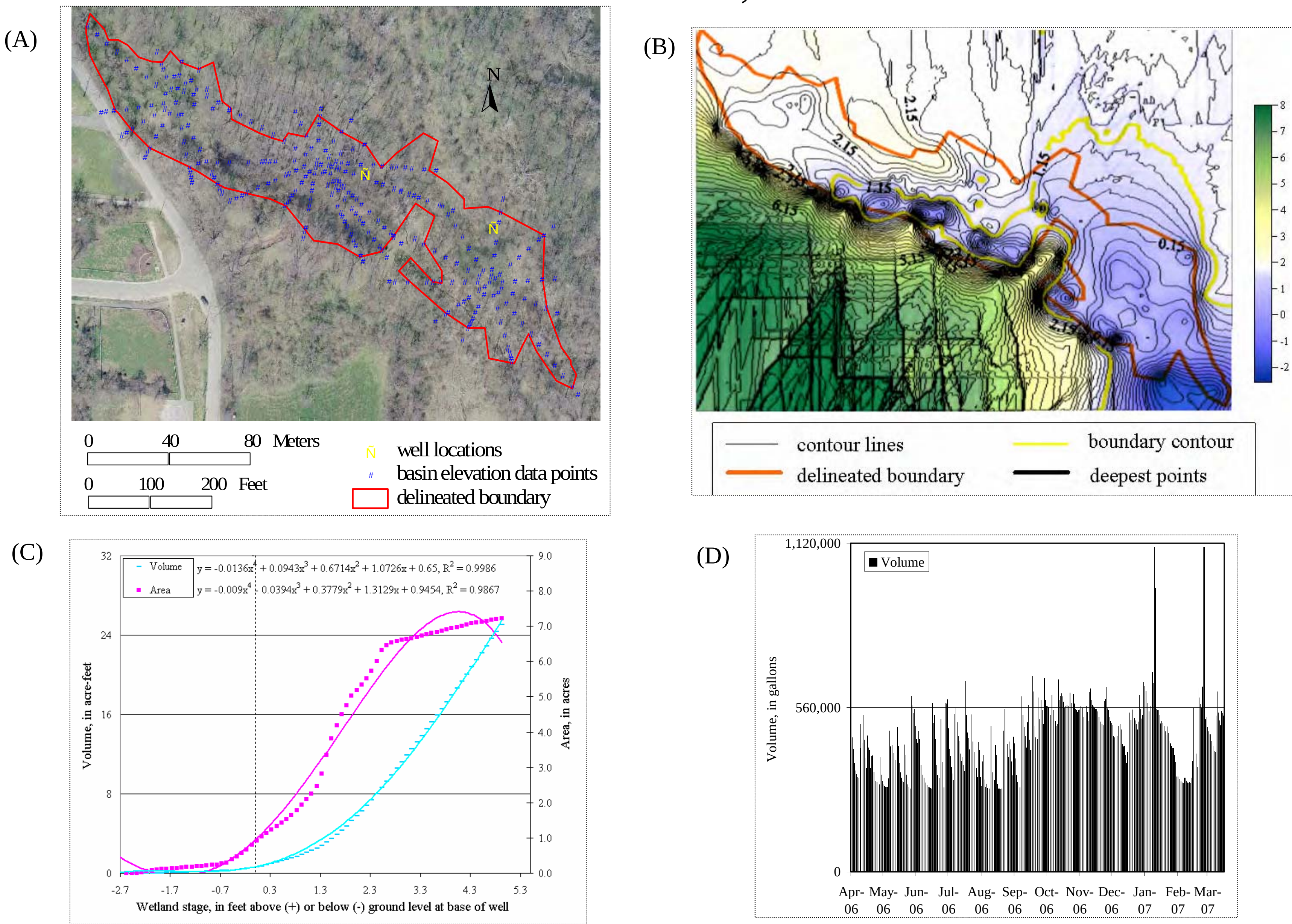

Figure 12 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of meadow well, (C) stage-volume and stage-area curves based on model output, and (D) volume of water stored in wetland over time based on combining meadow model (based on meadow well) and oxbow model (based on oxbow well).

Big Walnut Park, #76

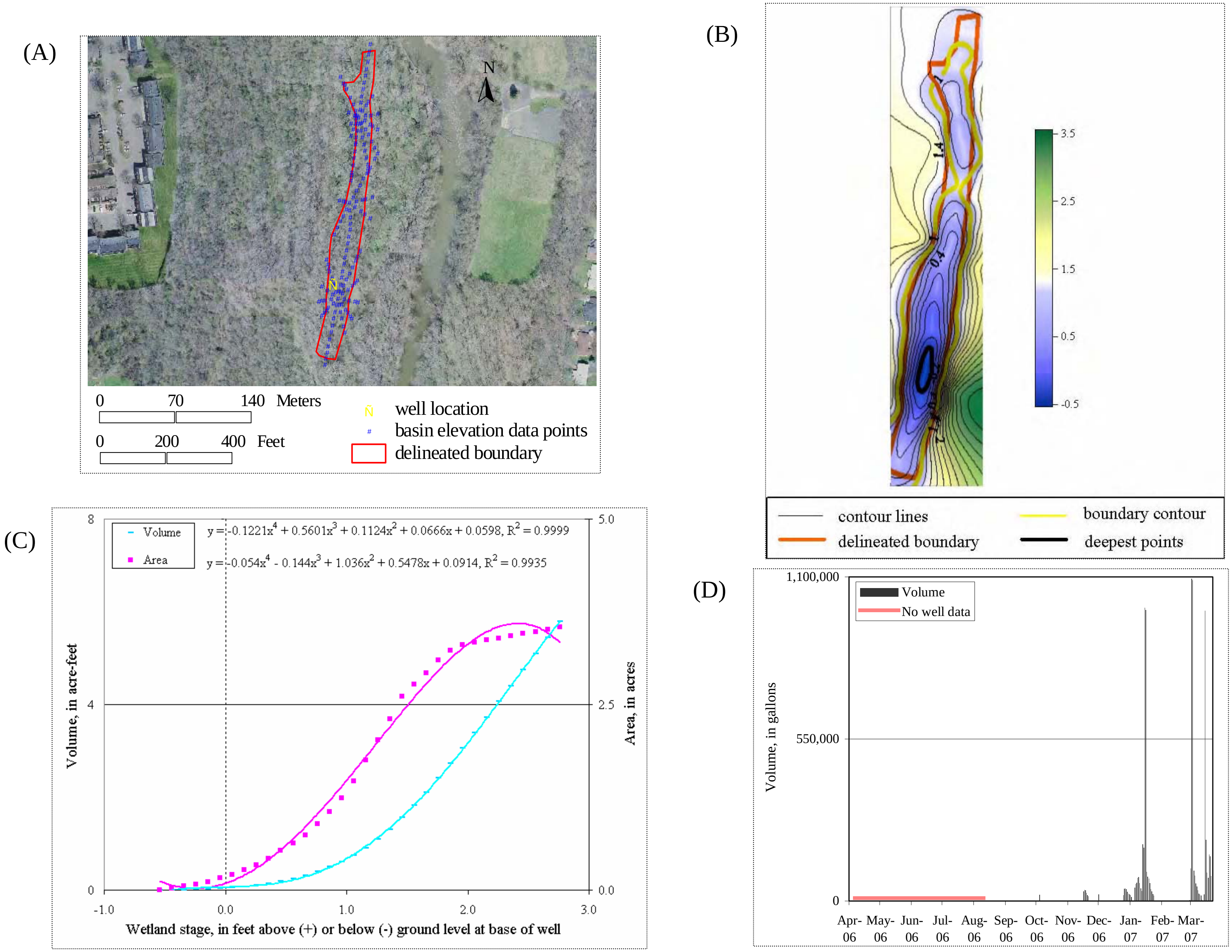

Figure 13 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

ATV, #82

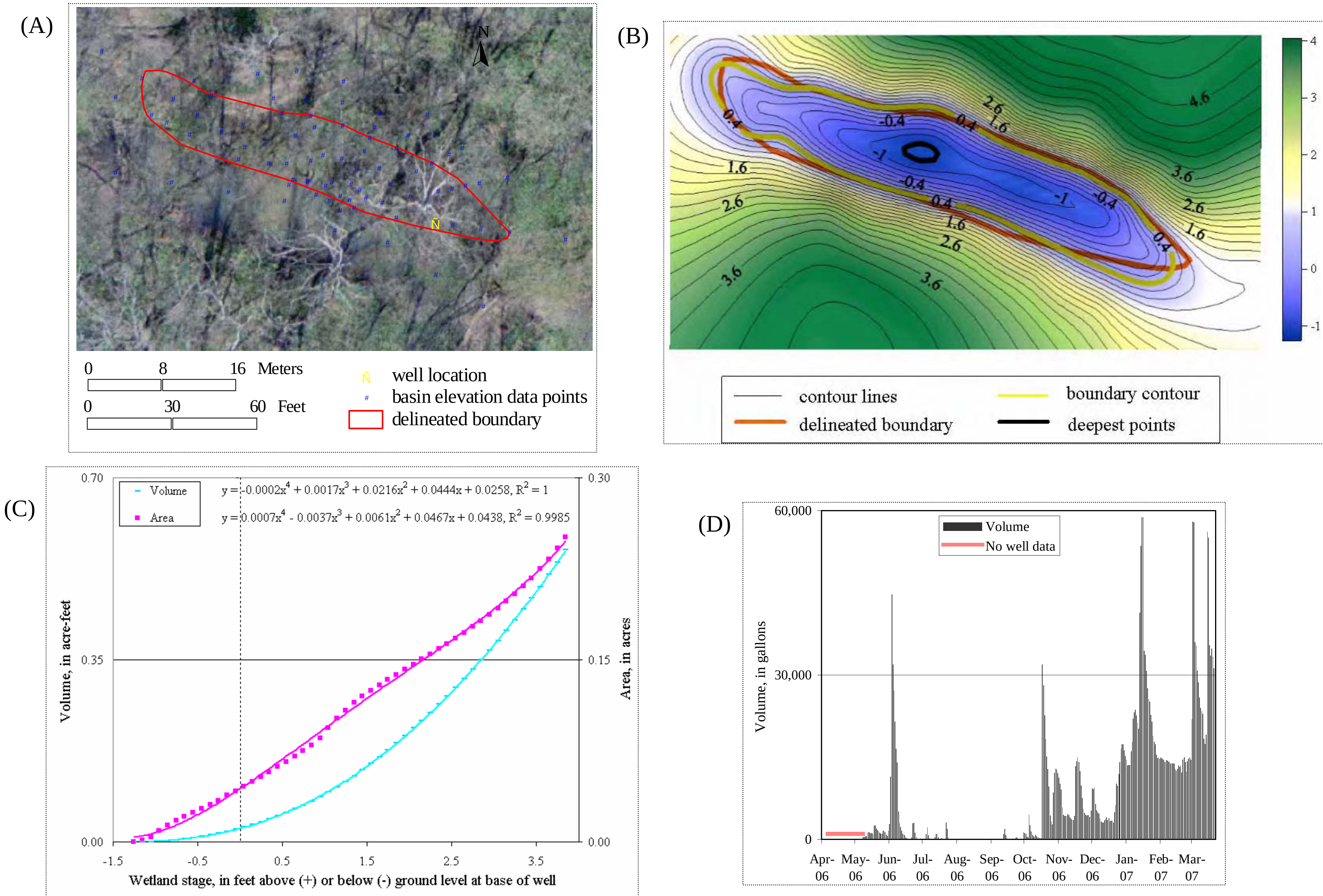

Figure 14 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves based on model output, and (D) volume of water stored in wetland over time.

Three Creeks, #201

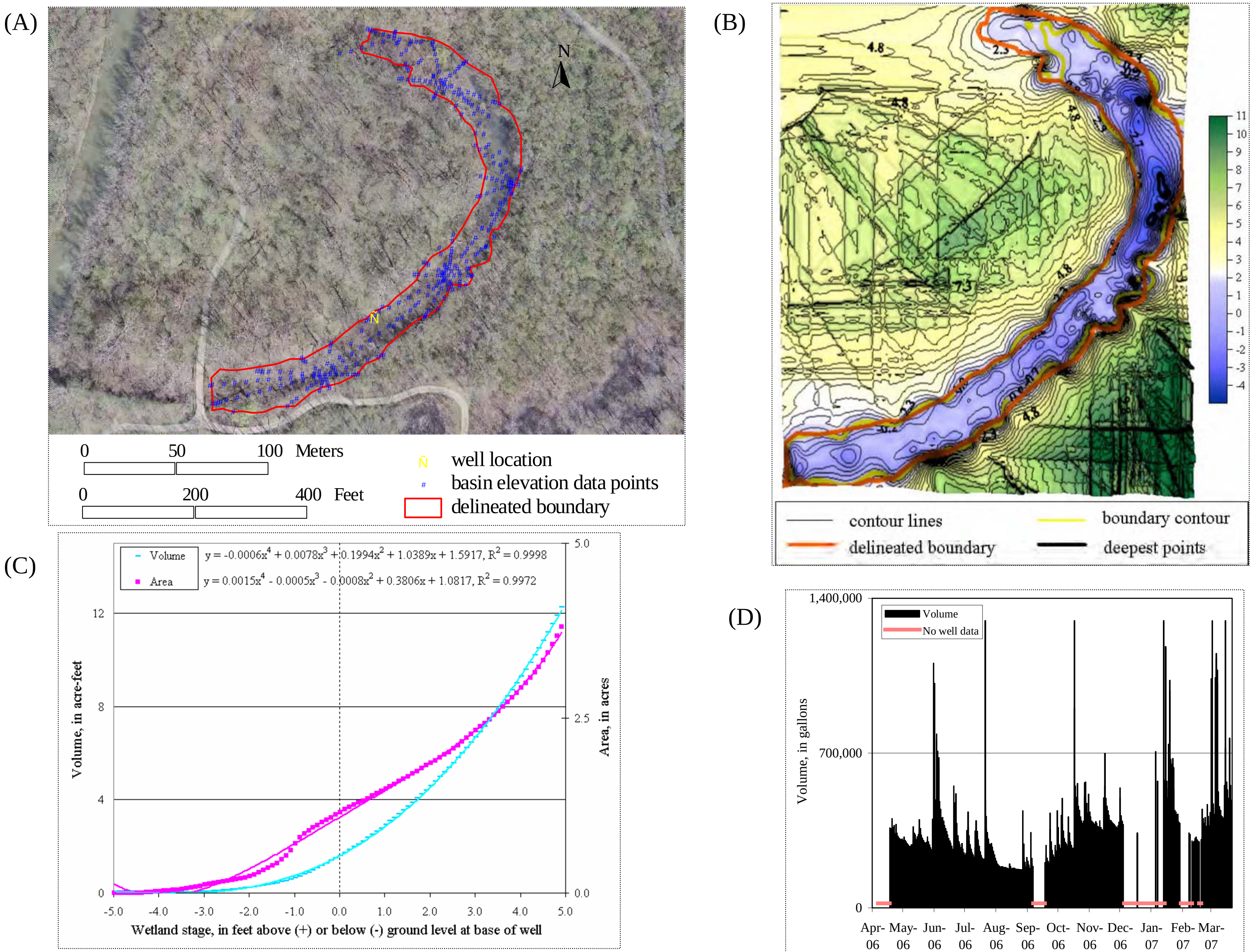

Figure 15 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.5 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Alum Creek, #204

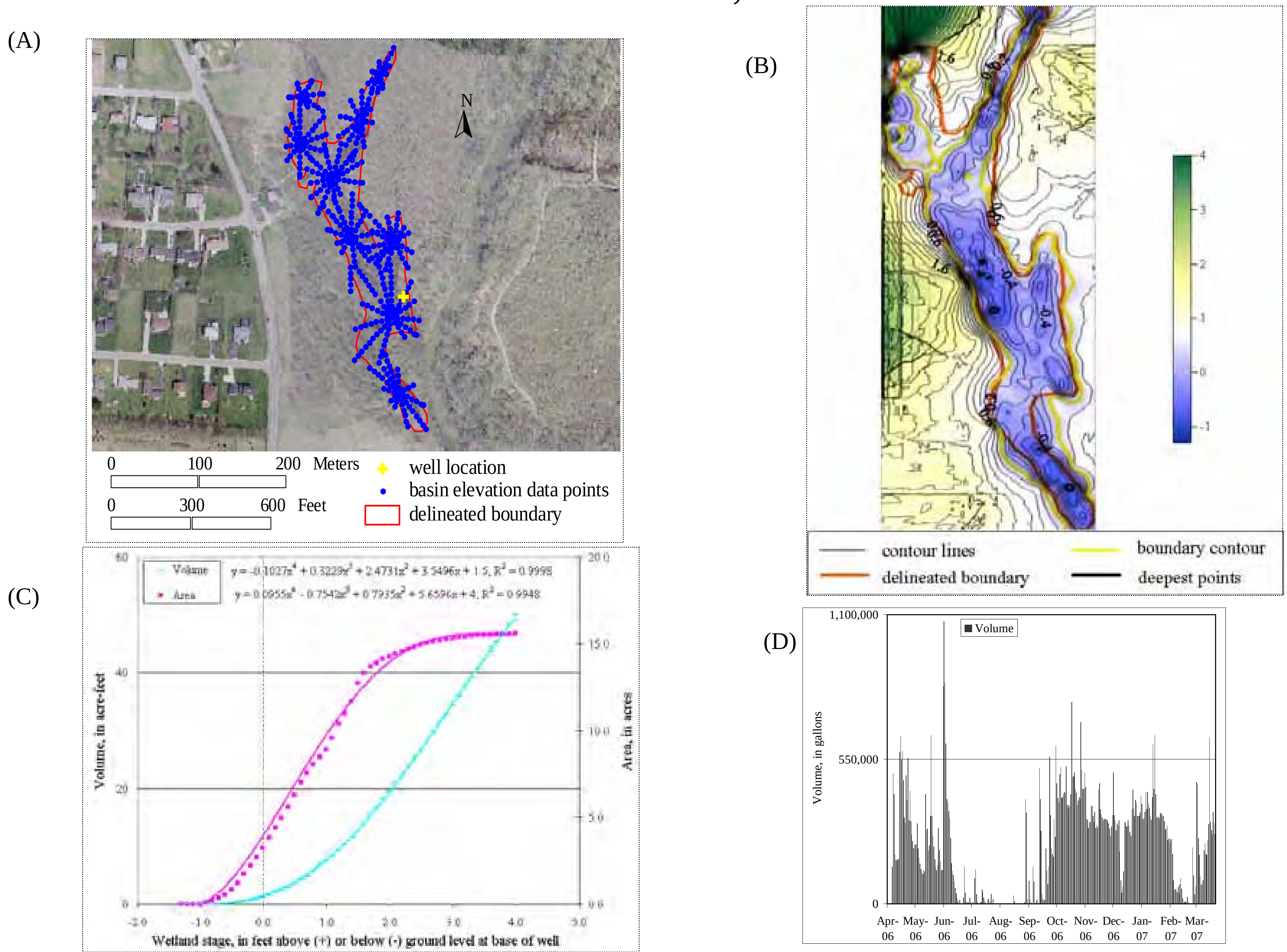

Figure 16 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Sunbury Rd, #242

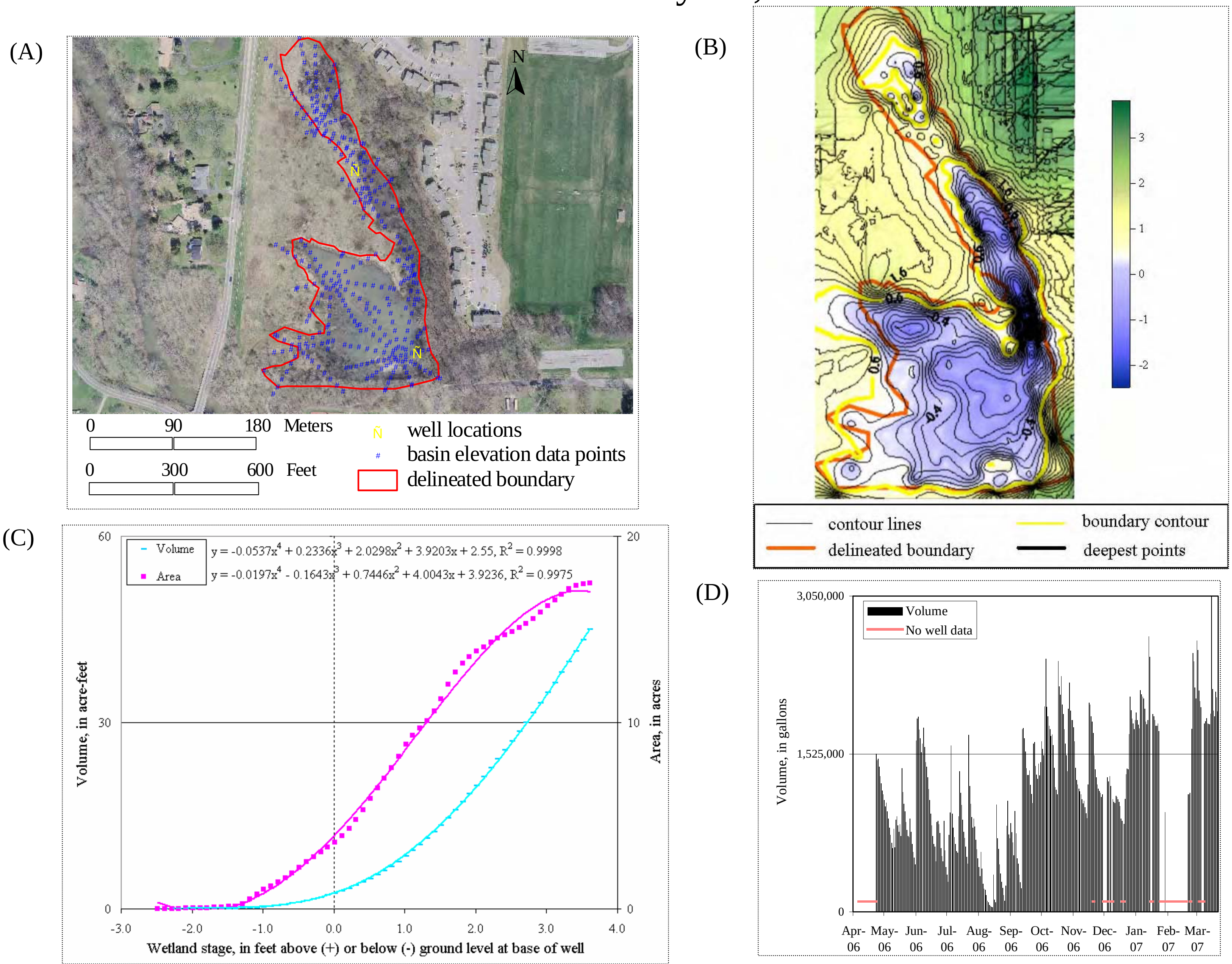

Figure 17(A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of south well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time based on combining north and south models' volumes based on both wells' data.

Worthington HS, #351

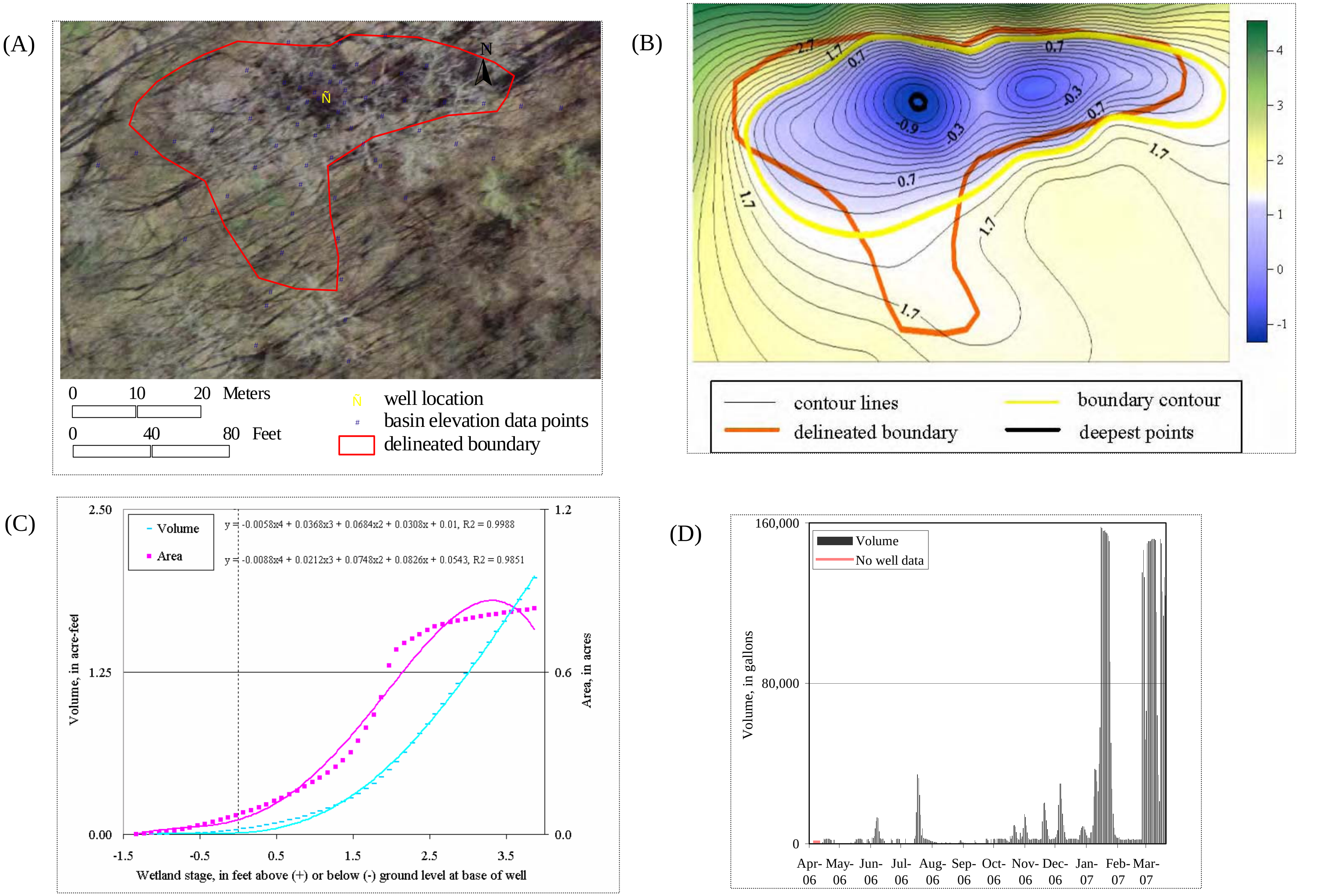

Figure 18(A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Worthington Park, #352

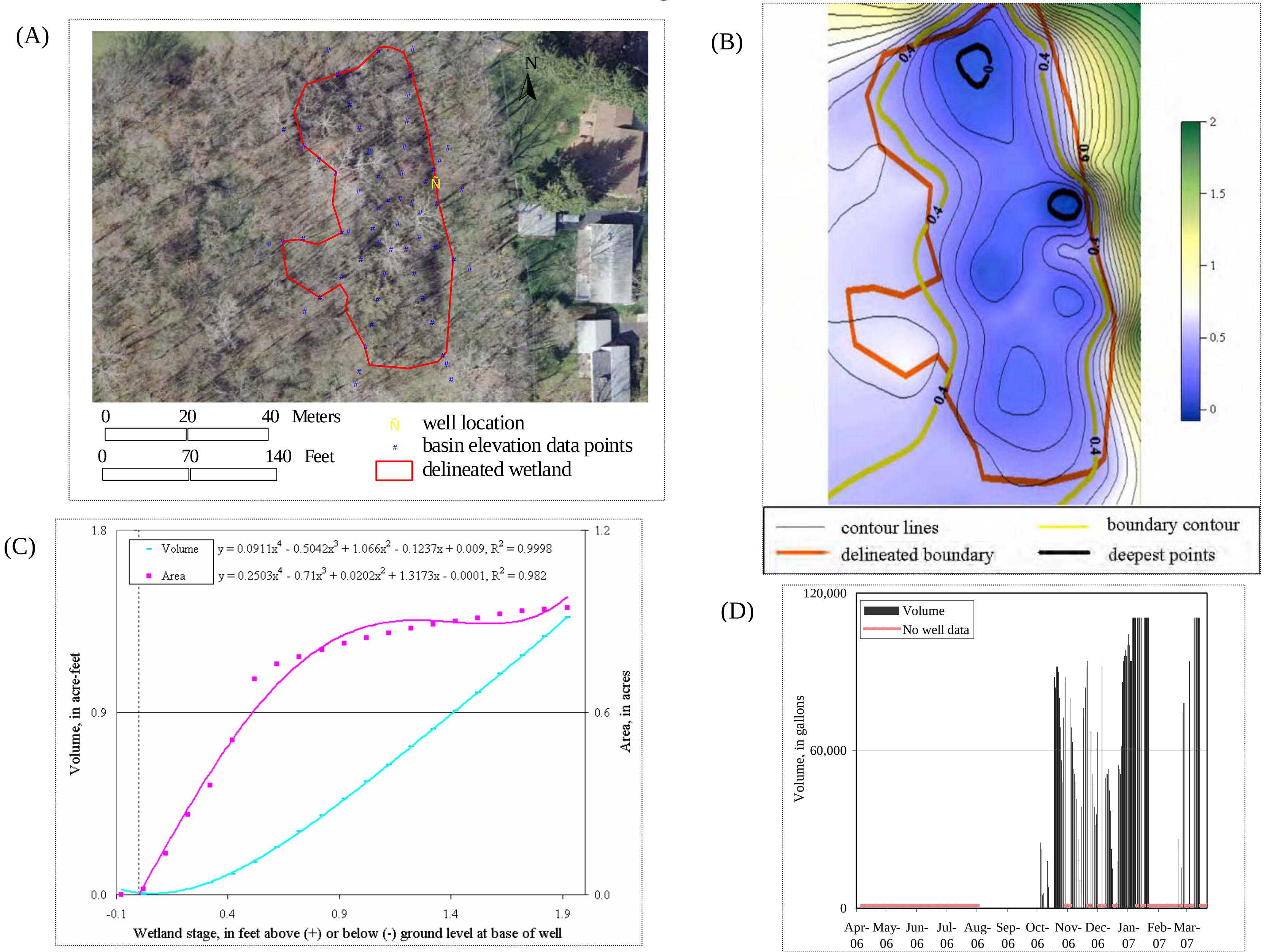

Figure 19(A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft. contour interval referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Antrim Park, #354

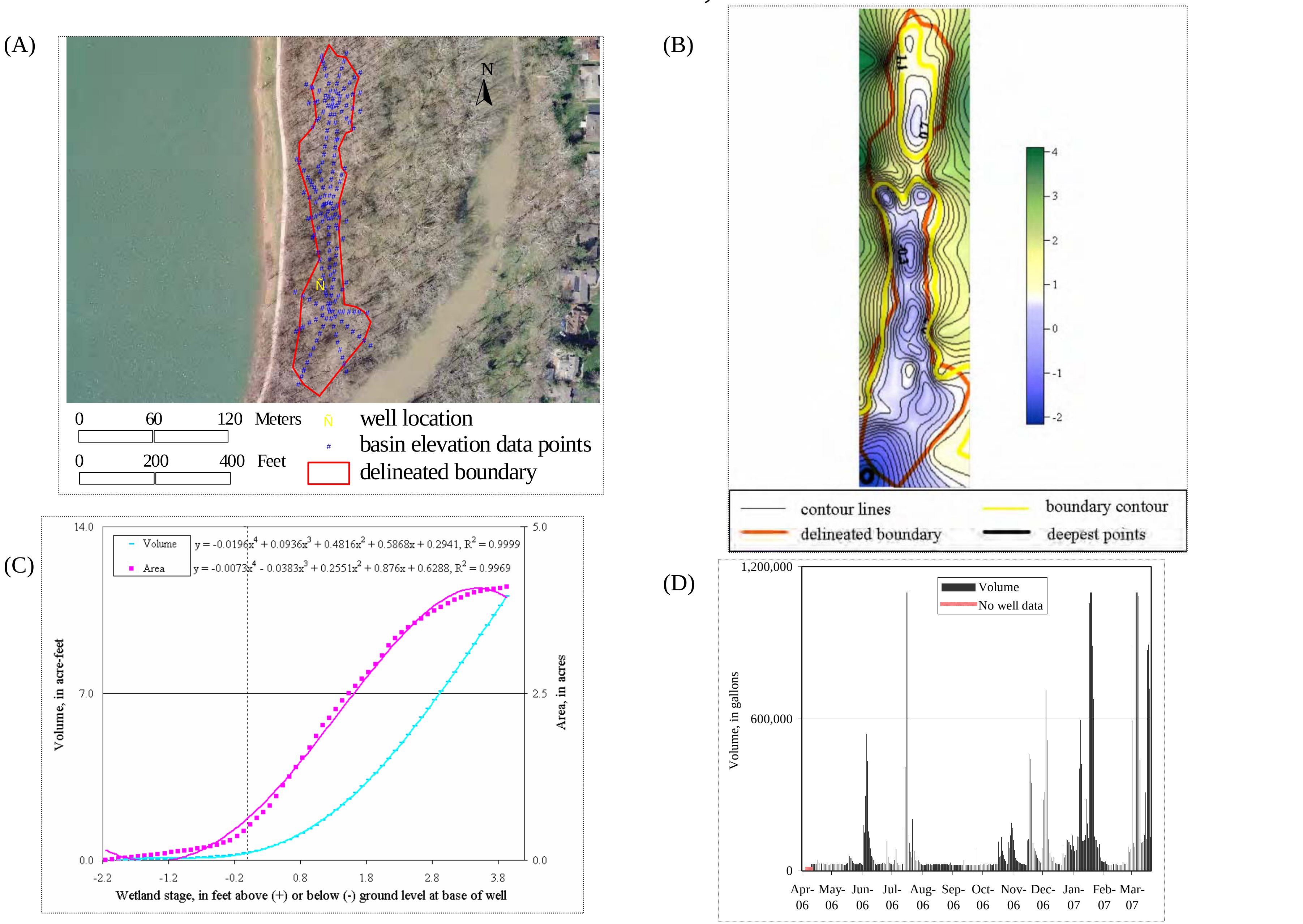

Figure 20 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) Wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Graceland, #358

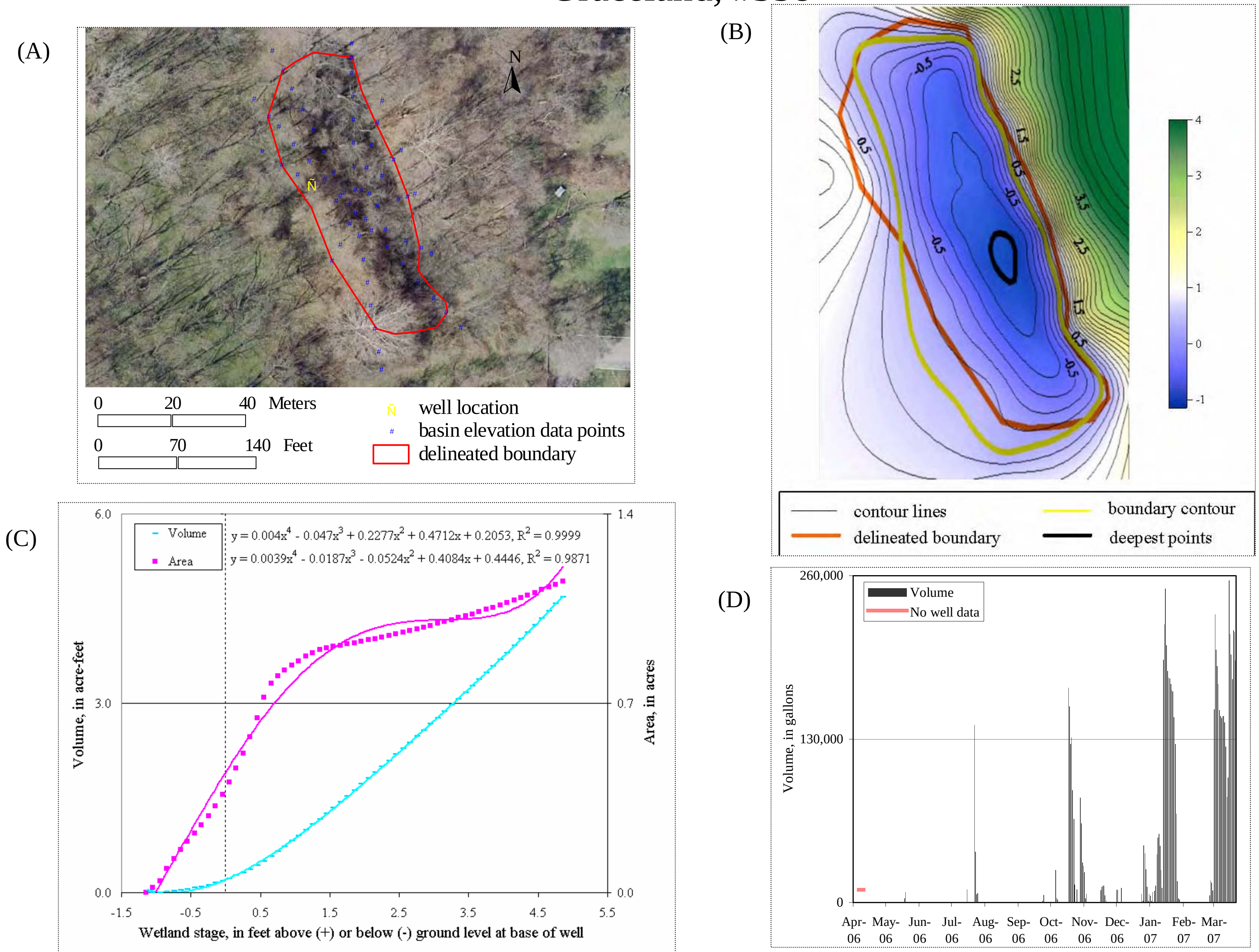

Figure 21 (A) aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Cherry Bottom, #529

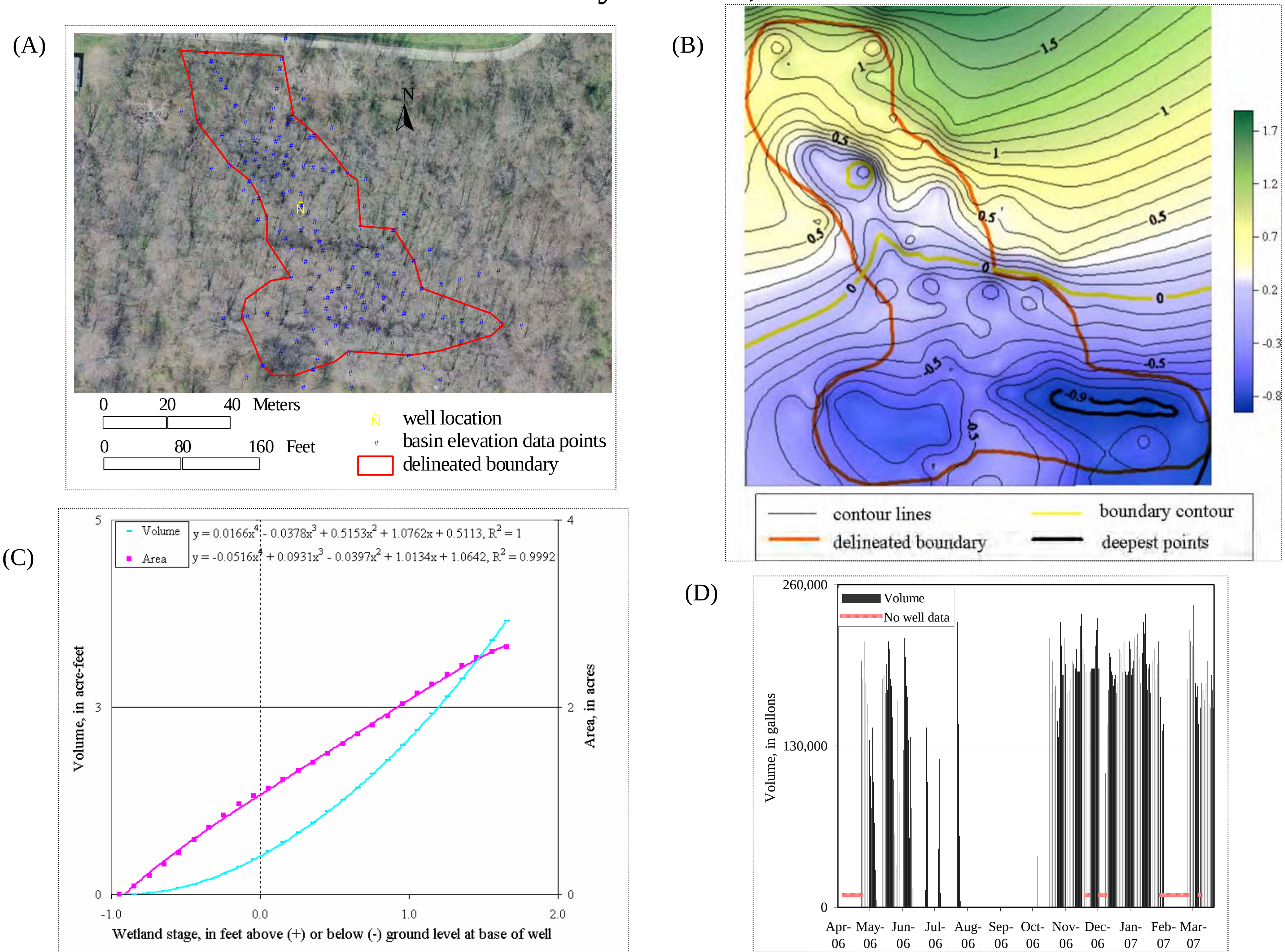

Figure 22 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model with 0.1 ft. contour intervals referenced to ground level at base of well, (C) stage-volume and stage-area curves from model output, and (D) volume of water stored in wetland over time.

Quarry, #464

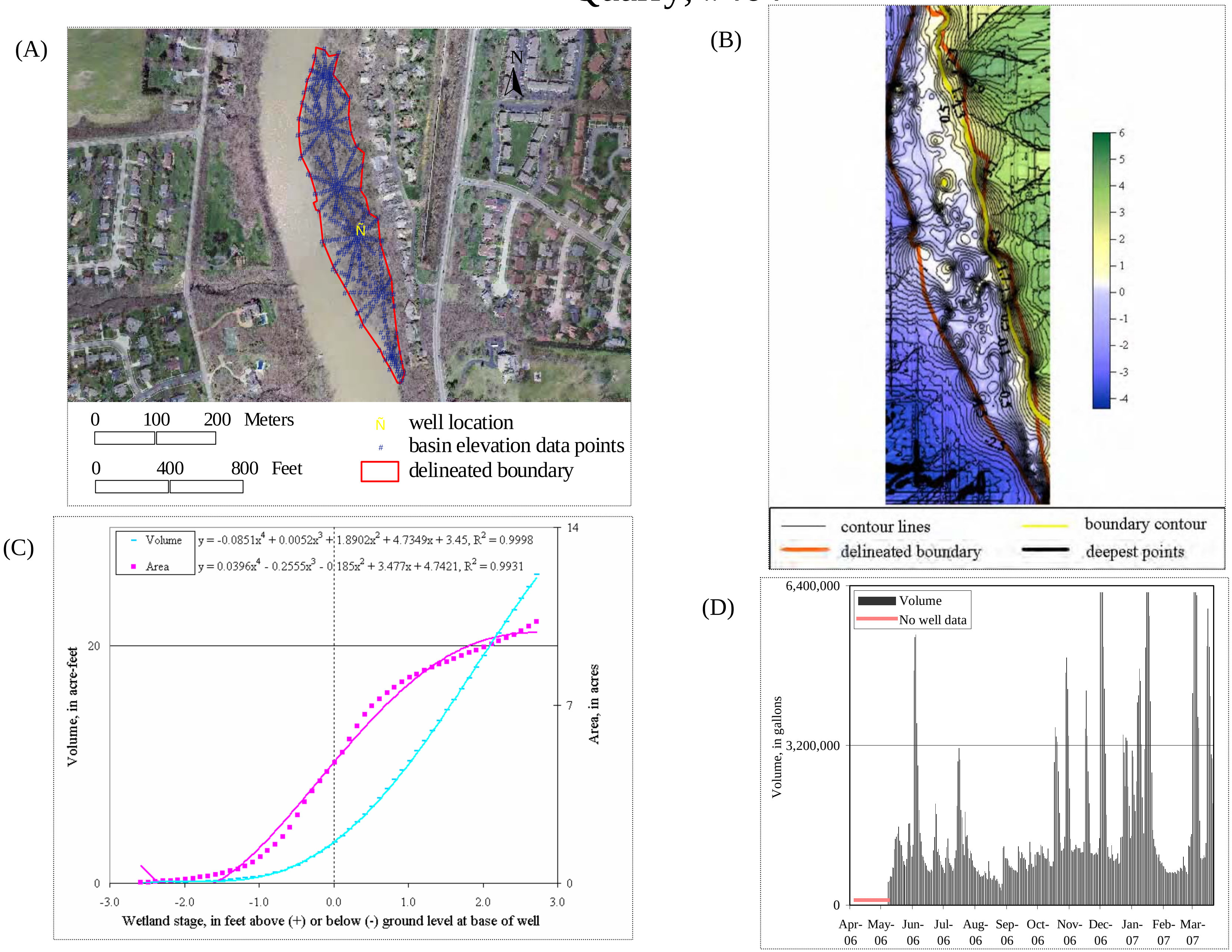

Figure 23 (A) Aerial photo showing density of data points, well location and delineated wetland boundary, (B) wetland morphometric contour model (reservoir side trimmed) with 0.2 ft. contour intervals referenced to ground level at base of well, (C) stage-volume & stage-area curves from model output, and (D) volume of water stored in wetland over time.

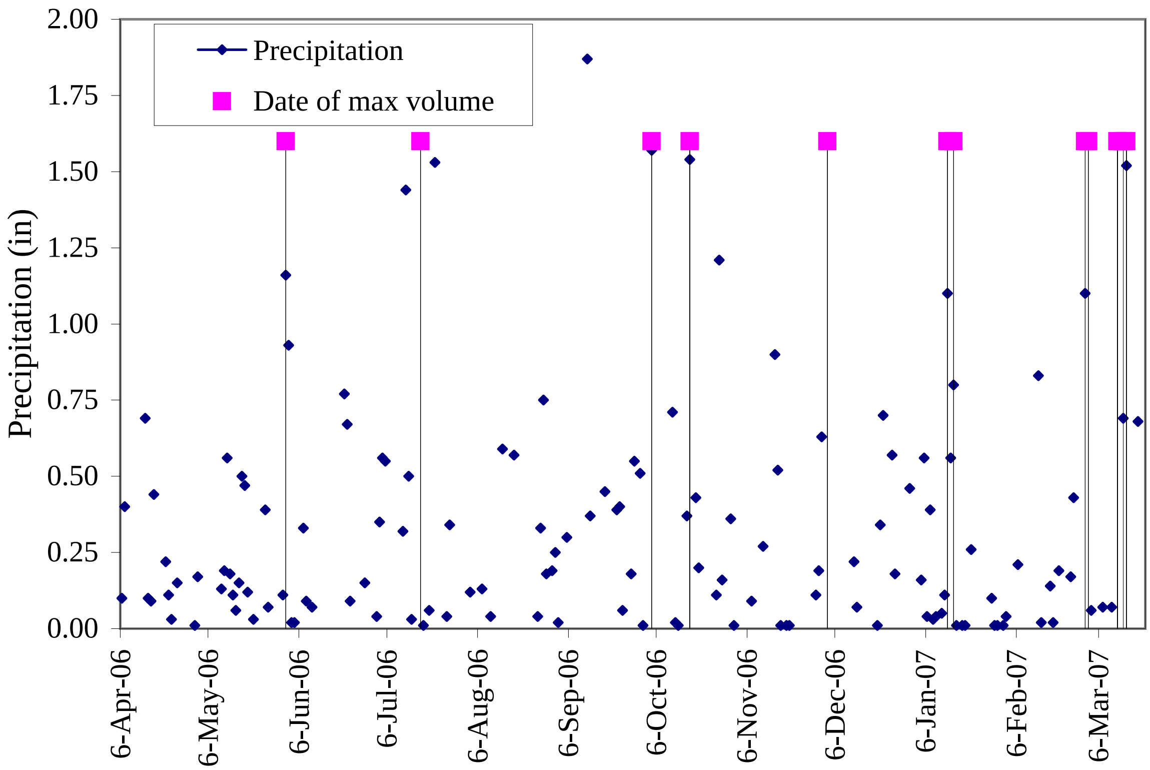

Figure 24 Precipitation data from Columbus International Airport weather station over study period with blocks with drop lines indicating dates maximum volume occurred in wetlands.

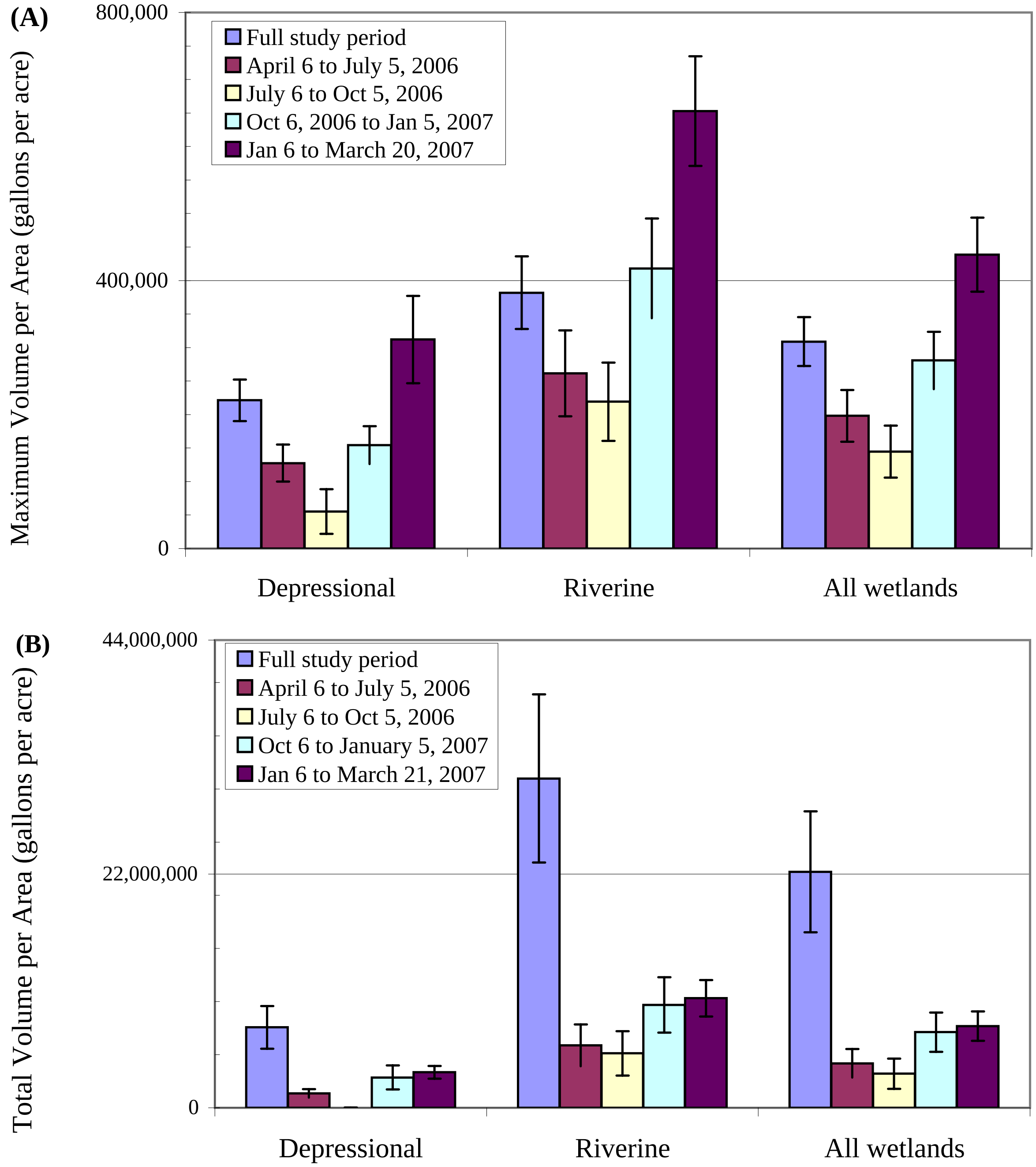

Figure 25 A) Maximum volume per acre and B) total volume of water per acre, ± s.e., for entire period (April 6 to March 21, 2007), Spring/Early Summer (April 6 to July 5), Summer/Early Fall (July 6 to October 5), Fall/Early Winter (October 6, 2006 to January 5, 2007), and Winter/Early Spring (January 6, 2007 to March 21, 2007) in depressional, riverine and all study wetlands. Total volume per area was calculated by summing daily volumes per area over period. Wetlands with wells operational less than 75% of study period were not included with the total volume calculation.

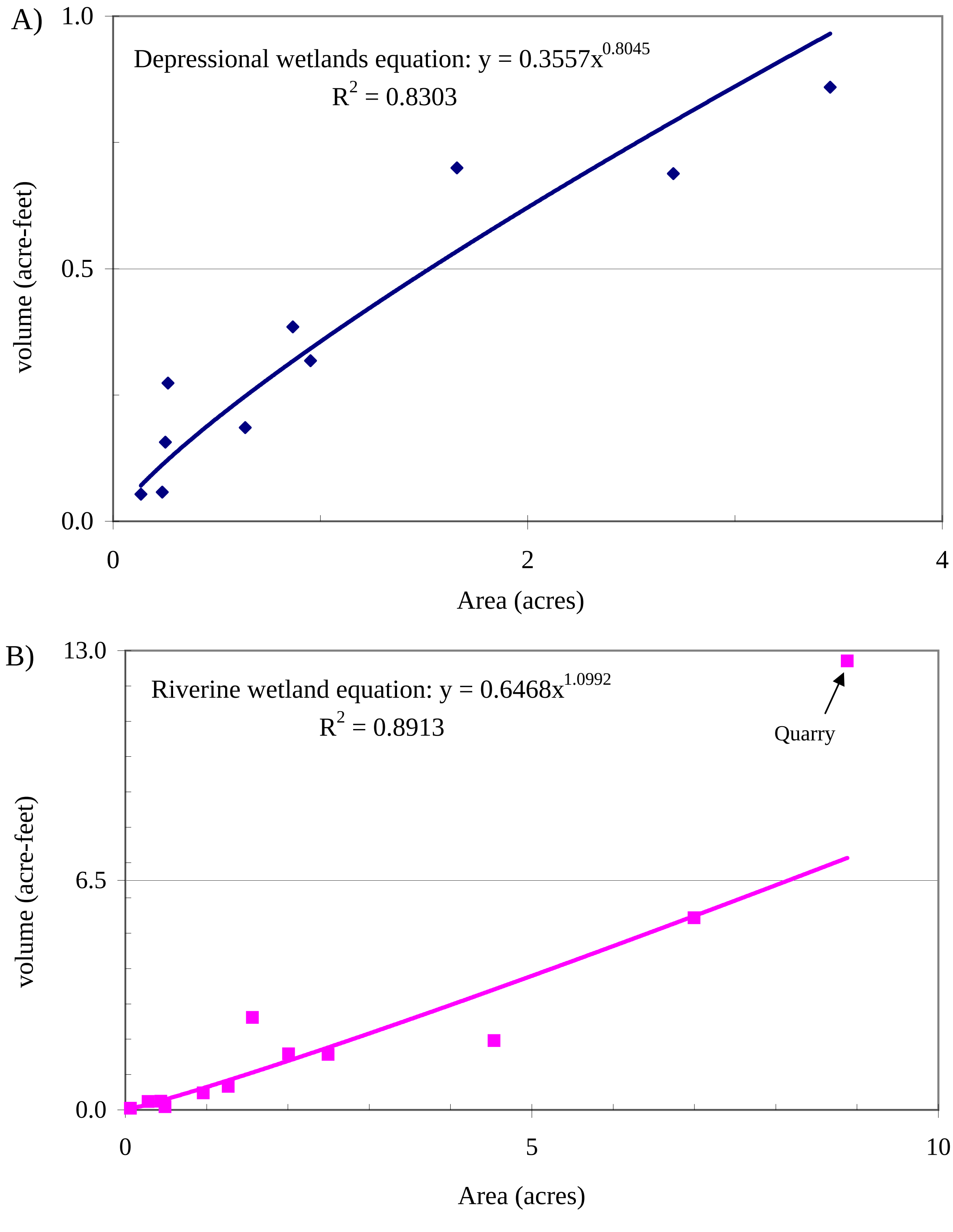

Figure 26 Area-volume relationship when water level at delineated boundary for A) depressional (Easton and Hills sites excluded) and B) riverine wetlands; power function trendline fitted to data.

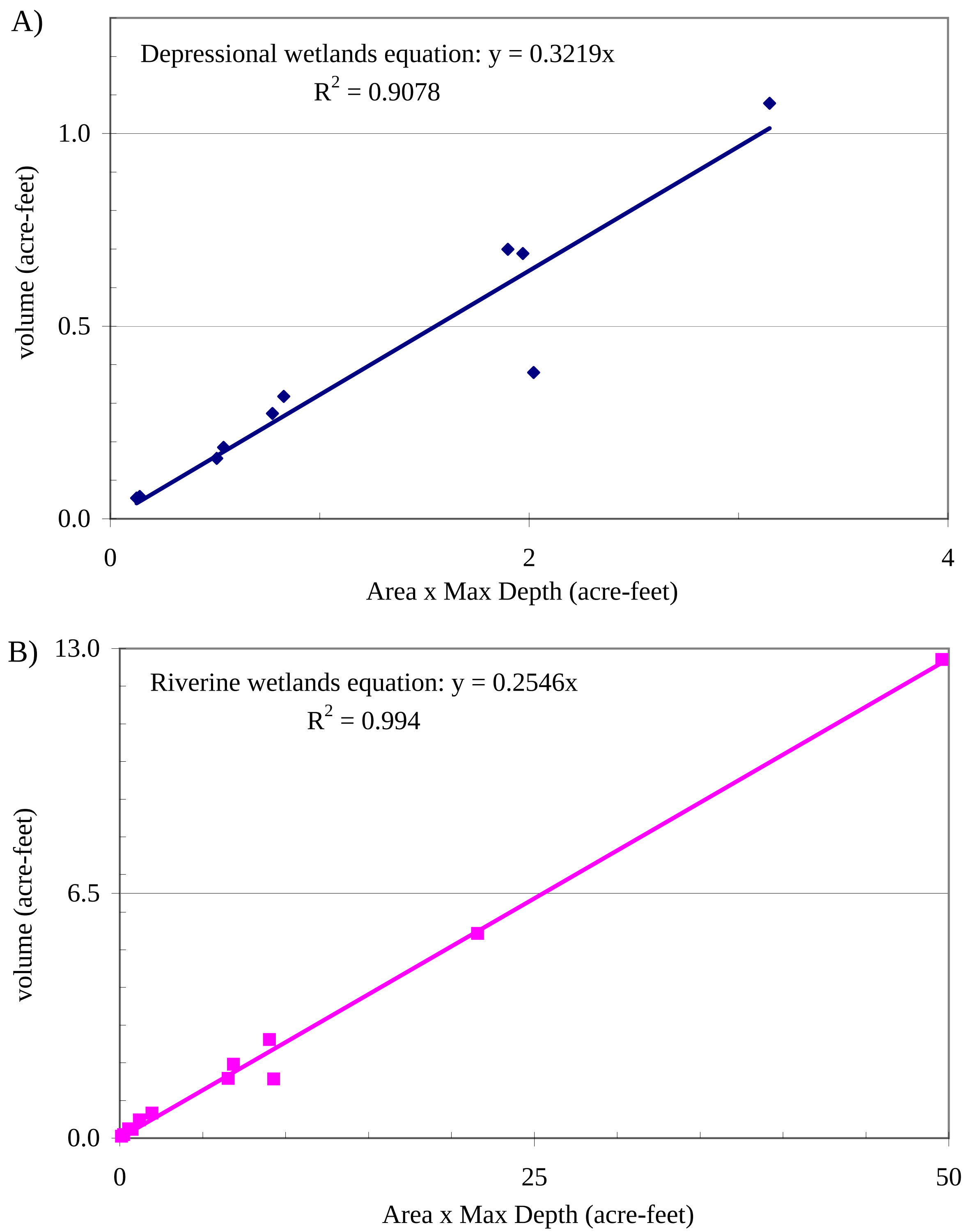

Figure 27 (Area x maximum depth)-to-volume relationship when water level at delineated boundary contour for A) depressional, and B) riverine wetlands; linear trendline fitted to data.

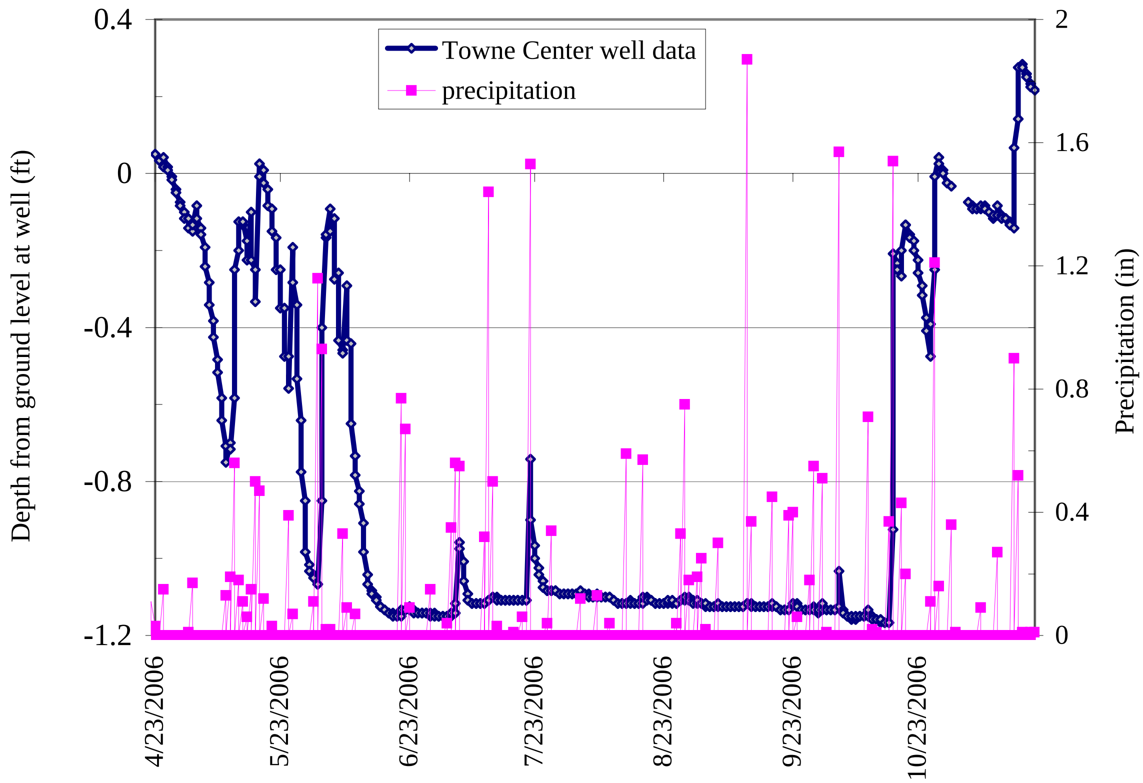

Figure 28 Well data from Towne Center site showing low water levels during the summer, while receiving repeated rain events.

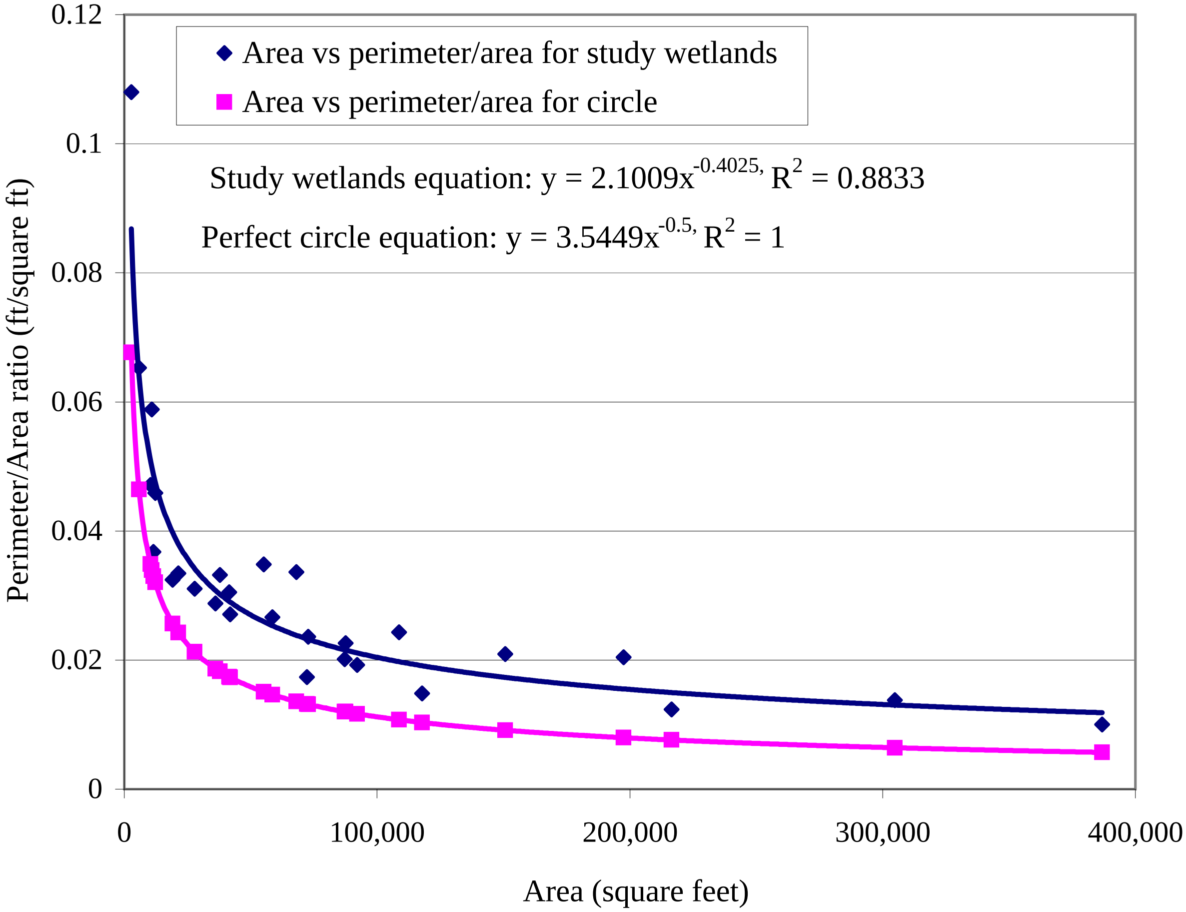

Figure 29 Comparison of area vs perimeter to area ratio for a perfect circle and for study wetlands; power equation used to fit trendline to data.

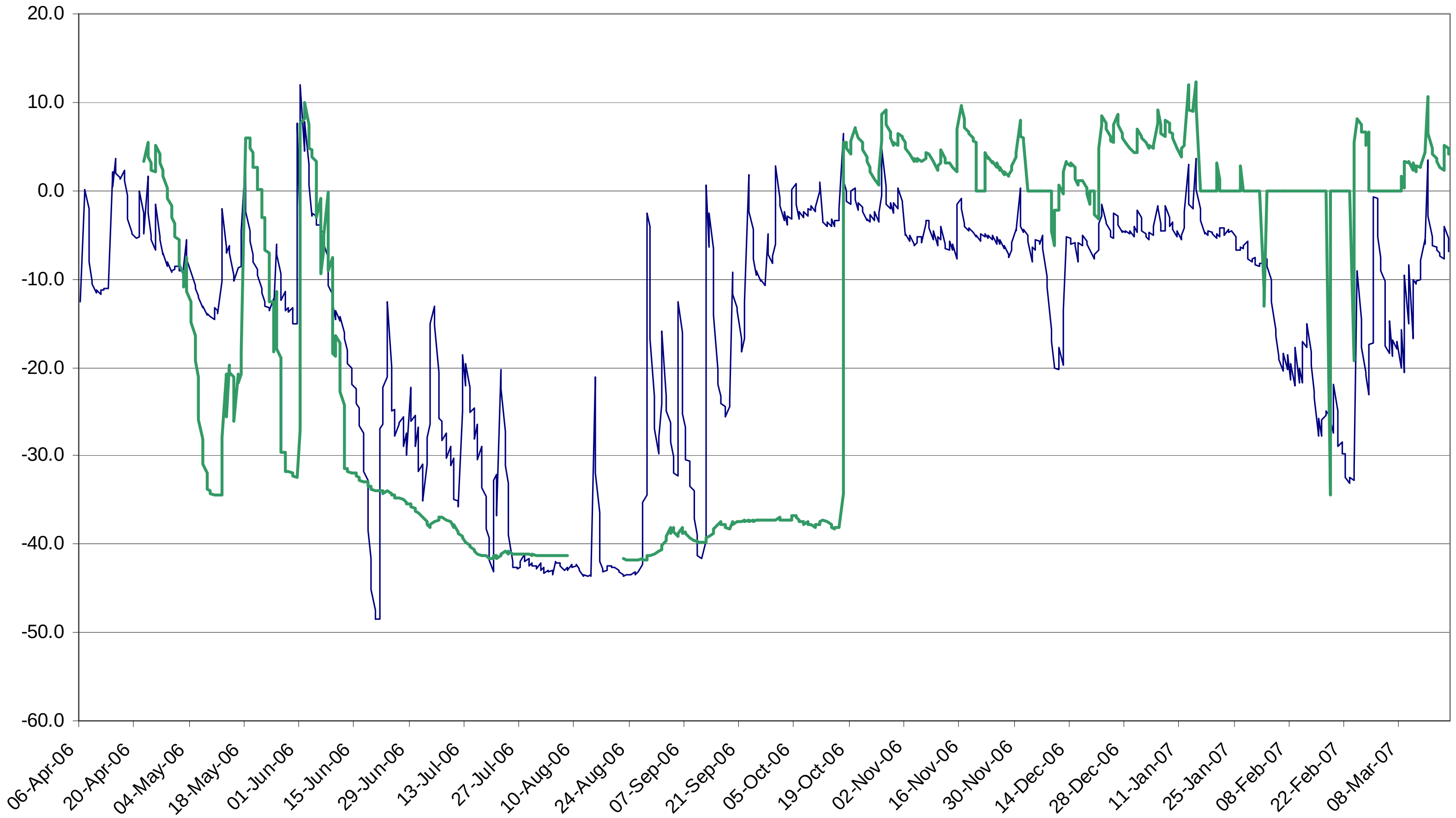

Figure 30. Comparison of annual hydrographs of Wilson Rd (Depression) and Alum Creek Dr (Riverine).

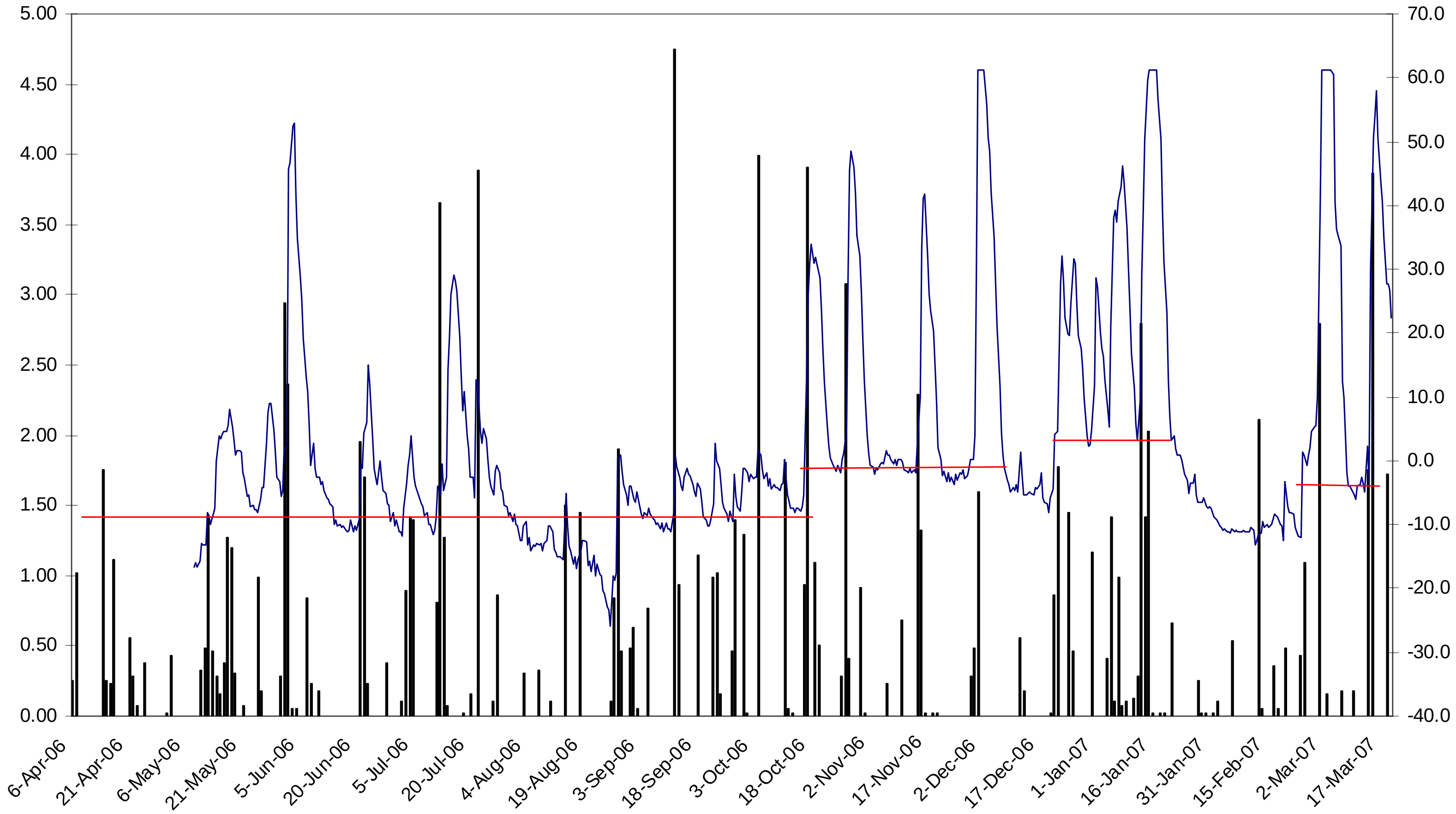

Figure 31. Annual hydrograph of Antrim Park site. Red lines represent approximate baseline inundation during that period of time.

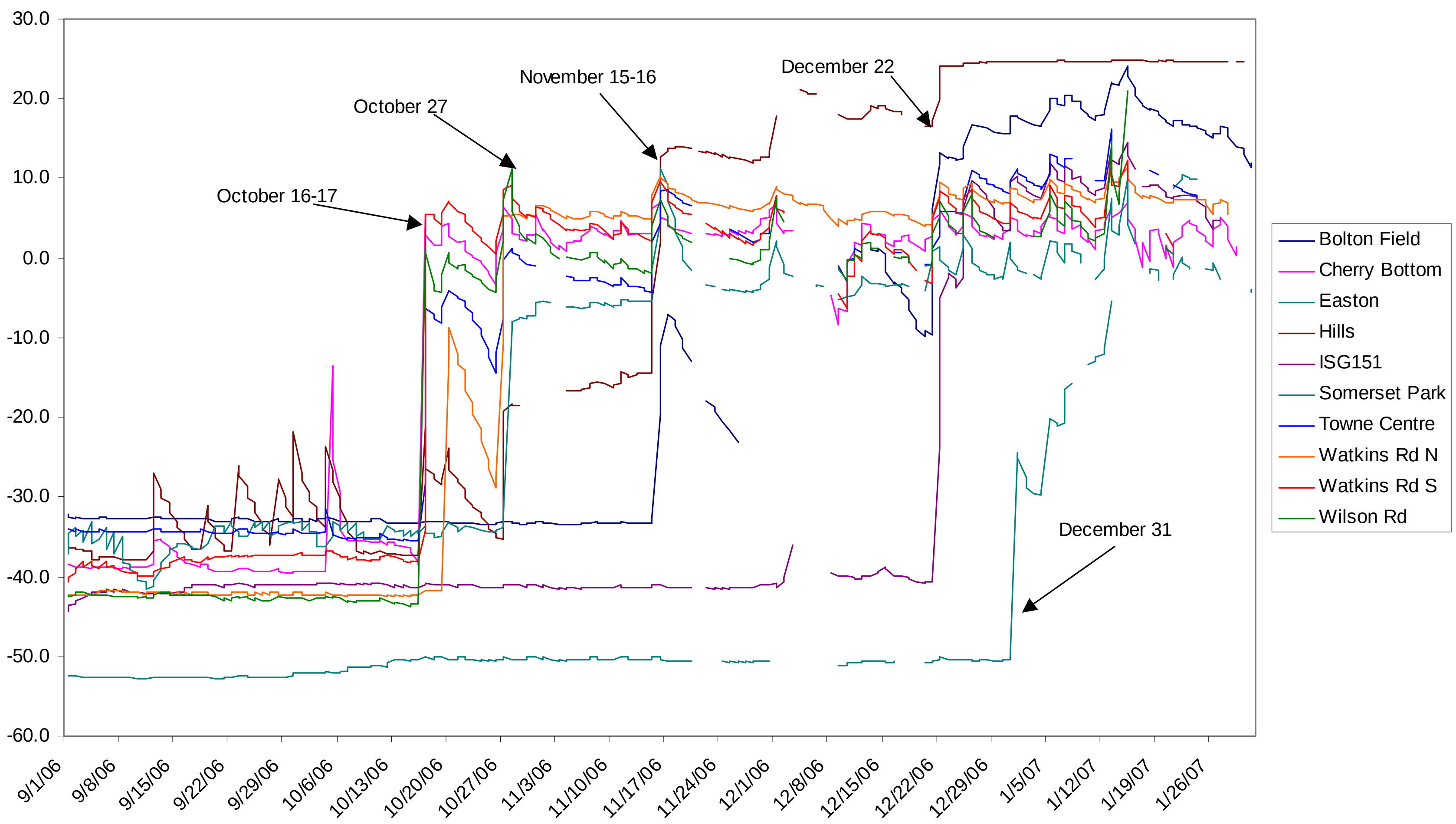

Figure 32. Abrupt synchronicity in reinundation of depressional wetlands. Dates refer to rain events on those days. Refer to Appendix for complete hydrographs of these wetlands and precipitation amounts.

APPENDIX

Annual Hydrographs

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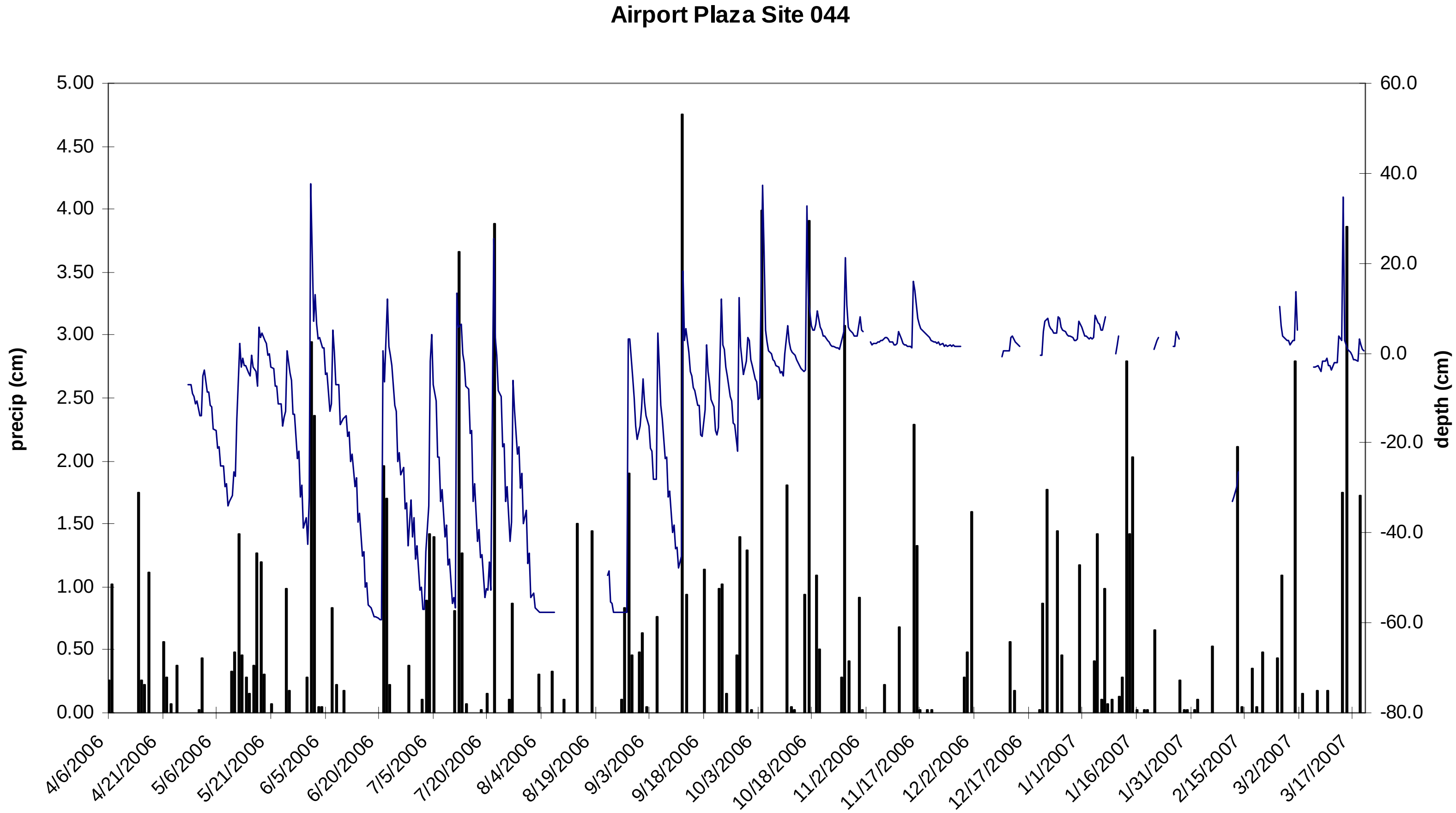
Airport Plaza Site 044
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
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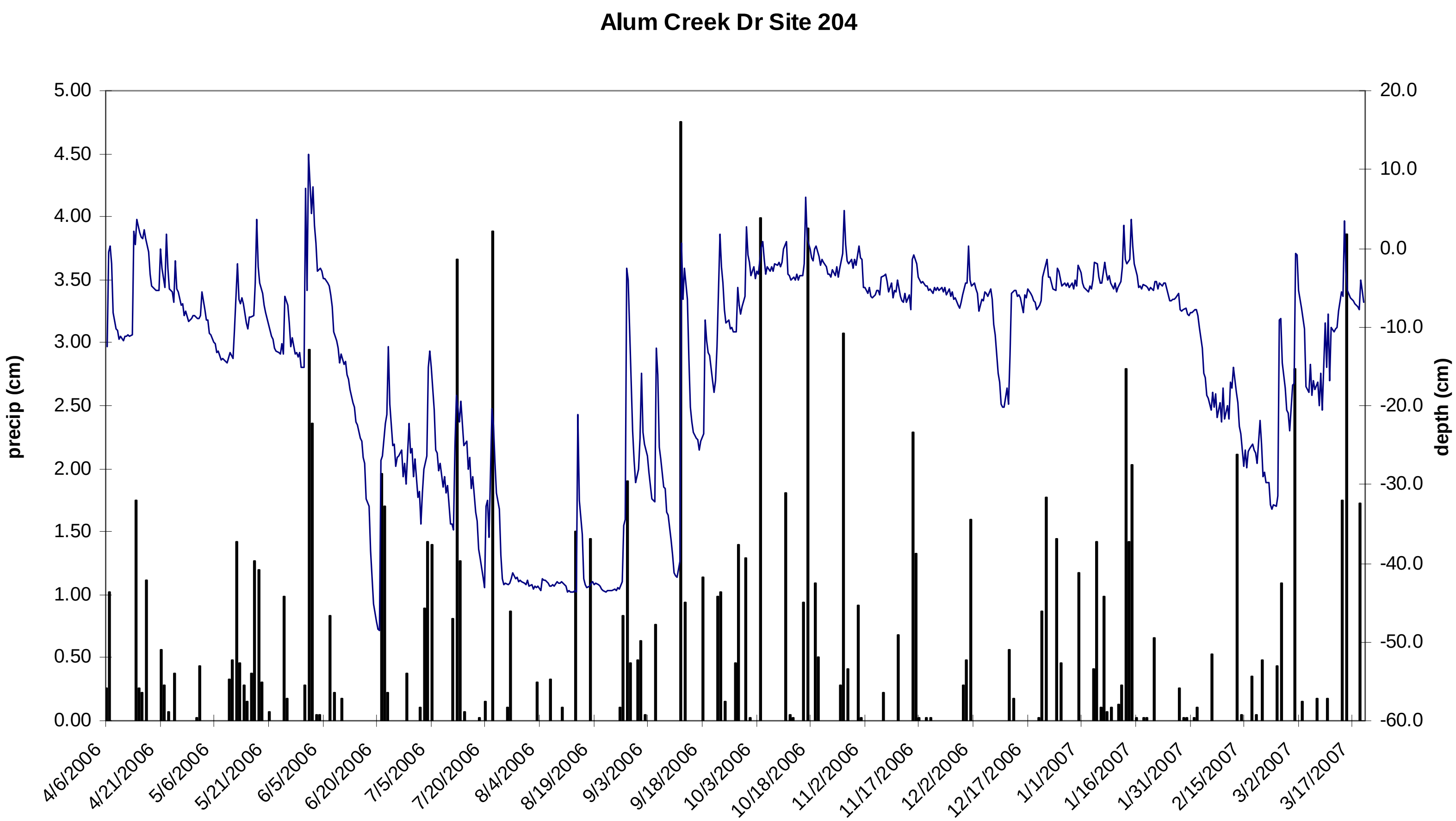
2/15/2007
3/2/2007
3/17/2007


Alum Creek Dr Site 204
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
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10/18/2006
11/2/2006
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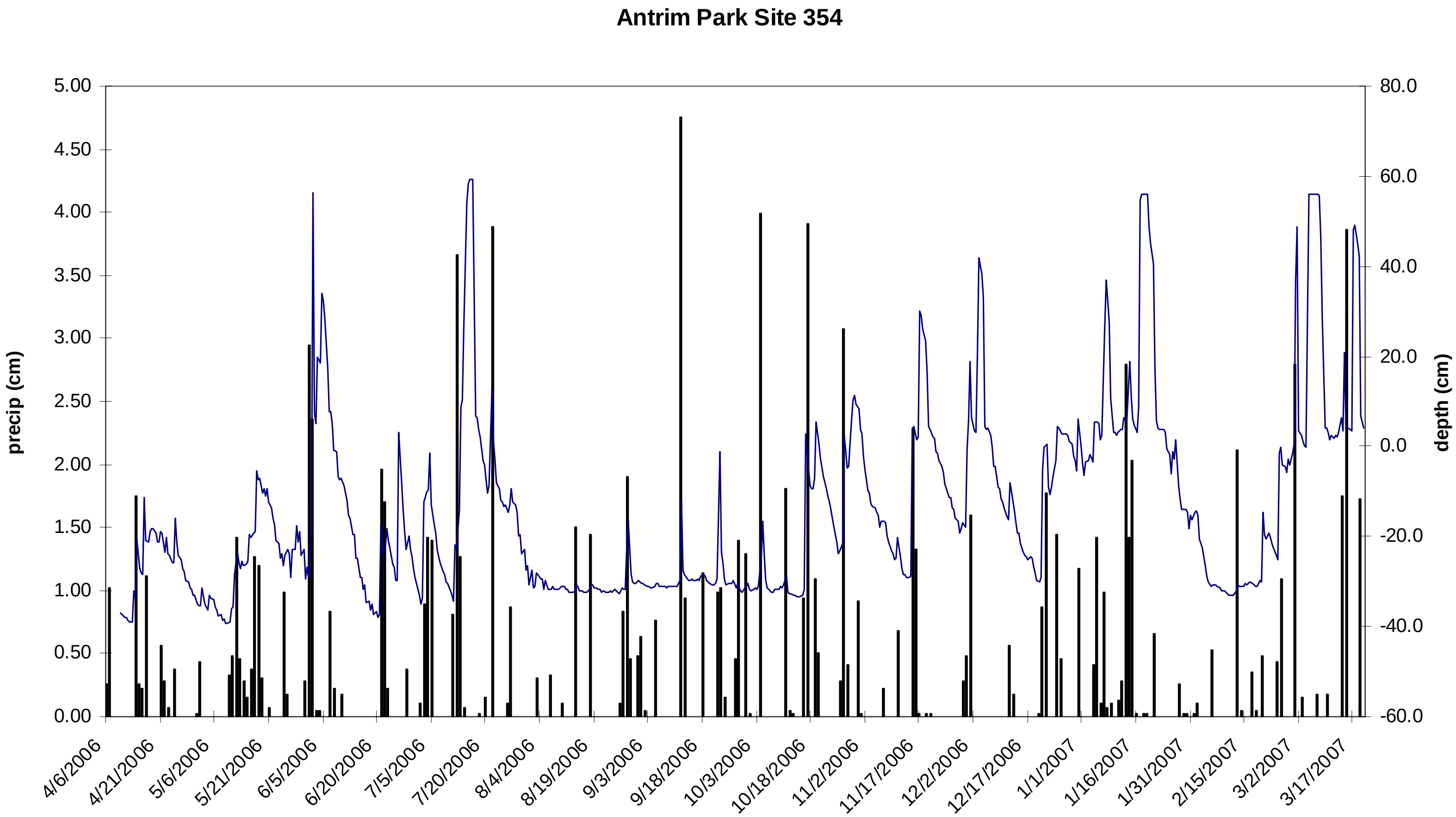
3/2/2007
3/17/2007


Antrim Park Site 354
precip (cm)
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3.50
3.00
2.50
2.00
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1.00
0.50
0.00
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
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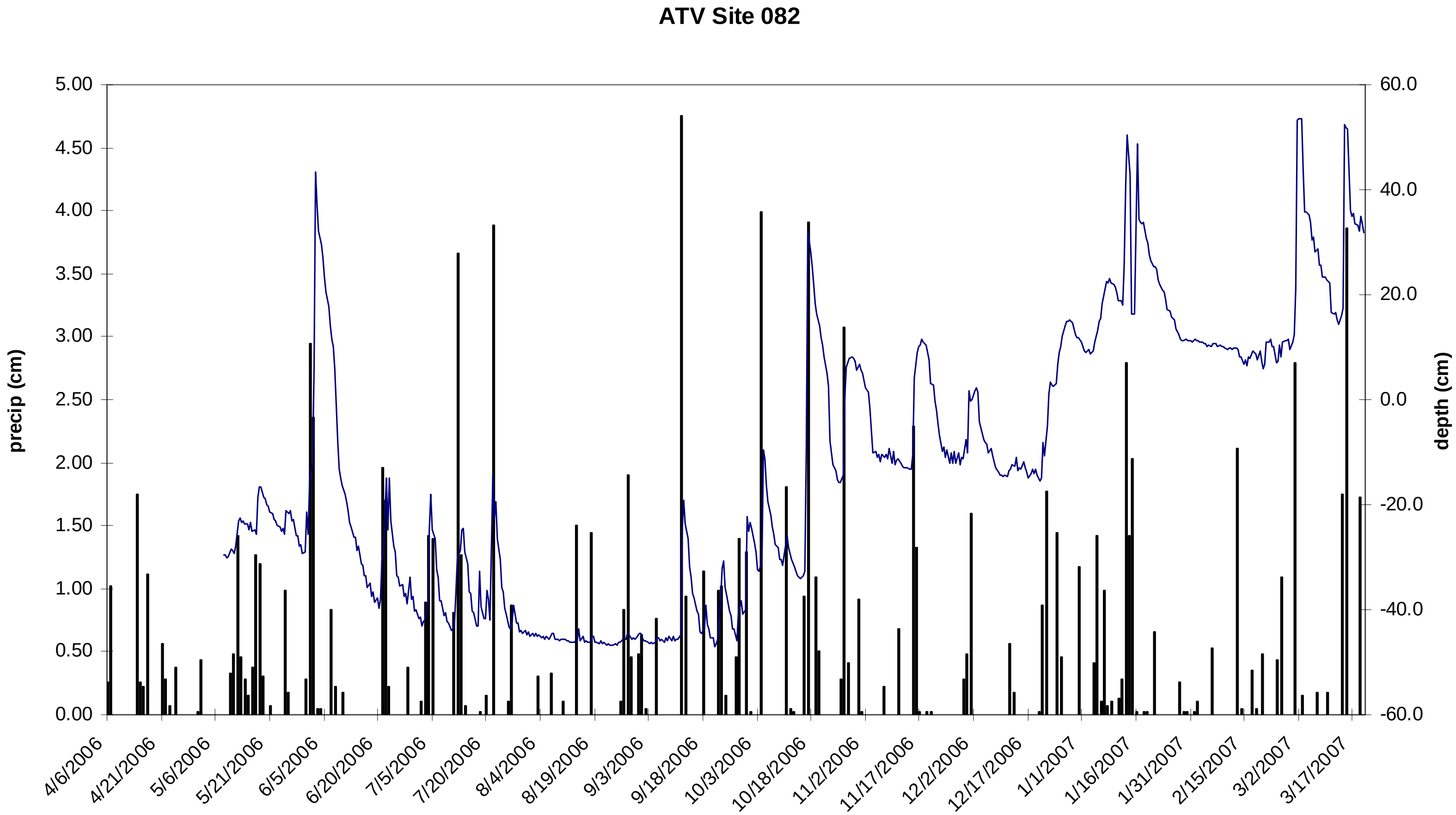
3/2/2007
3/17/2007


ATV Site 082
precip (cm)
depth (cm)
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4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
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10/18/2006
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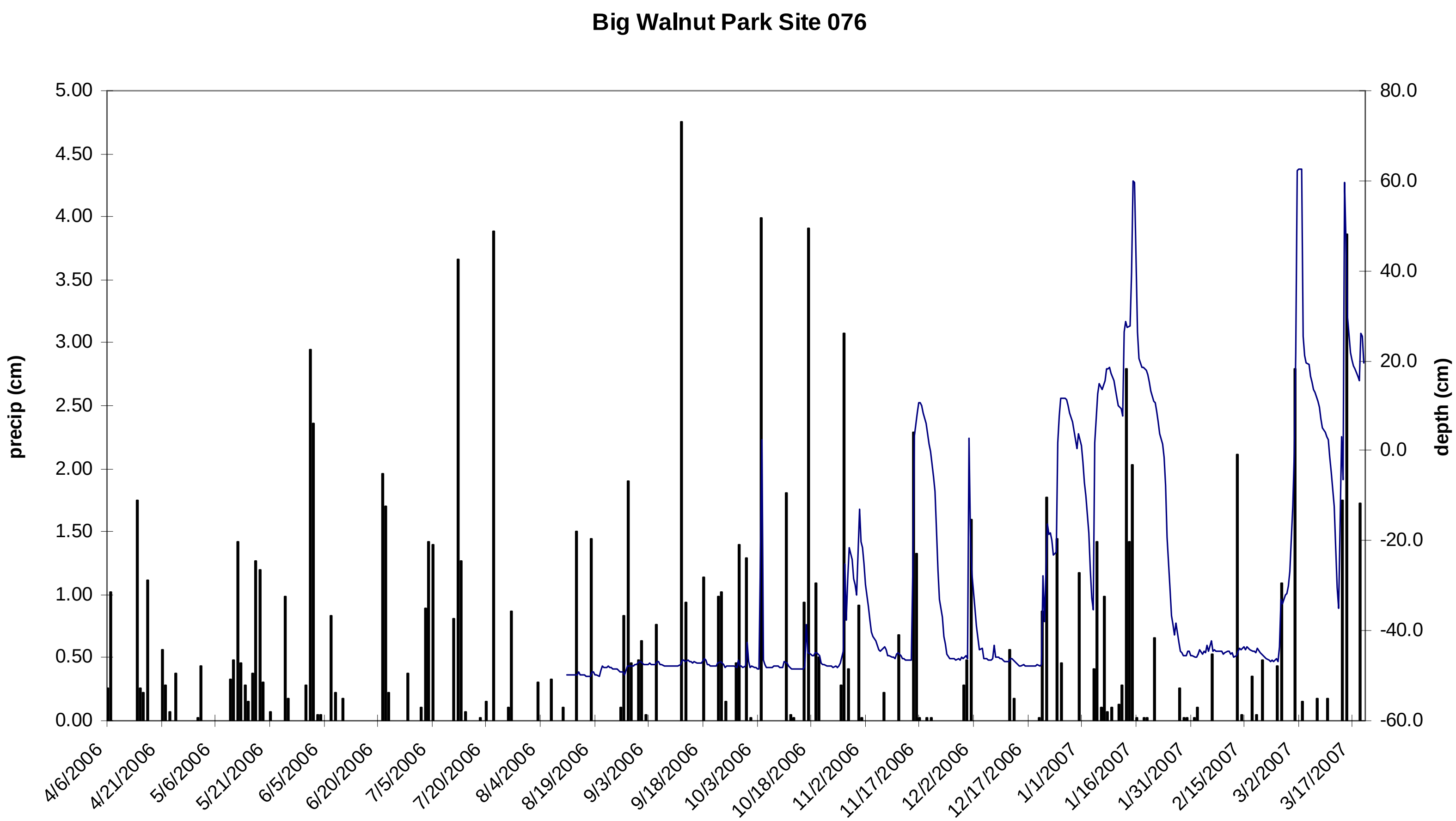
3/2/2007
3/17/2007


Big Walnut Park Site 076
precip (cm)
depth (cm)
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4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
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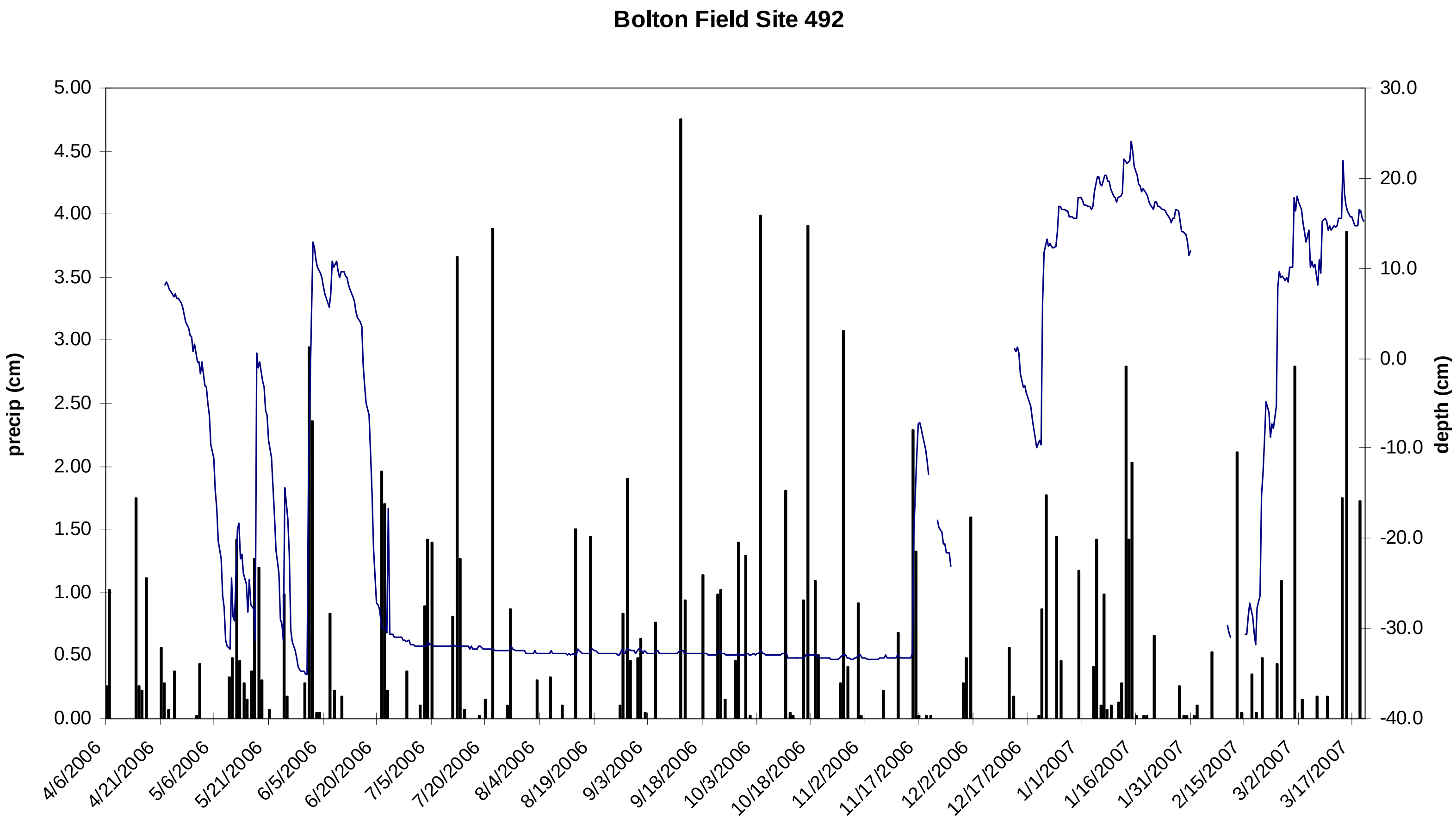
3/2/2007
3/17/2007


Bolton Field Site 492
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
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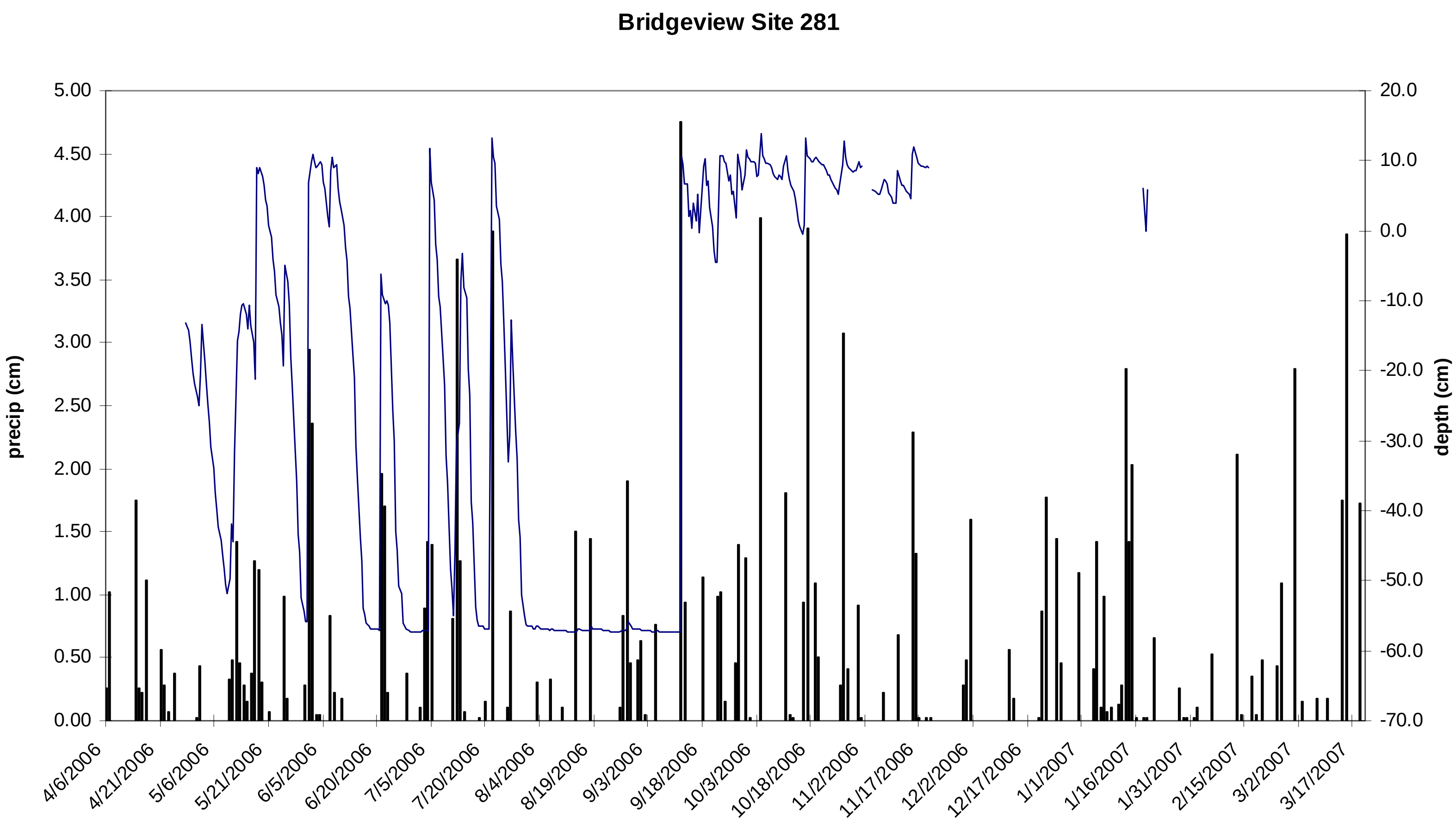
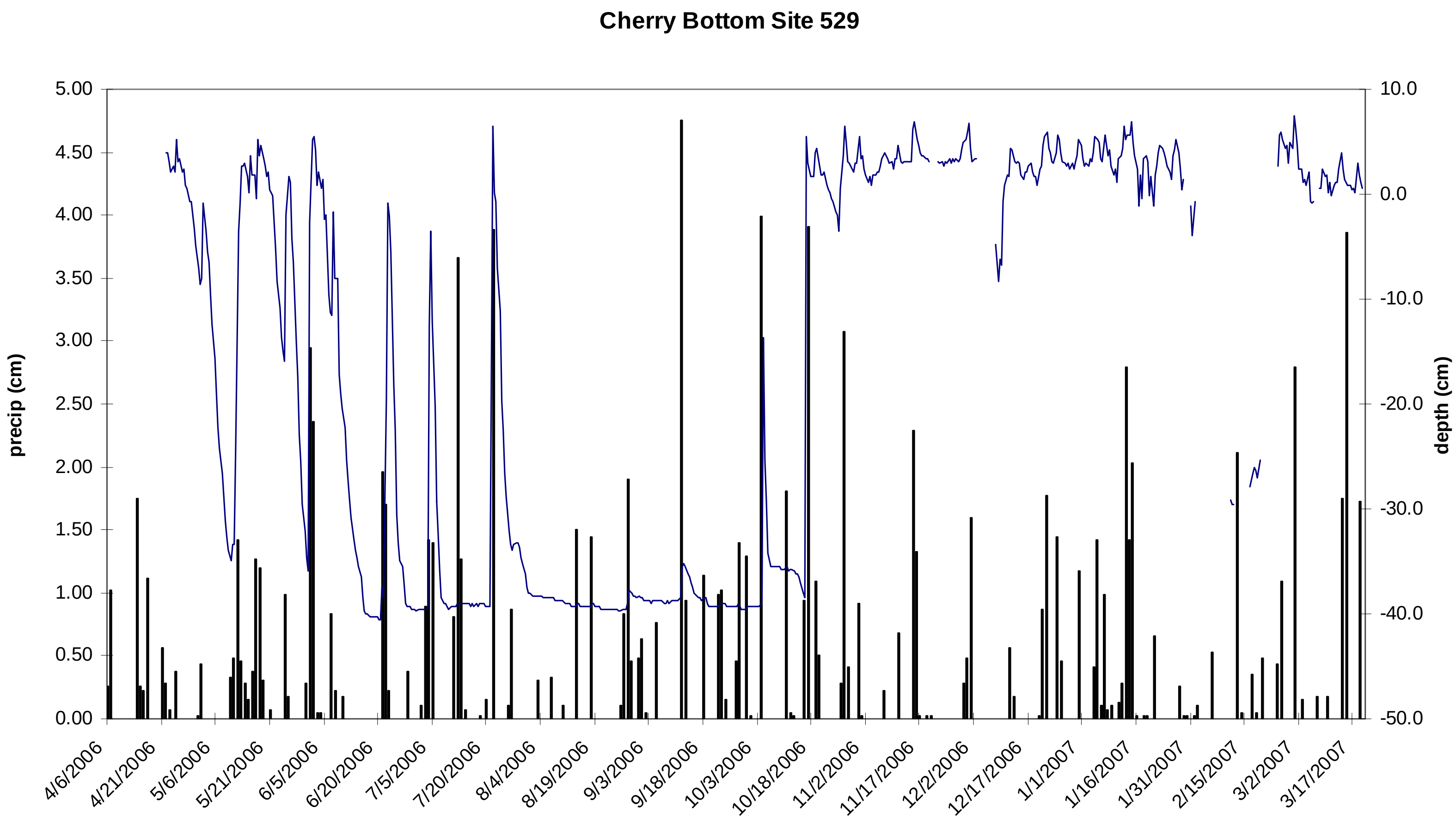
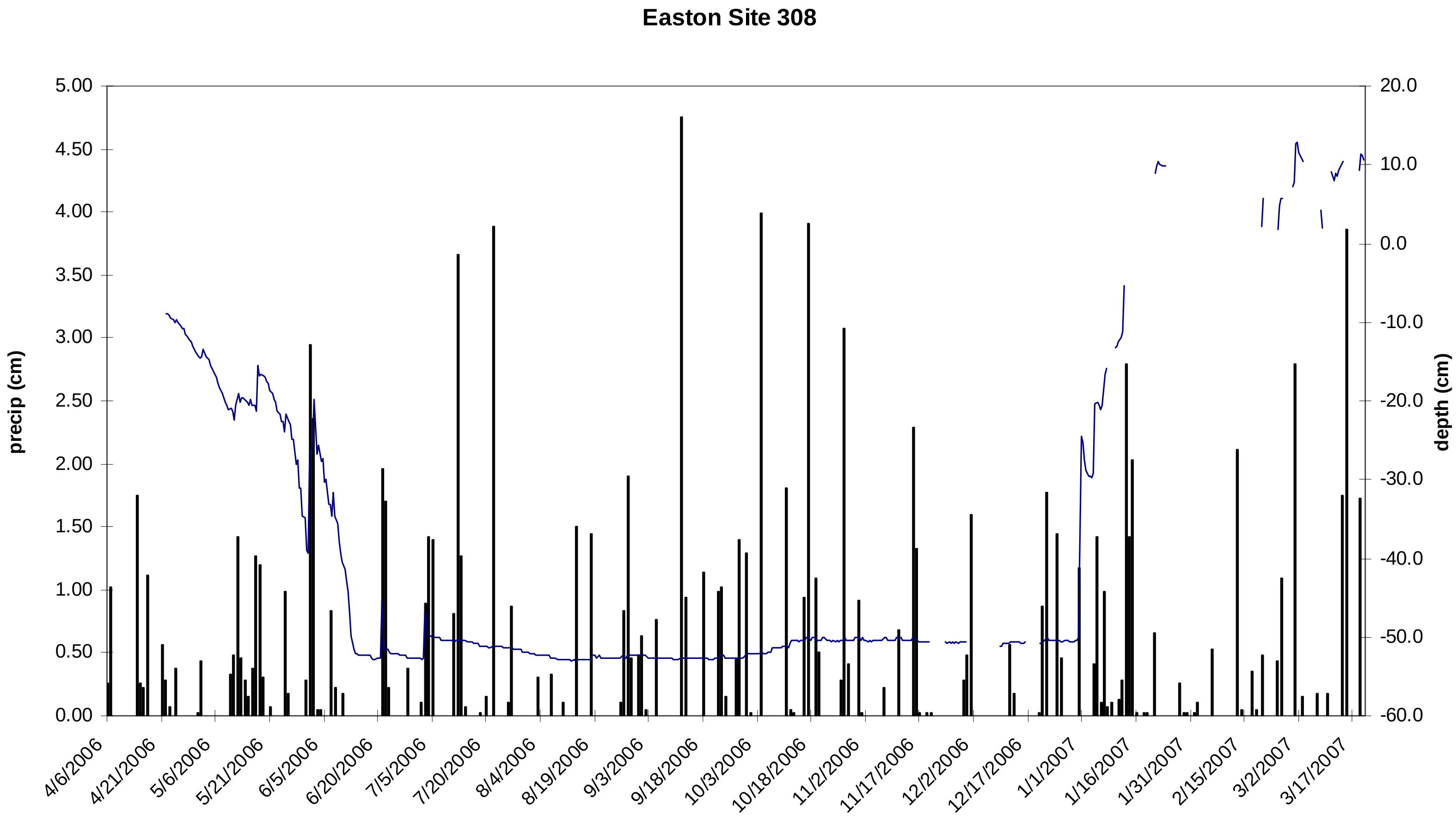
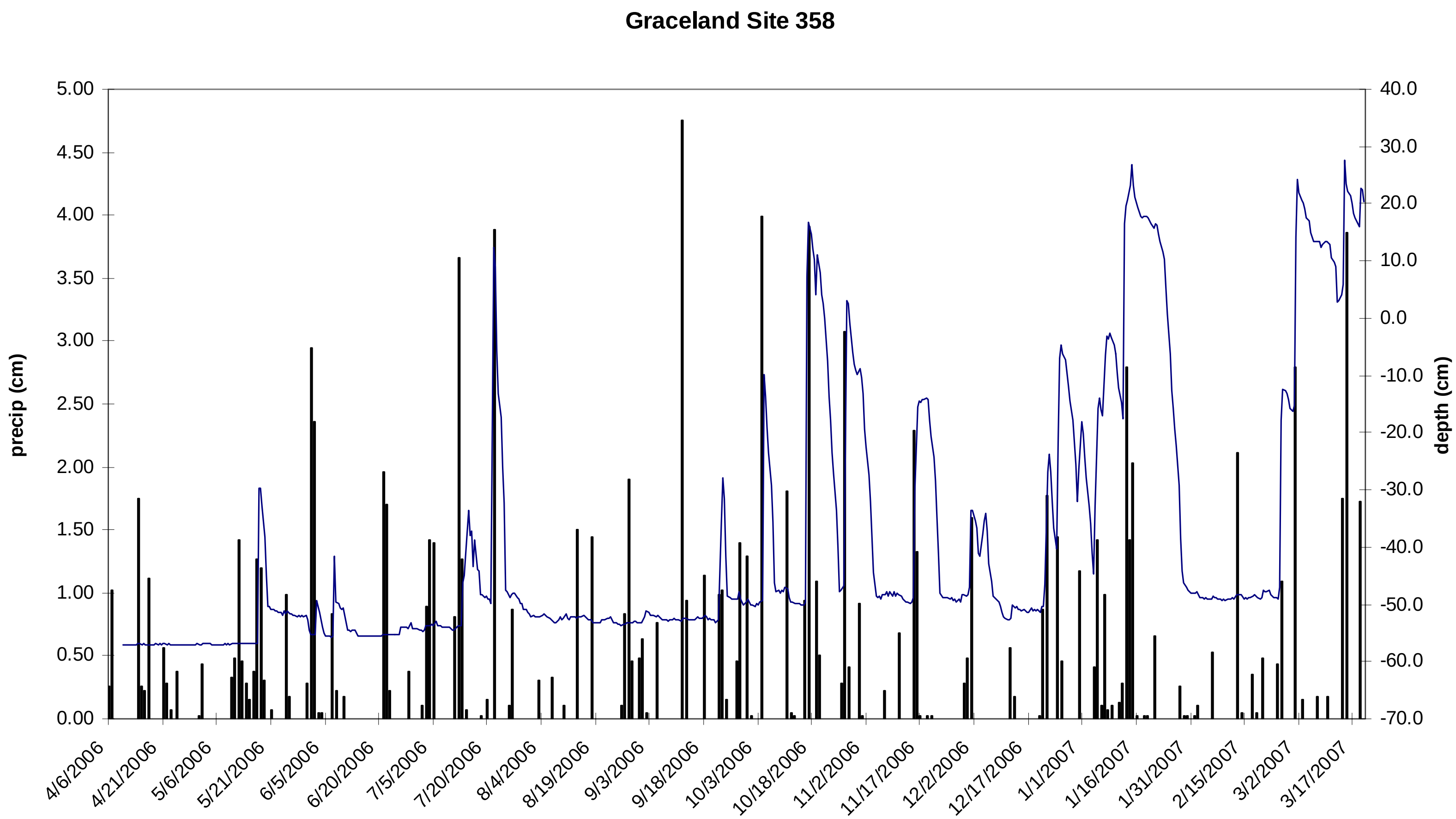
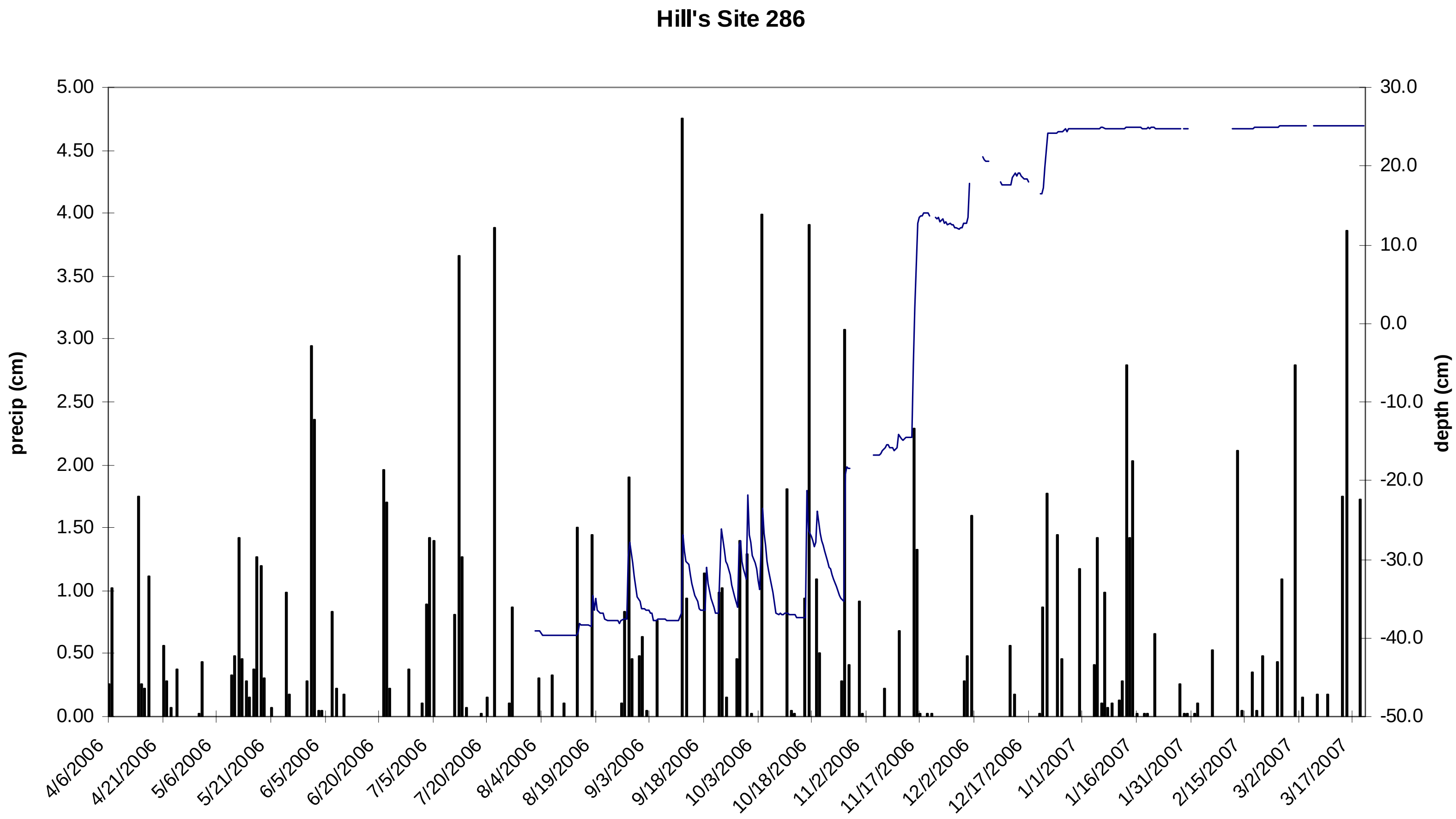
2/15/2007
3/2/2007
3/17/2007

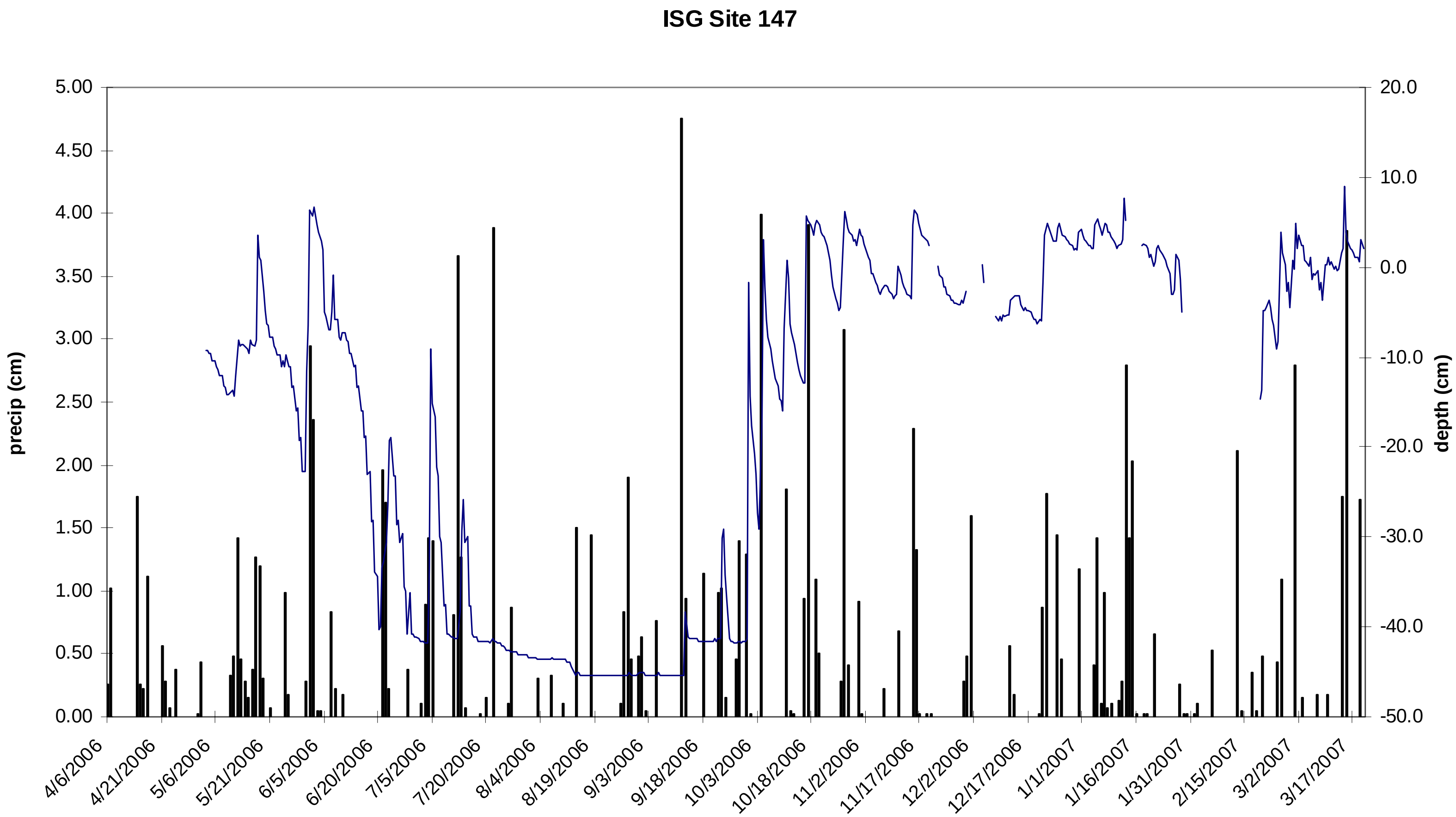

Bridgeview Site 281
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

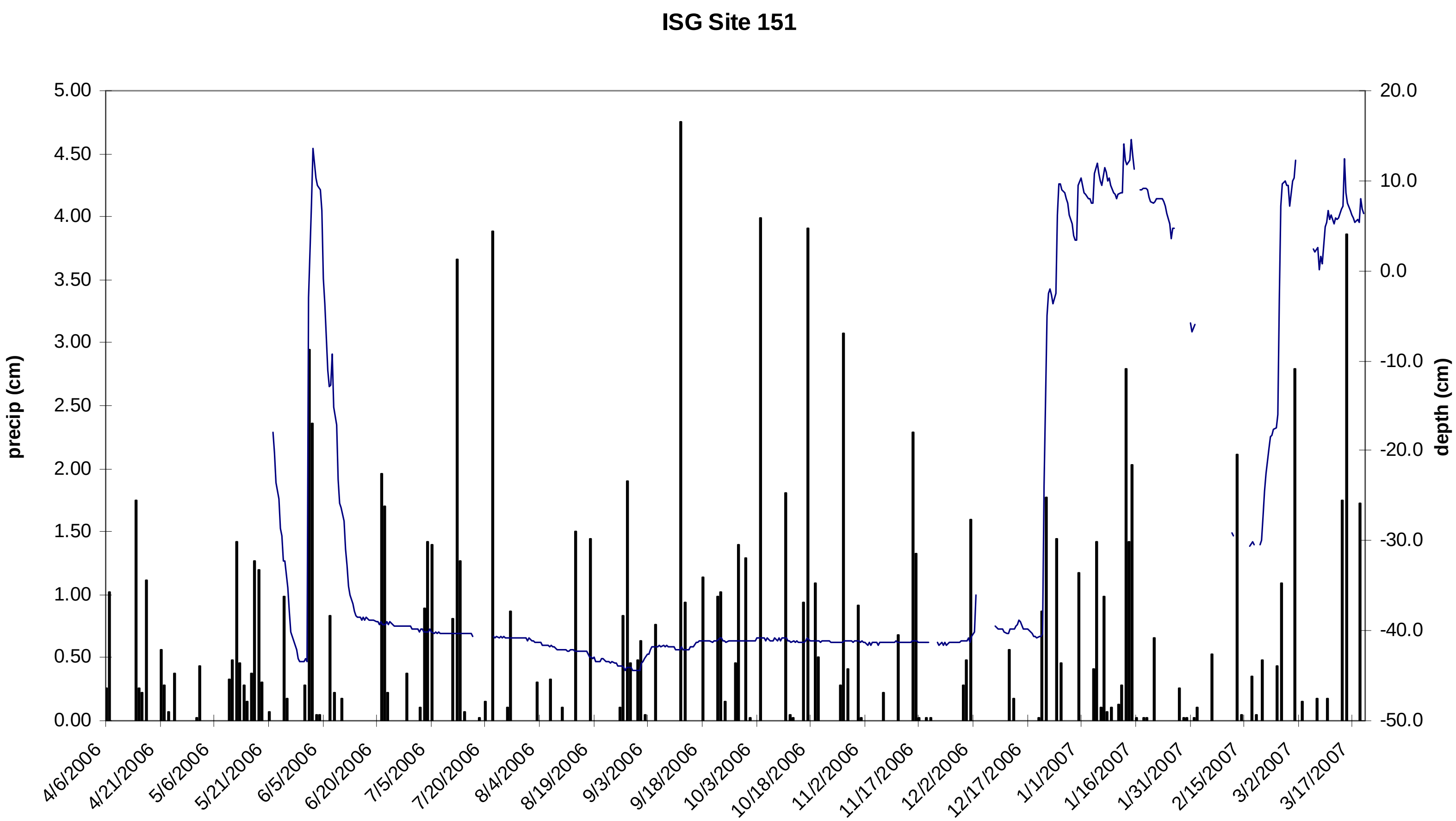

Cherry Bottom Site 529
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

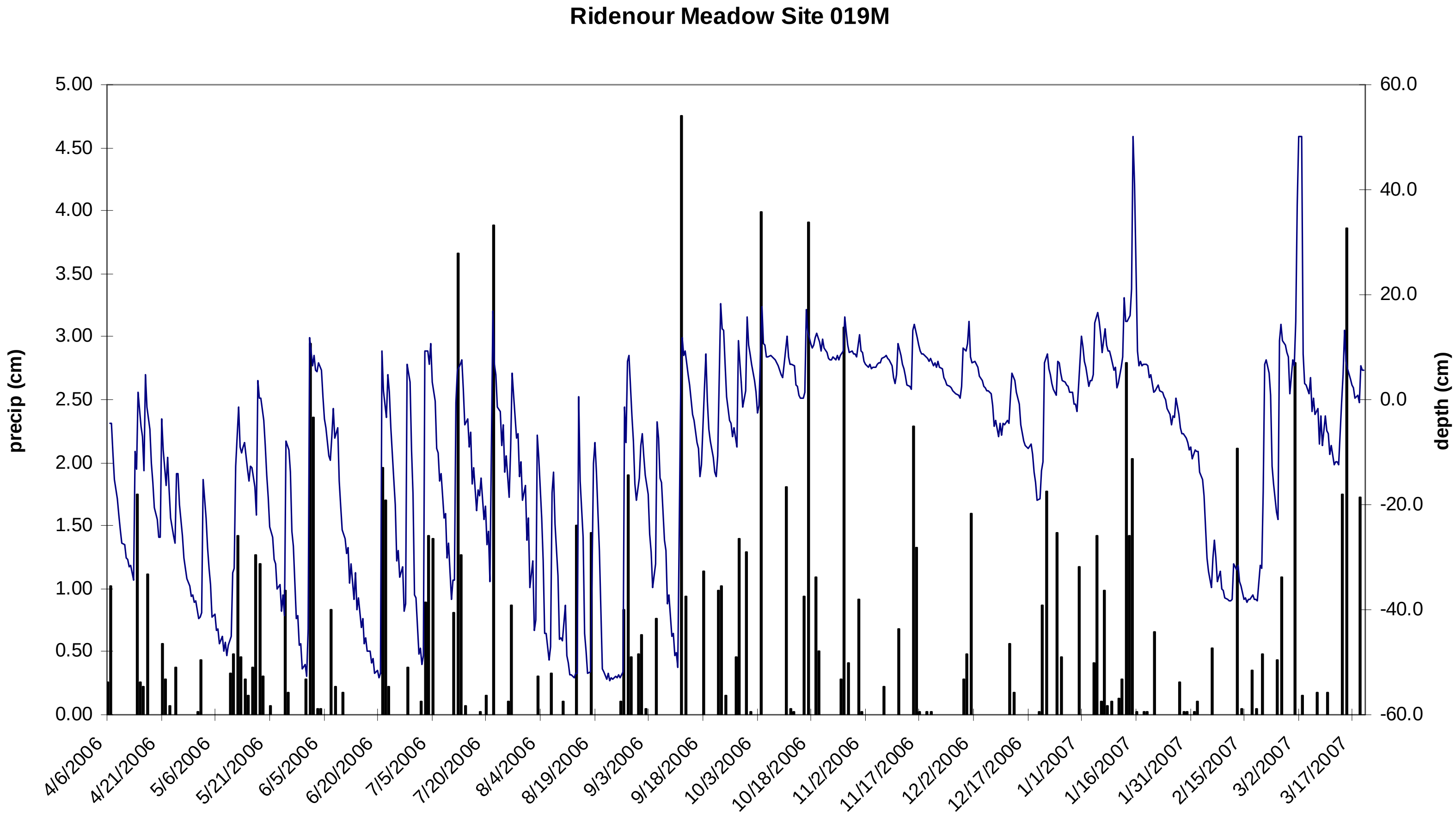

Easton Site 308
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

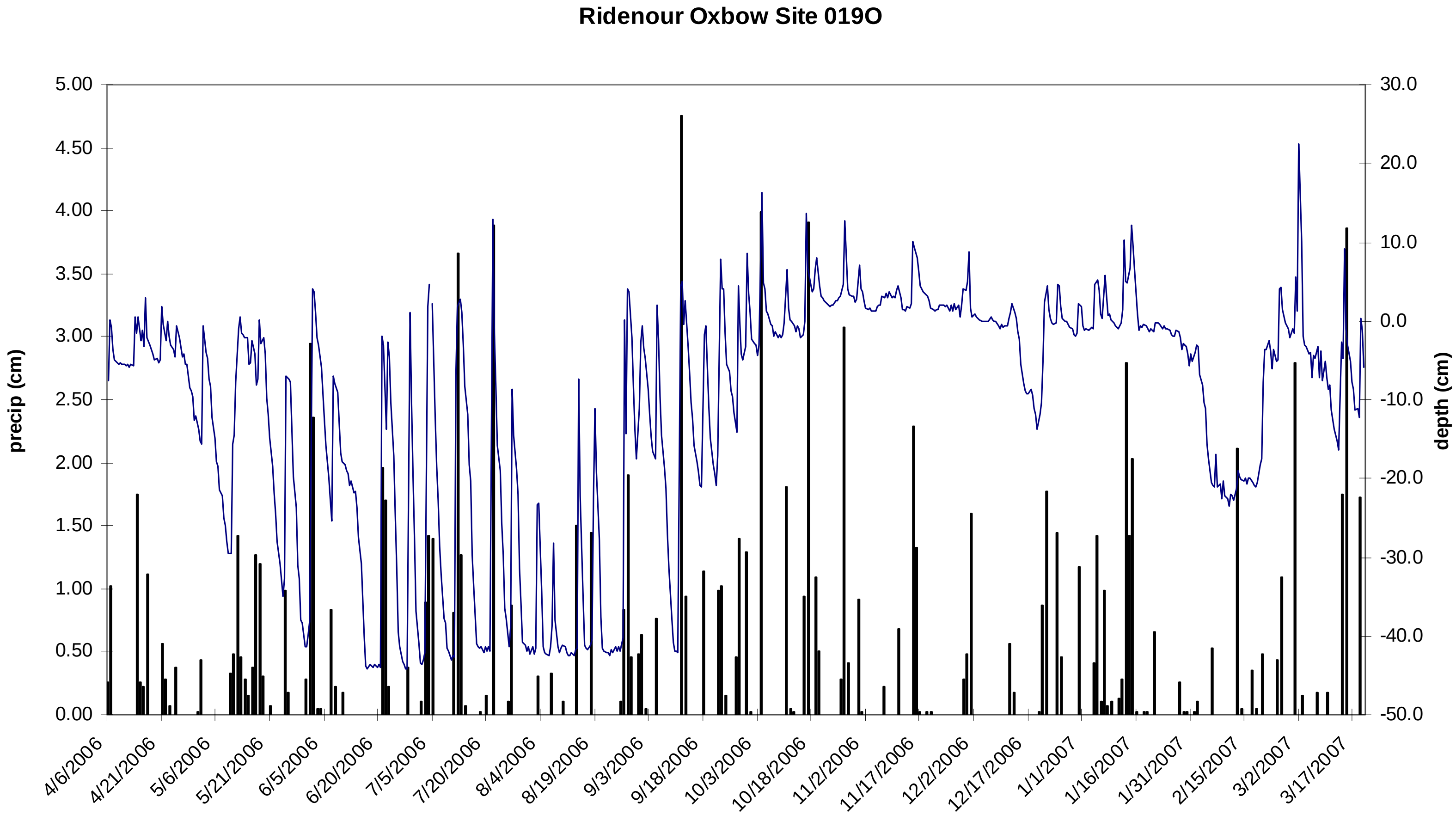

Graceland Site 358
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

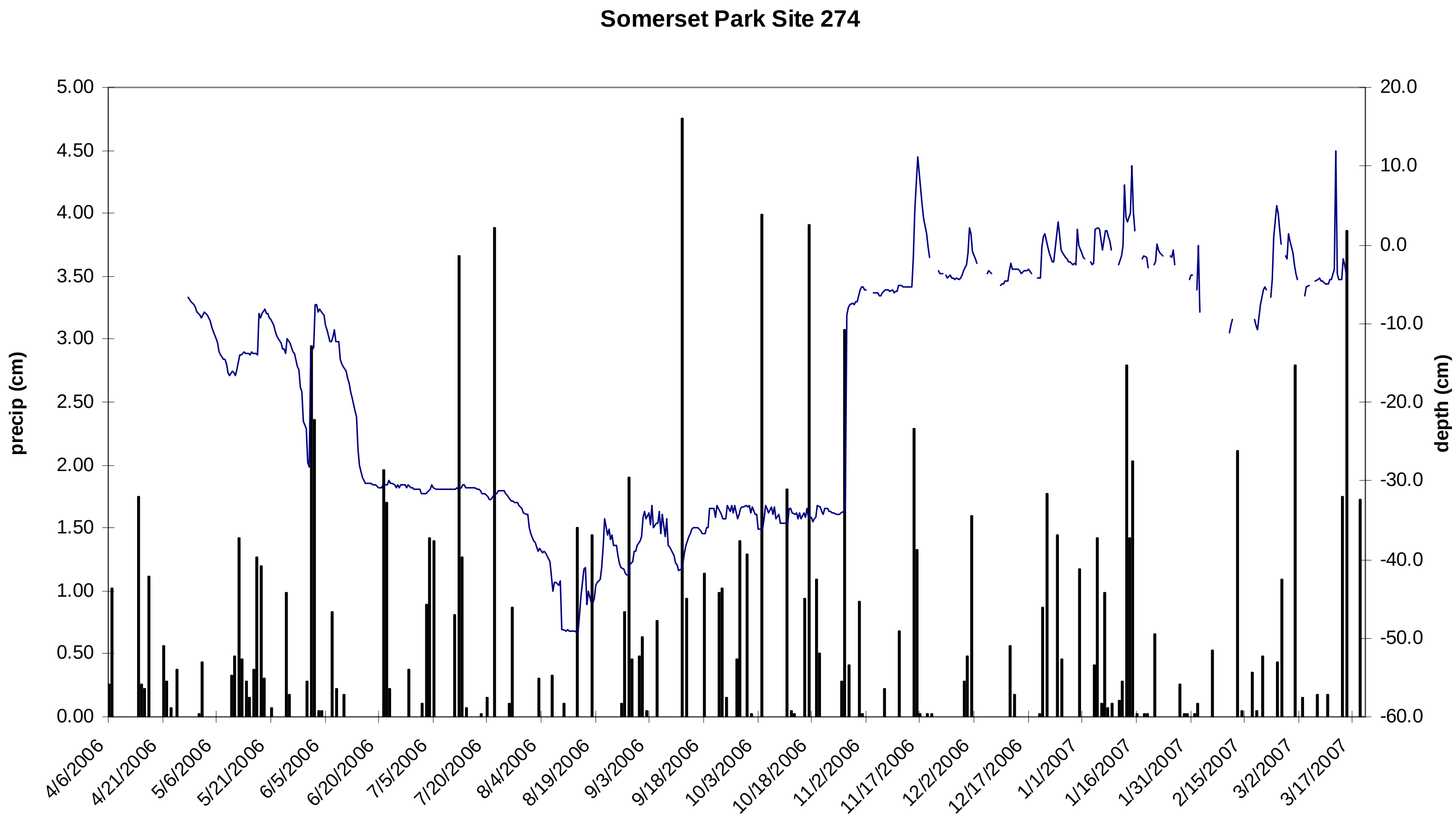

Hill's Site 286
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

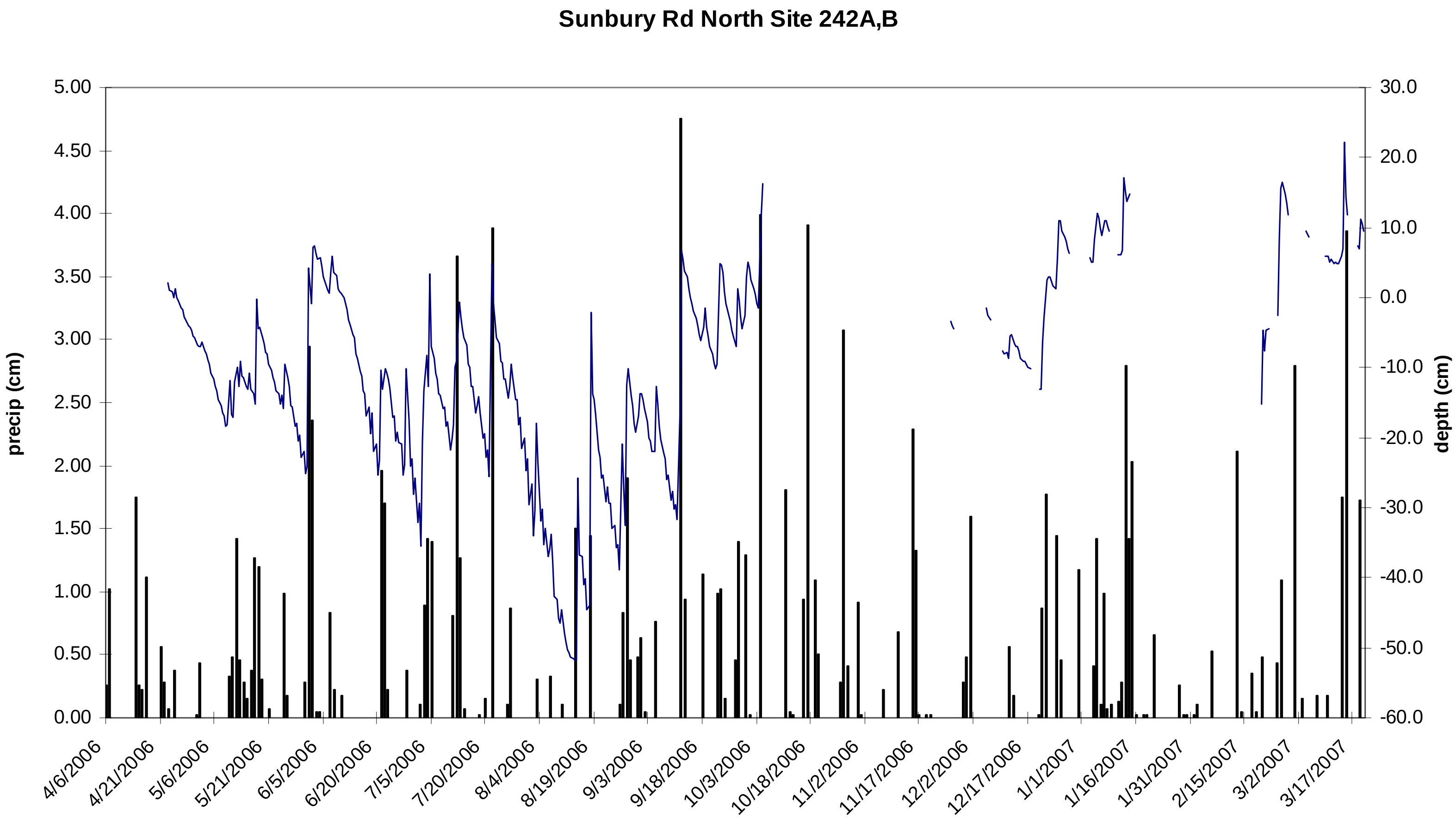

ISG Site 147
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


ISG Site 151
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

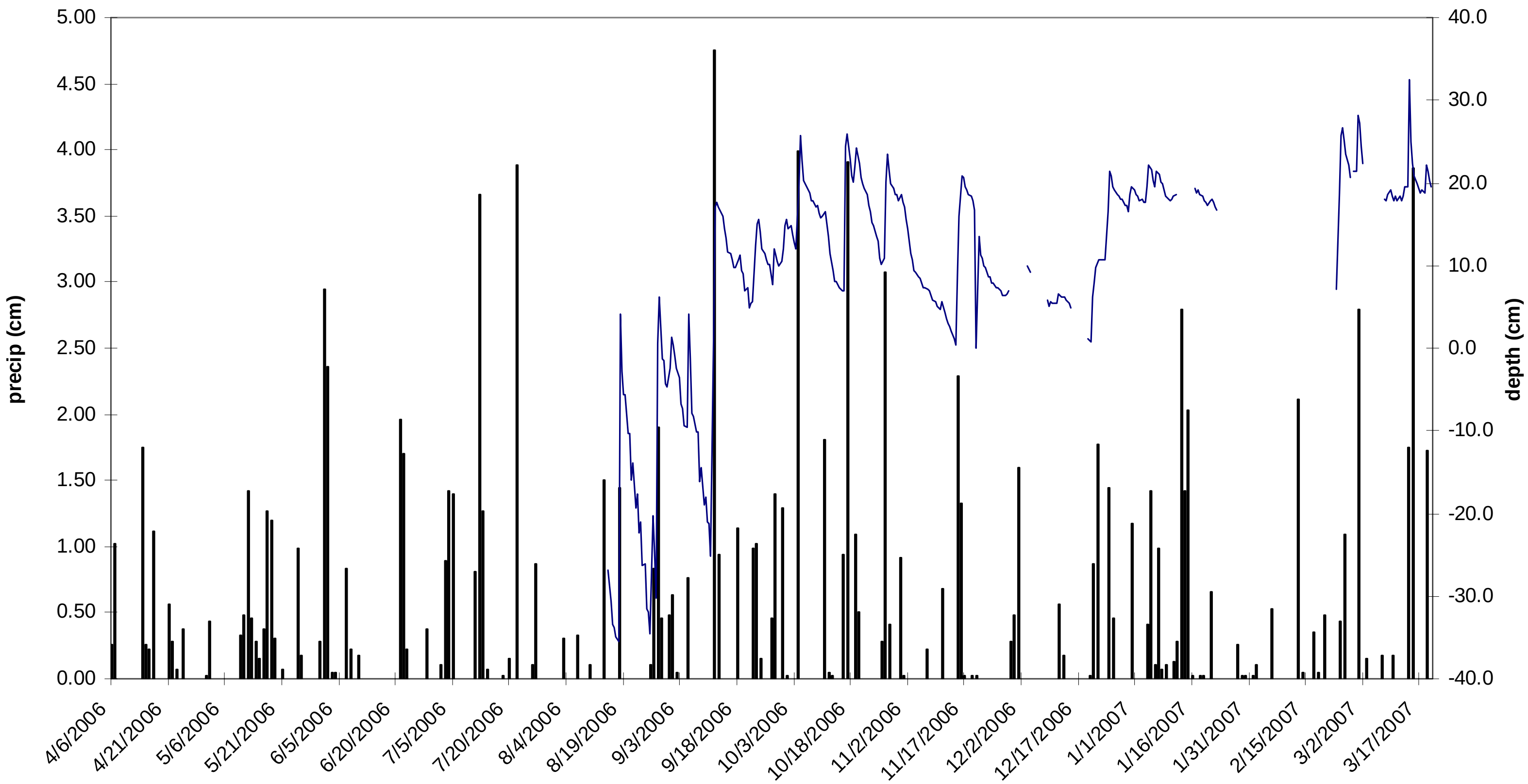

Ridenour Meadow Site 019M
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

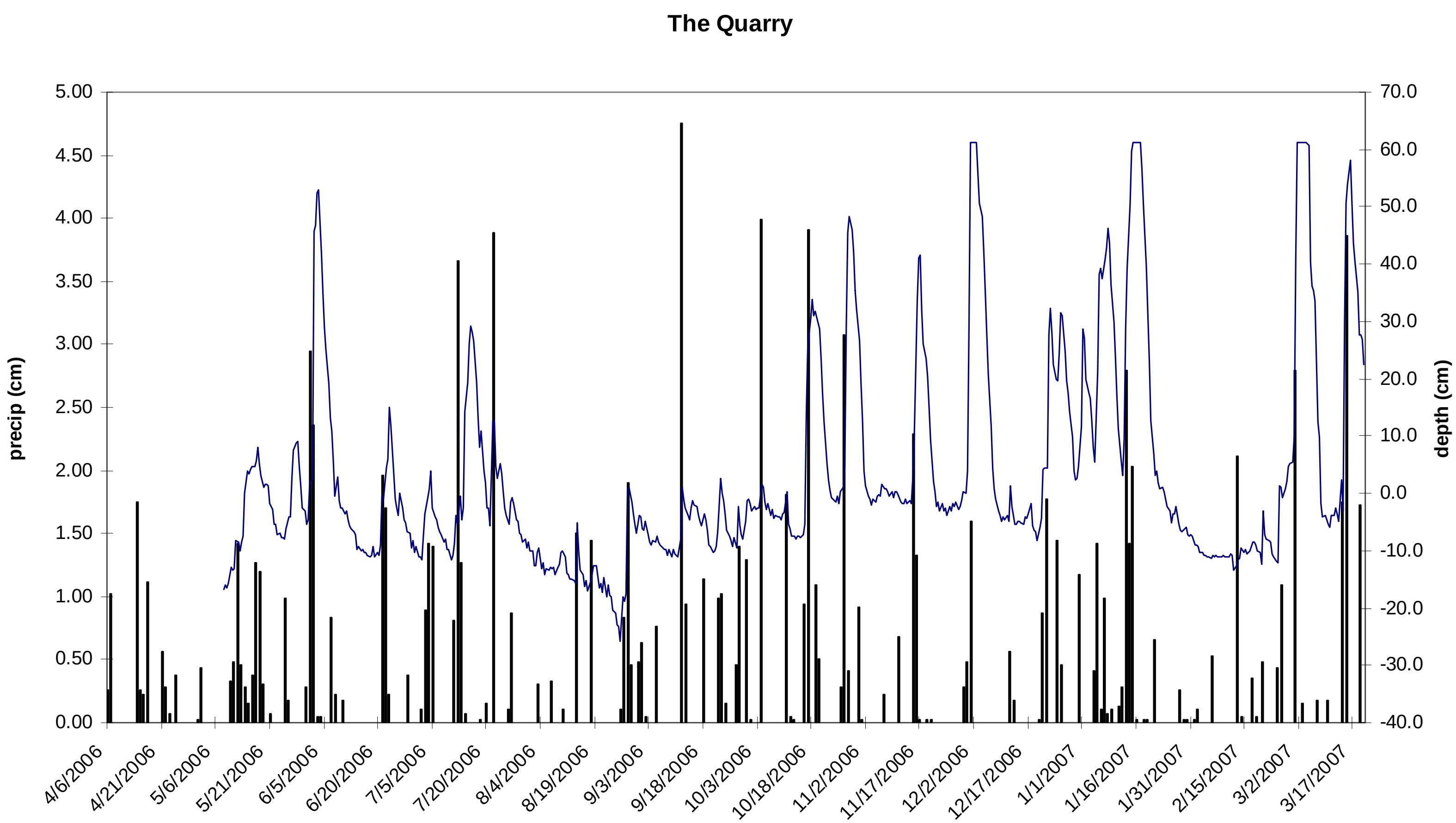

Ridenour Oxbow Site 019O
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

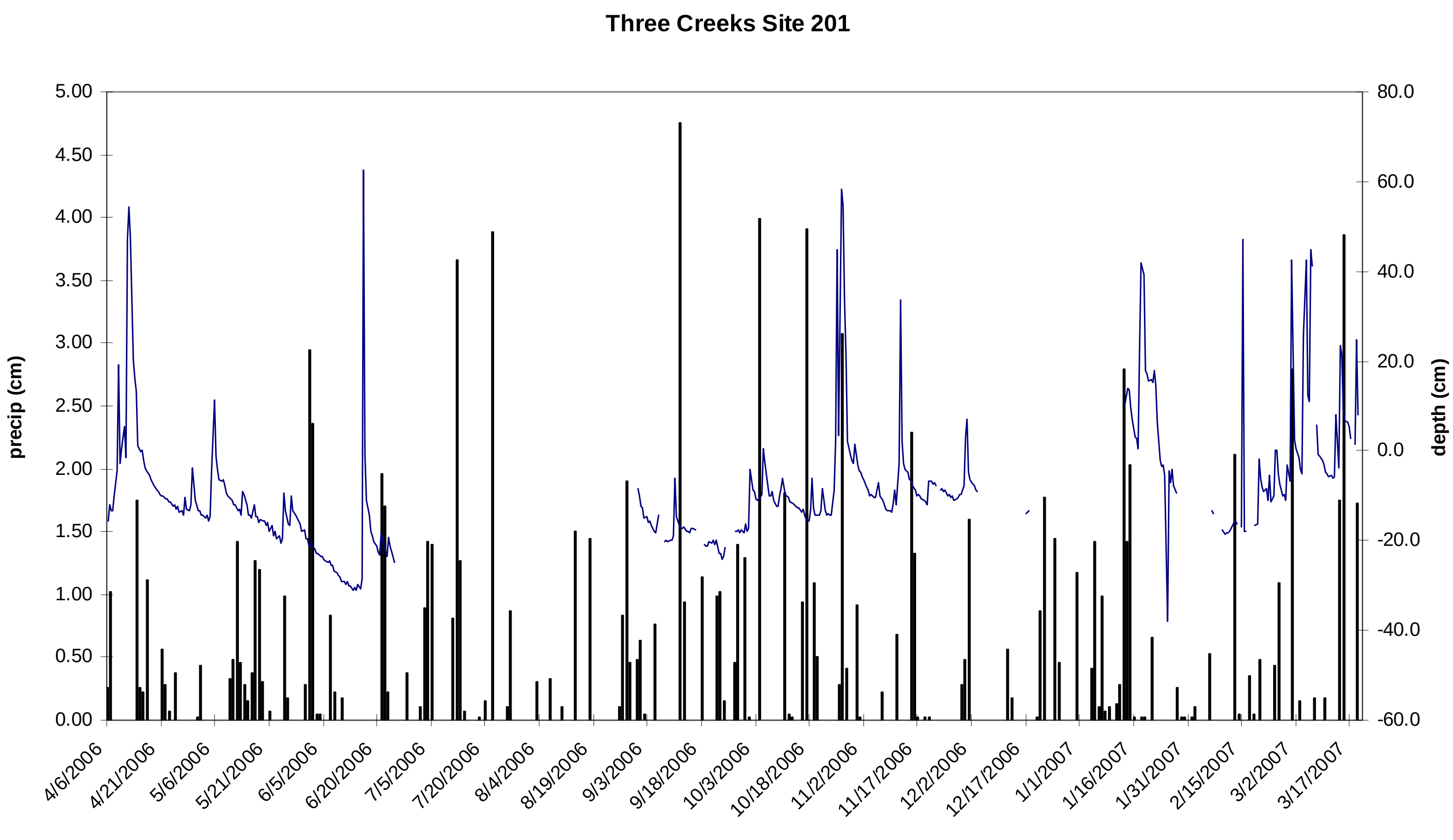

Somerset Park Site 274
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

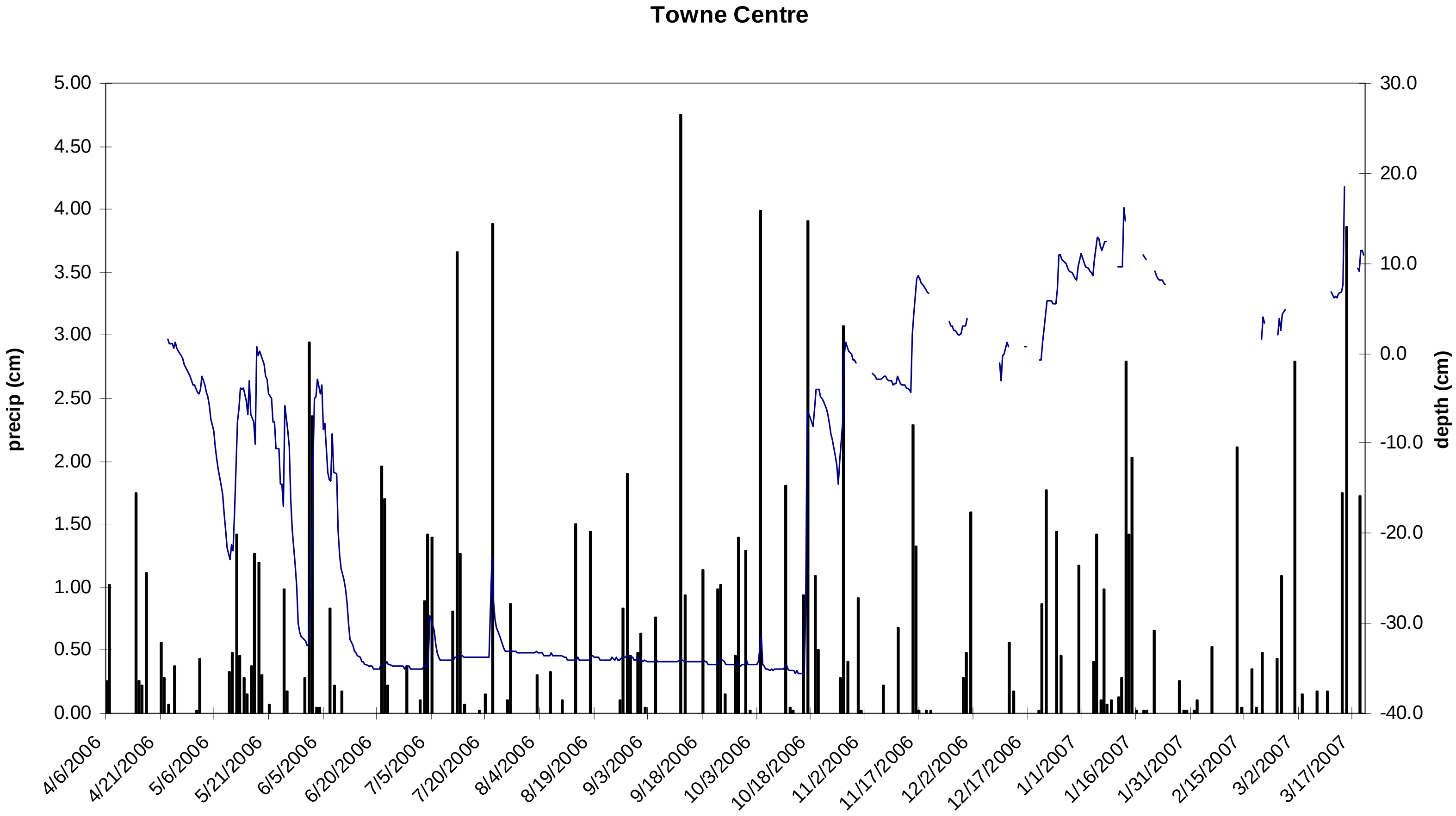

Sunbury Rd North Site 242A,B
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

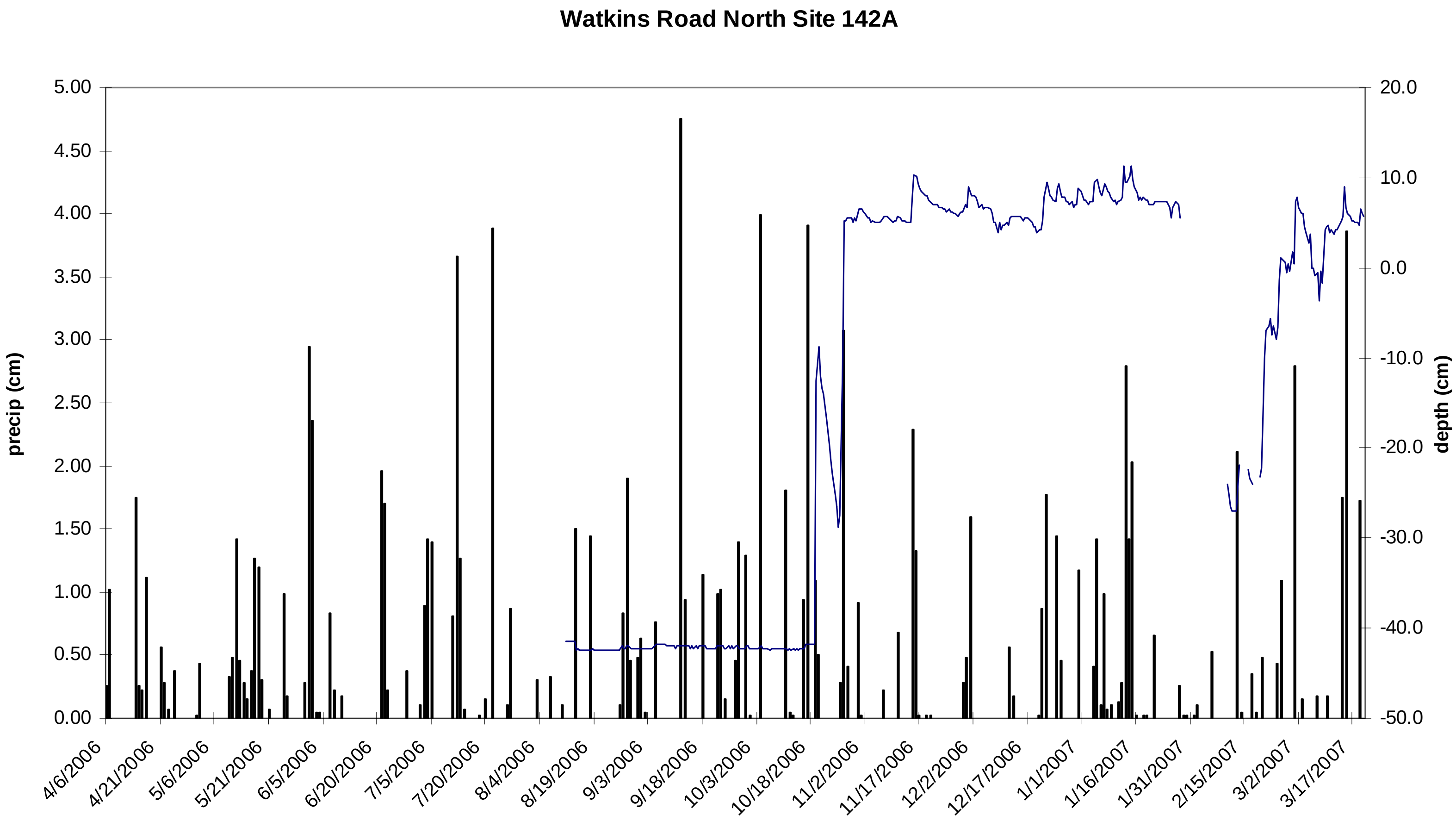
Sunbury Rd South Site 242C

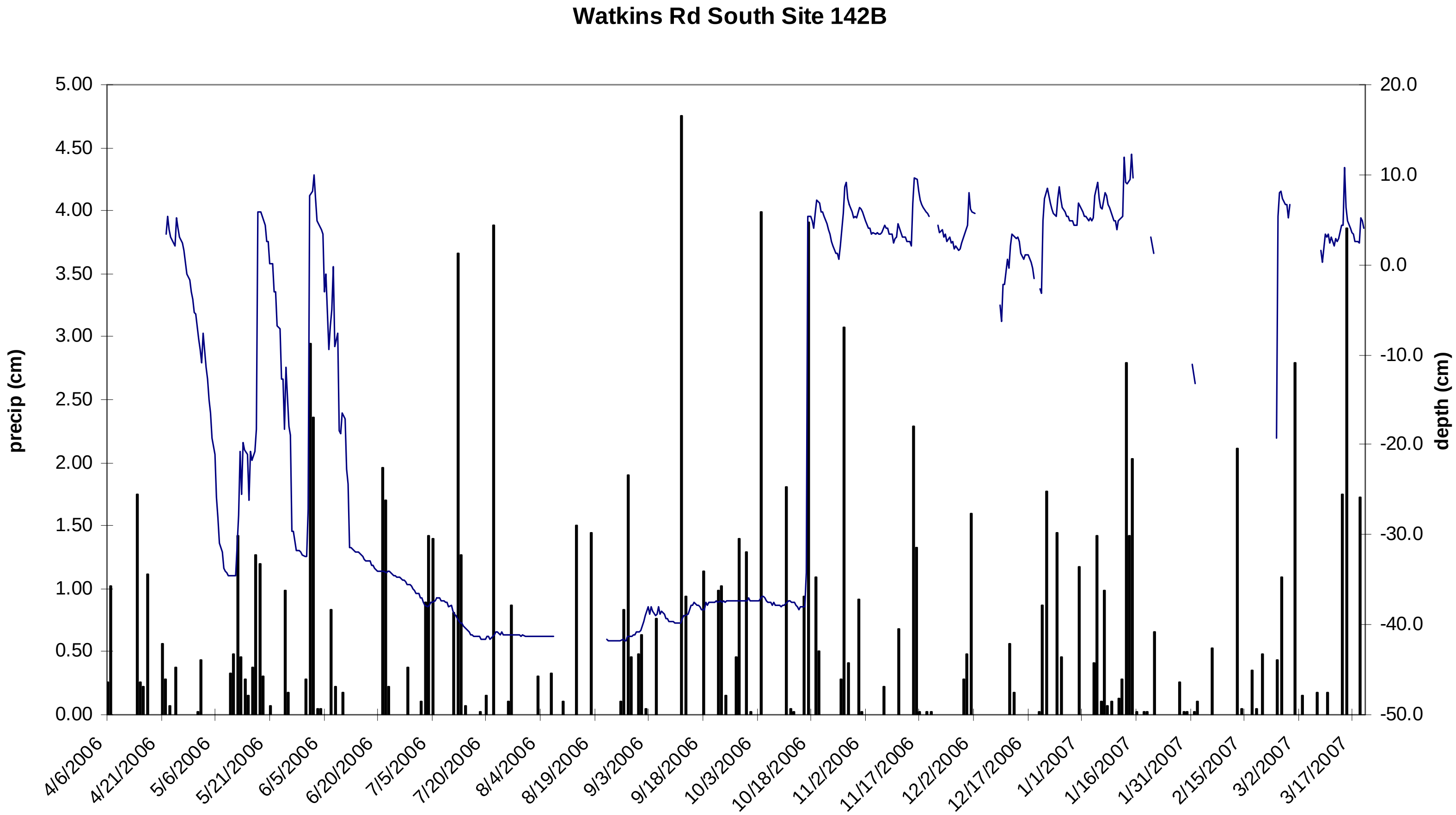


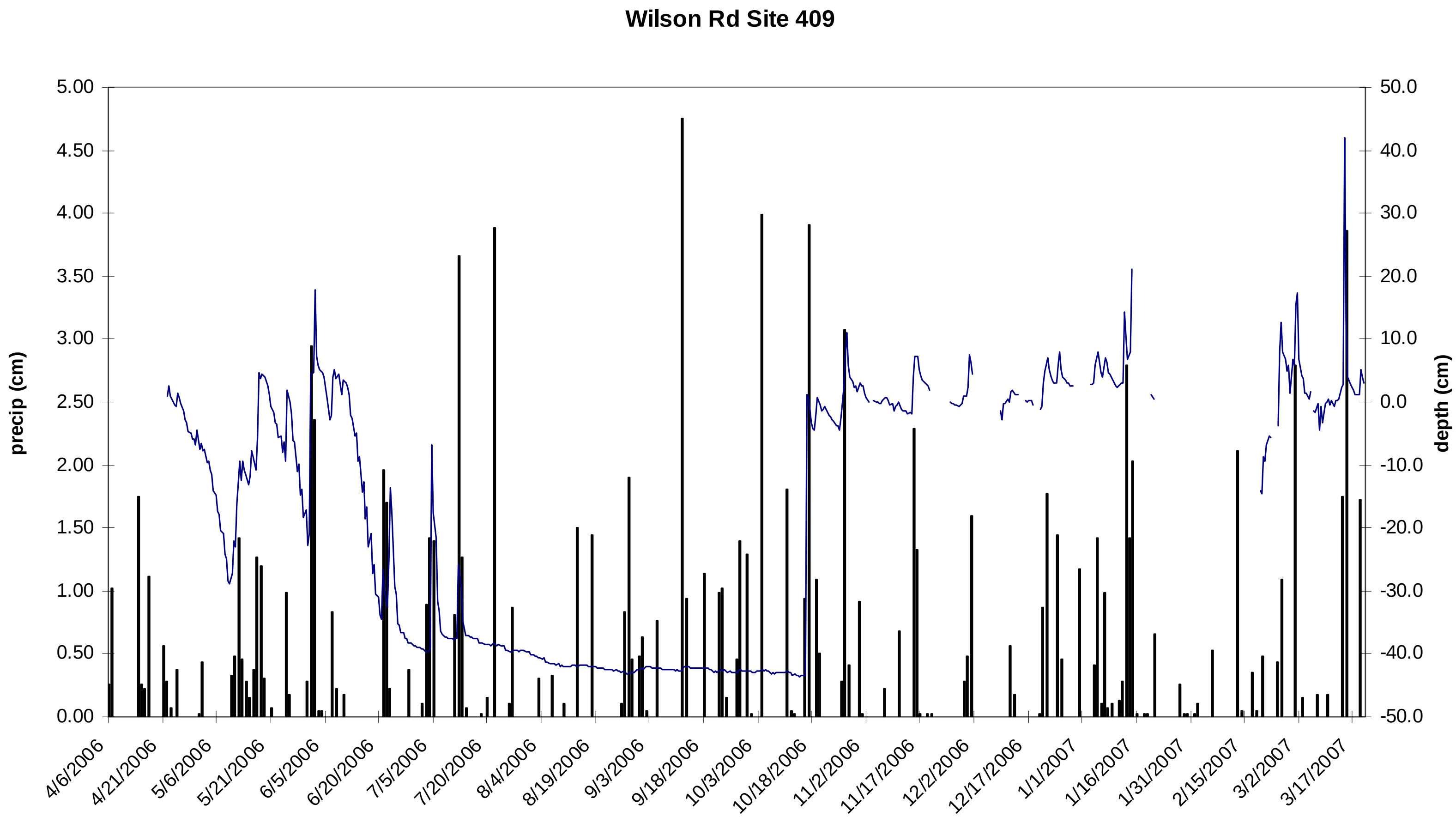

The Quarry
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

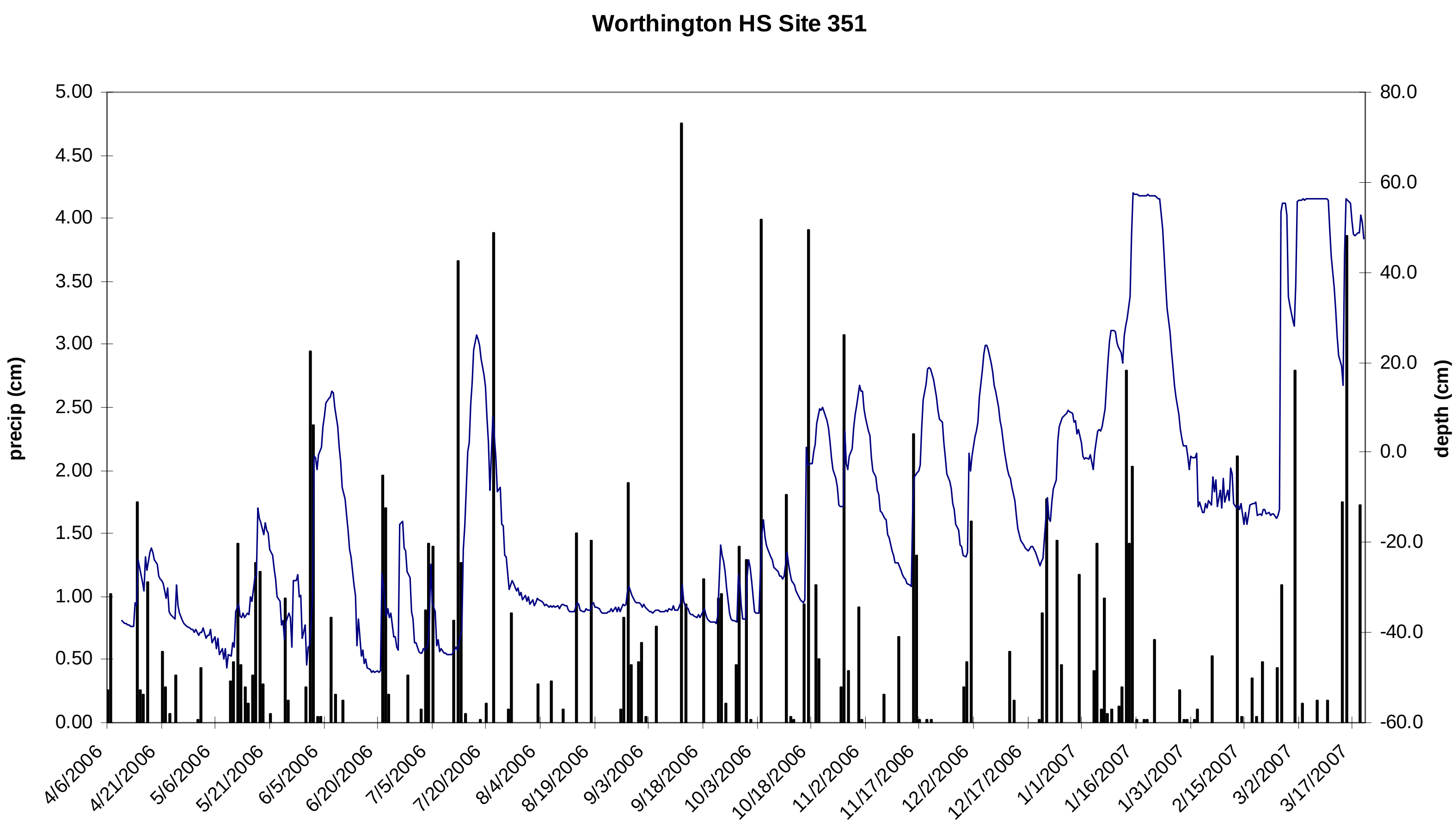

Three Creeks Site 201
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007

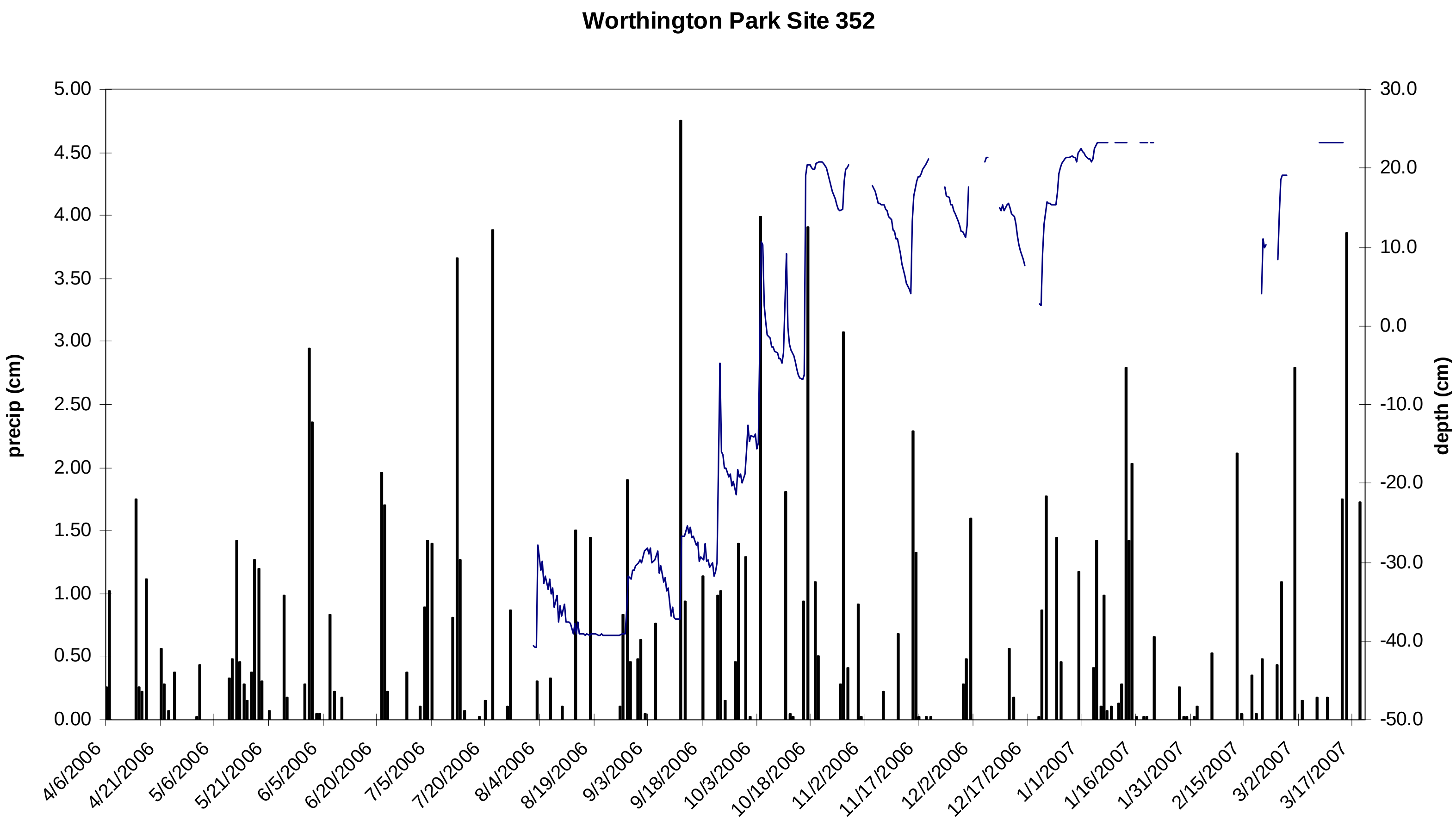

Towne Centre
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


Watkins Road North Site 142A
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


Watkins Rd South Site 142B
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


Wilson Rd Site 409
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


Worthington HS Site 351
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007


Worthington Park Site 352
precip (cm)
depth (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
4/6/2006
4/21/2006
5/6/2006
5/21/2006
6/5/2006
6/20/2006
7/5/2006
7/20/2006
8/4/2006
8/19/2006
9/3/2006
9/18/2006
10/3/2006
10/18/2006
11/2/2006
11/17/2006
12/2/2006
12/17/2006
1/1/2007
1/16/2007
1/31/2007
2/15/2007
3/2/2007
3/17/2007