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Surface-water groundwater interactions in the Middle Rio Grande, NM Implications for bank storage and native species

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Surface-water groundwater interactions in the Middle Rio Grande, NM
Implications for bank storage and native species

By

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Committee Approval

The Master of Water Resources Professional Project Report of **Tom Heller**, entitled **Surface-water groundwater interactions of the Middle Rio Grande: Implications for bank storage and native species,** is approved by the committee:

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Chair	Date
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Abstract

Riparian zones are important for ecological purposes and ecosystem processes, and are valued for aesthetic, recreational, cultural, and historical reasons. The declining integrity of cottonwood-dominated riparian systems in the Middle Rio Grande (MRG) of central New Mexico has been evident for several decades, of which the largest cause has been the severe alterations riparian hydrology. While cottonwood germination responses to changing flood regimes have been well studied, the response to changing groundwater dynamics - and the suitability of groundwater regimes in the MRG - is less well understood. This study used pressure transducer groundwater datasets installed in the Rio Grande riparian zone by the Bosque Ecosystem Monitoring Program (BEMP) to investigate groundwater behavior in the MRG and its impact on bank storage, cottonwood recruitment, and native riparian integrity. A relational database of BEMP's groundwater data was constructed, and its utility was assessed. It was concluded that BEMP's data are largely accurate, with some exceptions. Time series analysis of the data indicated that riparian groundwater responds rapidly to changes in streamflow, and that bank storage is transient and does not extend far from the river channel. This may be caused by agricultural drains, which induce an uncharacteristic permanent hydraulic gradient sloping away from the river. This gradient intercepts bank storage and causes rapid groundwater recessions after high discharge events. At all study sites but one, groundwater recession is controlled directly by the rate of discharge decline, and often exceeded the maximum rate tolerable by cottonwood seedlings. A single successful cottonwood recruitment event in 2009 at one of the sites was captured in the pressure transducer record. Groundwater observations from this event indicate that cottonwood seedlings can tolerate relatively rapid recession rates, as long as these rates are not prolonged, or are interspersed with slower or negligible rates. Ultimately, the primary difference between present day conditions and when large-scale recruitment events occurred is the flow regime of the Rio Grande and loss of high-discharge flood events.

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Introduction

The declining integrity of cottonwood-dominated riparian systems in the Middle Rio Grande (MRG) of central New Mexico has been evident for several decades (Campbell et al. 1964), of which the largest cause has been the severe alterations to the hydrograph of the Rio Grande (Howe and Knopf 1991). While the changing river flow and flood regime in the Middle Rio Grande has been well studied, the nature and suitability of groundwater regimes in the MRG riparian zone is less well understood. Cottonwood trees are keystone species of native riparian zones in the MRG, and their recruitment and integrity are strongly controlled by depth and vertical movements of the shallow water tables accompanying streams. In the Middle Rio Grande, groundwater suitability may be as much of a condition variable in native riparian integrity as flood frequency and magnitude (Stromberg 1993, Mahoney and Rood 1993).

This study investigated groundwater behavior in the MRG by using datasets from pressure transducers (PTs) in the Middle Rio Grande riparian zone installed and monitored by the Bosque Ecosystem Monitoring Program (BEMP). Groundwater behavior was compared to the Rio Grande hydrograph, and was observed and compared seasonally and across different hydrologic conditions. Local-scale transects of the shallow table potentiometric surface were used to depict and analyze bank storage and the depth, shape, and movement of groundwater through time and in response to hydrologic conditions. Associations were made with the morphology of the riparian surface, including the agricultural drains and efforts of active restoration such as bank cutting and artificial channels.

The pressure transducer datasets as collected by BEMP are currently unused, and in a format that is not conducive to examination. Additionally, the accuracy and utility of the data has not been thoroughly evaluated. A secondary goal of this project was to compile the multiple BEMP groundwater datasets and metadata into a relational database that is comprehensive and easier to use. The pressure transducer data was compared to BEMP's on-going monthly readings of groundwater levels taken manually, to assess the accuracy of the pressure transducer datasets. The construction of this compiled, complete database and associated evaluation provides a base for the data's use by BEMP's staff or future students.

Background

Riparian areas are defined as the interface between terrestrial and aquatic ecosystems in river systems (Gregory et al. 1991). As an interface, riparian zones influence lateral energy, nutrient, and moisture fluxes between the bounding terrestrial and riverine systems (Naiman and Decamps 1997). They represent some of the most biodiverse and dynamic systems in arid regions, and serve as important habitats, corridors, and refuges for wildlife. Riparian zones are fundamentally linked with the hydrologic characteristics of the streams they border, and are the result of the "horizontal" interaction of stream systems (Nillson and Svedmark 2002). Periodic flooding waters the floodplain, increases soil moisture, replenishes nutrients, clears debris, and prepares new substrate for seeding. Shallow water tables as induced by the close proximity to the stream channel support phreatophytic species during dry times, which further support understory and complementary vegetation through shading, temperature mediation, and increased surface soil moisture. Due to the tightly coupled nature between streamflow, groundwater, and riparian structure, hydrology is the single most important factor influencing riparian composition, structure, and integrity (Nillson and Berggren 2000).

In the Middle Rio Grande and other southwestern stream systems, cottonwood trees (*Populus fremontii, Populus deltoides* and regional hybrids) are keystone species of forested riparian areas of major rivers, especially in middle and lower reaches (Smith and Finch 2016). Cottonwoods are pioneer species, quickly propagating on newly created substrate during post-flood or post-sedimentation conditions, and their presence and life history define riparian succession (Irvine and West 1979). Cottonwood riparian succession in arid environments has been described as having seven stages (Boggs and Weaver 1994): (1) Fresh sandbar, as prepared by high-discharge flood events; (2) a seedling stage if the floods coincide with seedfall; (3) a sapling stage with some herbaceous undergrowth, often willows; (4) pole-size trees of ages 15-20 years, now with canopy cover and a diverse understory; (5) mature cottonwoods, a stage lasting 40-50 years, and characterized by the pathway's highest amounts of biomass, surface organic matter, and above ground nutrients; (6) cottonwood senescence, occurring at 60-100 years since establishment, when the site transitions into a phase dominated by low woody shrubs; and (7) an arid grass/shrub land.

Today, southwestern riparian systems are among the most threatened ecosystems (Nillson and Svedmark 2002), primarily due to the altered hydrology and flow regulation of rivers, for the purposes of flood control, water supply, and hydropower production (Nillson and Berggren 2000). The primary effect of this on riparian areas has been mediation of flows, reduced flood frequency, reduced lateral movement, and, ultimately, the disconnection between the stream channel and the floodplain (Smith and Finch 2016). Cottonwoods depend on overbank flooding for the clearing of substrate for new stands and germination of seedlings (Mahoney and Rood 1998). Flow manipulations from dams and diversions on the Rio Grande and other southwest streams have reduced or stopped the recruitment of new cottonwood generations (Howe et al. 1991). Most living riparian stands in the MRG are aging and progressing to later successional stages, a rarity in natural riparian regimes (Boggs and Weaver 1994).

Declining native riparian health, altered hydrologic regimes, and a changing climate have led to the proliferation of exotic species in the MRG (Glenn and Nagler 2005). Two significant species are saltcedar (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*); both are highly suited to southwestern stream systems and have spread rapidly (Morisette et al. 2006). While cottonwood can compete effectively with saltcedar under natural hydrologic conditions, saltcedar is advantaged in regulated and altered systems, and in general has greater stress tolerance (Glenn and Nagler 2005).

As phreatophytic, woody pioneer species, saltcedar and Russian olive are capable of replacing cottonwoods as the dominant large woody plant in riparian systems, but there are significant differences in exotic dominated systems which may have broader effects on ecological and ecosystem processes, and many reasons why native systems are preferred. Native areas tend to have higher diversity of plants and animals (Howe and Knopf 1991, Ellis et al. 1994). Stands of saltcedar are dense, and discourage understory vegetation, recruitment of native species, and vegetative heterogeneity (Howe and Knopf 1991). Saltcedar litter increases soil salinity and acidity, which further hinders native species recruitment (Ladenburger et al. 2006). Exotics may also significantly disrupt nutrient cycling in riparian soils (Simons and Seastedt 1999,). All these factors may further encourage diversity losses and spread of invasive species as the system shifts to different successional, structural, or nutrient regimes. Saltcedar invasion enhances fuel load, increasing fire frequency and intensity (Mandel et al. 2011). Finally, native riparian systems are desired for their recreational value, aesthetics, and historical and cultural significance. In the Middle Rio Grande, the riparian area is colloquially called the Bosque (Spanish for “forest”), and the region’s endearment to this system is evident in that it serves as the namesake for local schools, streets, parks, and a brewery.

Riparian groundwater

Groundwater in riparian areas is controlled by river stage, topography, regional aquifer levels, and vegetation evapotranspiration. High river stages and flood events result in a groundwater ridge – bank storage – that recedes slowly due to vertical anisotropy of floodplain soils. Shallow water tables are strong controls on surface soil moisture of riparian areas. Capillary forces above the water table convey water upwards, significantly enhancing surface soil moisture even with deep water tables. The degree of this interaction is a function of soil type and water table depths (Miguez-Macho et al. 2008).

After overbank flooding, water tables in a natural system recede slow enough to maintain advantageous soil moisture, and high river stages induce high water tables during non-flooding periods.

In addition to overbank flooding, cottonwood recruitment and health depend on specific groundwater conditions. These conditions have likely similarly been altered by regulation of river flow and channel morphology. The importance of specific groundwater conditions for cottonwood recruitment is evident by the fact that recruitment events have often failed at times even when suitable flooding events have occurred (Howe and Knopf 1991). Cottonwoods are adapted to and require the natural variations and conditions of groundwater levels as induced and controlled by un-altered stream hydrographs (Cooper et al. 1999). After establishment via overbank flooding, a slowly receding water table encourages the deep growth of cottonwood taproots. In natural riparian settings, cottonwoods are obligate phreatophytes, so the ability to reach the water table is essential. After germination during overbank flooding, the maximum rate of groundwater recession that cottonwood seedlings can accommodate has been experimentally shown to be 4 cm/day (Mahoney and Rood 1993), but this largely depends on local conditions of climate and soil type, and slower recession rates are more beneficial (Segelquist et al. 1993).

As there are no accurate and high-resolution groundwater records from the time before the Rio Grande became heavily managed, these groundwater requirements of cottonwoods provide a link to the nature of pre-development behaviors and properties. Because of the historical presence of cottonwood stands in the Middle Rio Grande riparian zone, it can be inferred that water tables here were shallow, their movements subdued, and their recessions slow. However, just as in a natural riparian setting we would not expect cottonwood recruitment events to be possible everywhere, the associated groundwater dynamics would not be expected at every reach or for every landform. However, the maximum tolerable groundwater recession rate of 4 cm/day, while experimentally derived and not applicable to all settings, can serve as a good benchmark from which to compare observed groundwater behavior.

All riparian species take advantage of soil moisture as induced by shallow water tables, especially during dry periods. Cottonwoods do as well, as the trees generally only become fully phreatophytic after several years of growth, and the consistent moisture reduces drought and heat stress of establishing seedlings and saplings (Cooper et al. 1999, Mahoney and Rood 1993).

In post-regulation riparian systems, the rare flooding events may no longer induce responses in water table elevations to which riparian species are adapted. Engineered incision of the Rio Grande main channel, pumping of the regional aquifer, and agricultural drains bordering the length of the floodplain have likely decreased the level and altered the shape and behavior of the immediate shallow aquifer. The depths to water table for many riparian landforms have likely permanently increased, and bank storage may be receding too rapidly to induce surface soil moisture or cottonwood recruitment. This change may be due to reduced river flows, channelized streambeds, municipal groundwater pumping, and agricultural drains. The drains have the intended effect of draining groundwater at quicker than natural rates in the agricultural areas they service, and this pattern may also be occurring in the riparian area. In the MRG as in other southwest stream systems, the alteration of natural groundwater levels and behavior has led to the desertification of riparian zones, especially in upland areas or those farther from the stream channel (Stromberg et al. 1996).

Overbank flooding has been artificially encouraged in recent years for the facilitation of species habitat and riparian restoration, but unless advantageous groundwater conditions are present, recruitment and long-term integrity of native riparian species may be unsuccessful. For the same reasons, manual planting of cottonwood trees may be ineffective as a restoration effort when local water table levels are not considered. Suitable groundwater behavior is still necessary for riparian stands in managed areas, as evidenced by the fact that manual addition of water to the surface has little effect on cottonwood productivity (Cox et al. 2005).

Previous Work

Several studies have analyzed surface water - groundwater interactions in the MRG, some of which are summarized here. Isaacson (2009) used BEMP data along with several hydrologic modeling platforms to create large-scale groundwater surface elevation maps of the MRG riparian area, as controlled by Rio Grande discharge. Part of the study involved comparing this model to experimental depth-to-groundwater requirements of cottonwoods, which found that the areas furthest from the main channel exhibited groundwater levels unfit for cottonwood health. Faiza (2011) also modeled surface water/groundwater interactions in the MRG, in a localized area near a constructed wetland. Lejuene (2008) used BEMP data to create short-term time series visualizations of local well sites to investigate groundwater response to the construction of a diversion dam, altering dam configurations, a rain event, and river surface fluctuations. The study indicated that groundwater levels are tightly coupled with river surface elevations, disturbances are short lived, most reaches of the MRG are usually losing reaches, and that wells in close proximity can exhibit discernibly different groundwater behaviors. It also made brief observations of the depth to water table in some circumstances, as compared to cottonwood requirements. Samson (2012) created a groundwater model based on field observations to analyze bank storage behavior at a MRG site during different hydrology conditions. He concluded that bank storage is quite transient due to alterations made to the hydrologic system.

Worthington (2013) conducted a study similar to this project, using data from monitoring wells installed by the USGS and monitored from 2003 to 2011. The study examined the potentiometric surface and hydraulic gradients across several transects of the Middle Rio Grande. Worthington concluded that hydraulic gradients primarily drove groundwater flow away from the river channel and are controlled by Rio Grande discharge, and possibly also by vegetation density. While the river stage was universally shown to be a strong boundary condition, the opposite drain channels are only connected with floodplain water tables at certain locations, and during certain seasons. This depends on the depth of the drain channel and its proximity to the river channel.

These studies provide valuable insight into the nature of water table elevations in the riparian MRG. Further knowledge of MRG riparian groundwater will help inform policy decisions regarding stream management and restoration efforts, and can help avoid wasted effort and resources. This will lead to better-targeted restoration efforts, and the identification of areas which may be better left to shift away from a cottonwood dominated regime or be replaced with a novel yet still desirable system.

Study Area

The study areas for this project were in the riparian zone of Albuquerque and Belen reaches of the Middle Rio Grande in Central New Mexico (Fig 1). This stretch of the Rio Grande is heavily managed, confined, and subject to pressures from urban and agricultural sectors. The natural flow regime has been highly altered by multiple policy and infrastructural choices, the most significant of which was the construction of Cochiti Dam in 1973 for flood control (Fig 2). The width of the active floodplain/riparian zone in the study area – several kilometers wide in pre-management eras – has been narrowed to between 300 and 800 meters. Seasonal discharge patterns are dominated by spring snowmelt and late summer monsoons. Streamflow of the Rio Grande in this area ranges from 0 to ~6000 ft^3/s (cfs) currently. Due to river management and diversion, the riparian zone of these reaches of the Rio Grande has experienced separation from the stream channel, desertification, and declining integrity and recruitment of native species (Crawford et al. 1993, Howe and Knopf 1991). Levees and agricultural drains managed by the Middle Rio Grande Conservancy District (MRGCD) border both sides of the narrow floodplain.

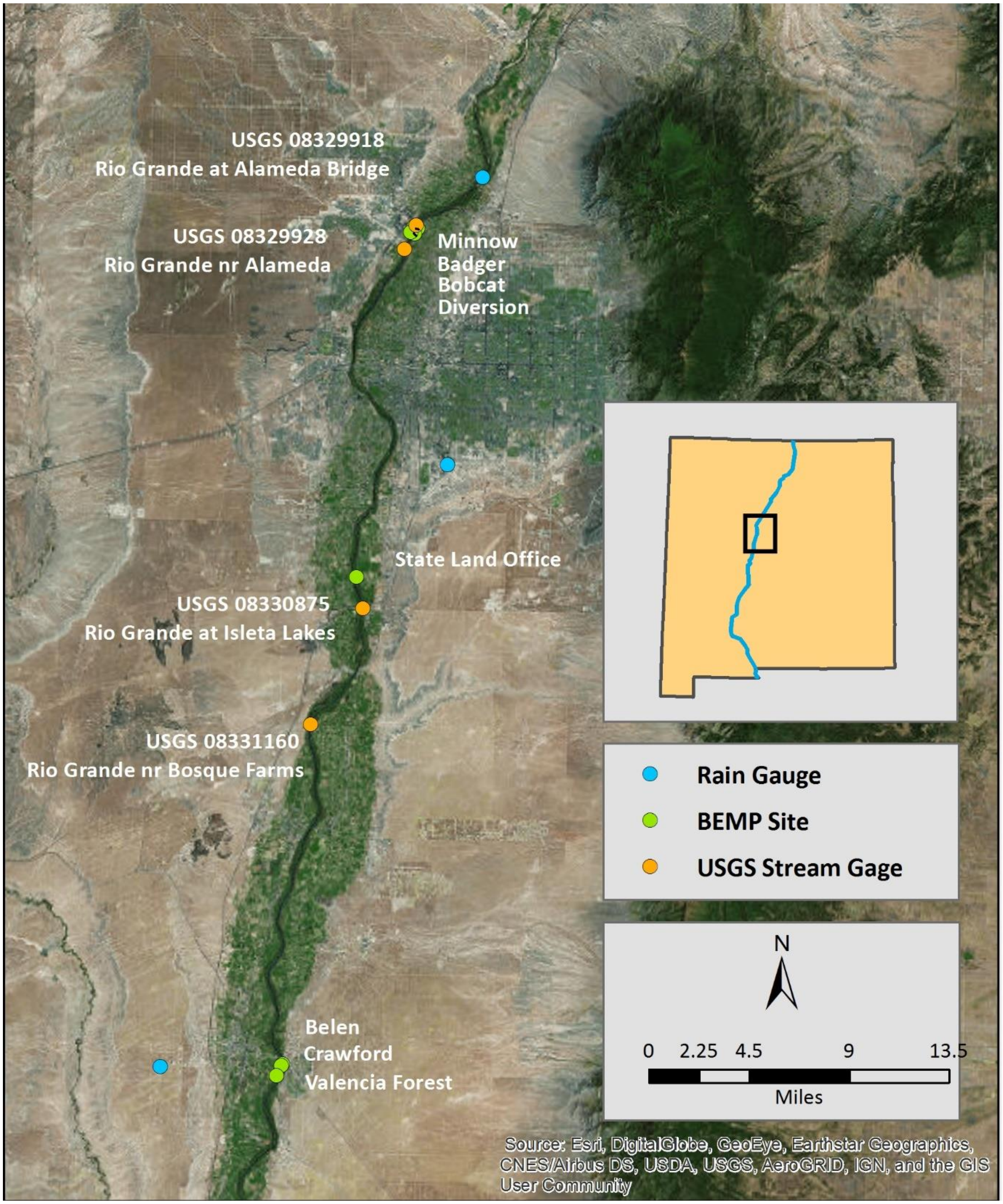


Figure 1. Study area, Middle Rio Grande, New Mexico, including BEMP sites with PT data, USGS streamflow gages, and precipitation gauges.

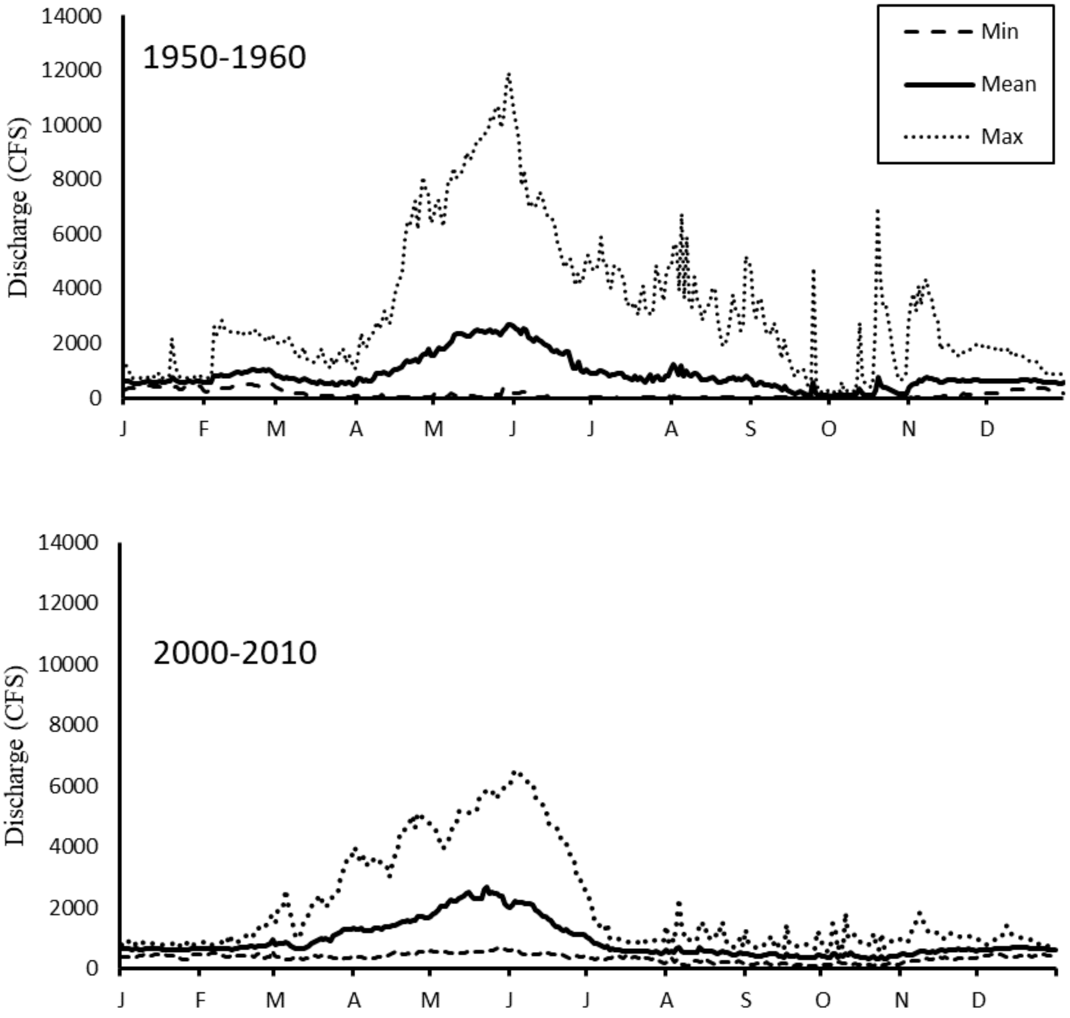


Figure 2. Mean, min, and max of 10 year periods of daily discharge of the Rio Grande in the Albuquerque reach, before (top) and after (bottom) major flow management via the construction of Cochiti Dam in 1973. (Data from USGS Gage 08329918 Rio Grande at Alameda B)

Study Period

Potential study periods and events were constrained by data availability. Data collection at the earliest PT sites began in 2006, with the last site beginning PT recordings in 2015. Several of the sites have at least one operating PT well with continuous data from 2013 to 2018; these were used for general observations of long-term trends. As a particularly wet year with a strong spring runoff and an active monsoon season, 2017 was examined in closer detail, with a focus on the spring and late summer seasons. High river-stage/water-table events from across the study period were examined and compared.

Data Sources

Depth to water table and water table elevations

The Bosque Ecosystem Monitoring Program (BEMP) is a collaborative program between the Biology Department of the University of New Mexico (UNM) and the Bosque School, a preparatory school in Albuquerque that focuses on natural science education and citizen science participation. BEMP formed after a report from a multiagency group of Rio Grande stakeholders assessing the biological resources of the MRG (Crawford et al. 1993) and was tasked with monitoring broad ecological variables of the MRG riparian areas. This has included recording ecological and groundwater depth data at many sites along the MRG. Ecological data that BEMP collect include litterfall, vegetation cover, cottonwood diameter, and other parameters. Monitoring data are collected by students and volunteers, with oversight by BEMP's staff.

Depth to groundwater is measured monthly at all sites by BEMP staff and/or supervised volunteers. Each site is configured with five groundwater monitoring wells approximately 40 meters apart in a cross pattern, designated East, West, North, South and Center (Fig 3). Eight sites - four in north Albuquerque, one in south Albuquerque, and three in Belen - are equipped with pressure transducers (PTs), which record temperature-corrected absolute pressure head in units of length every 30 minutes. A barometer logger accompanies the monitoring wells at each study area, in order to correct for effects of atmospheric pressure above the well.

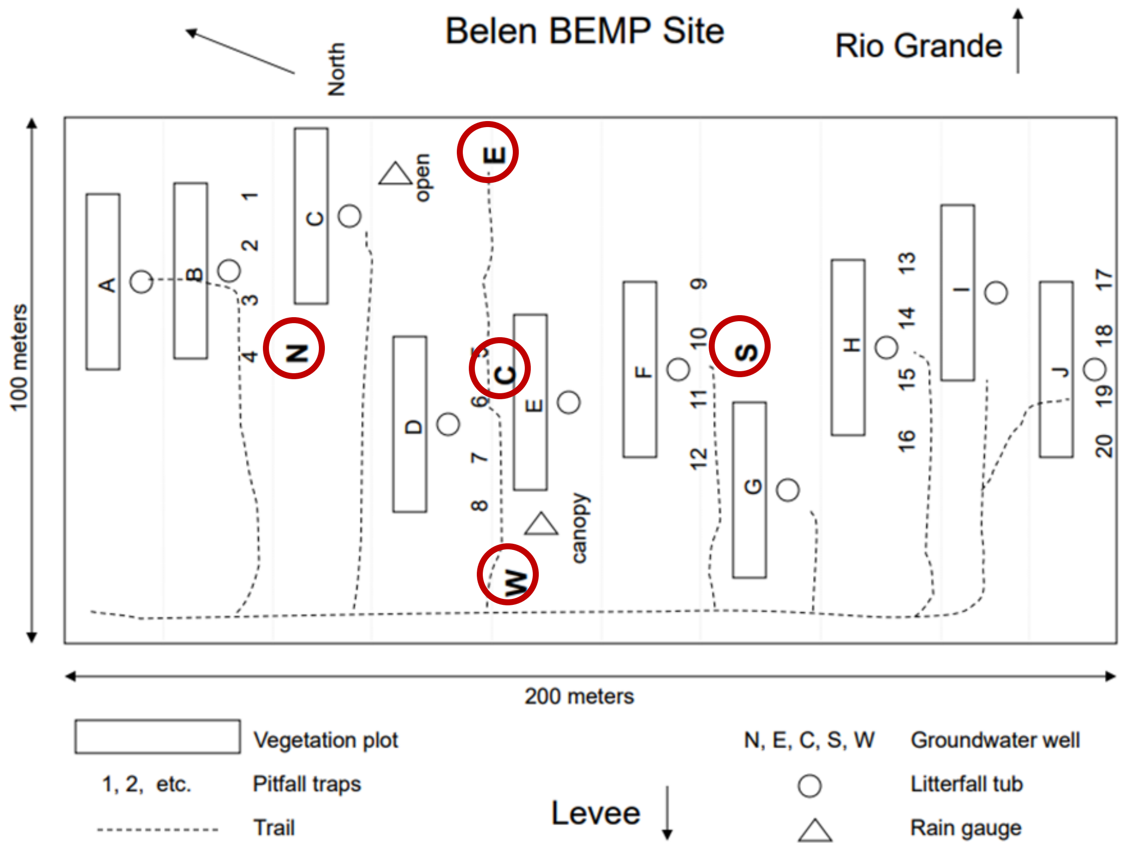


Figure 3. Example layout of BEMP monitoring sites. Groundwater monitoring wells are notated as N, E, C, S, W, indicated by a red circle. (Adapted from BEMP.org 2018)

Sites with pressure transducers are the focus of this study. These are described in more detail in the following section. Since 2008, the PT data have gone largely unprocessed and unanalyzed since their collection. These data were used in this study to investigate riparian groundwater behavior. The 30-minute readings of pressure head allow for high temporal resolution depiction of water table movements, important for determining response and recession times. Because of incomplete or inaccurate data, not all sites are included in analysis of the PT data in this project.

Most, but not all, of the BEMP PT sites have been professionally surveyed. The Crawford site near Belen and the State Land Office site in southern Albuquerque have not been surveyed, so have no associated location or elevation parameters.

Rio Grande streamflow

USGS streamflow data were retrieved from http://waterdata.usgs.gov to compare Rio Grande discharge and gage height to observed groundwater behavior in the riparian zone. Specific gage locations were chosen to best reflect streamflow conditions at each study site (Fig 1). USGS 08329918 Rio Grande at Alameda Bridge at Alameda, NM was used for North Albuquerque sites upstream of the Albuquerque Bernalillo County Water Utility Authority diversion dam. USGS 08329928 Rio Grande near Alameda, NM was used for North Albuquerque Sites downstream of the diversion dam. USGS 08331160 Rio Grande Near Bosque Farms, NM was used for Belen sites, and USGS 08330875 Rio Grande at Isleta Lakes near Isleta, NM was used for the South Albuquerque site.

Precipitation

Even in an arid climate such as the Middle Rio Grande, local rain is a possible source of recharge to riparian zones, and can influence water table levels and movements. Precipitation data from gauges near each study site were used for selected time periods to assess this interaction (Fig 1). For North Albuquerque sites, data from the Sandia Lakes gauge #SNLN5 were used. This gauge recorded accumulated rainfall over the study period. The data were transformed for this project to daily accumulations. For the South Albuquerque site, data from the National Weather Service operated Albuquerque International Airport #KABQ gauge were used. For the Belen sites, gauge #KE80 at the Belen Alexander Municipal Airport were used. These two gauges measured daily accumulation over the study period. All precipitation data were retrieved from http://mesowest.utah.edu.

Elevation and topography

With the exception of two sites – Belen and State Land Office - all BEMP PT sites have been professionally surveyed, including elevation, using the NAVD88 datum. Due to ecological significance, depth to water table is predominantly the metric used in this project to describe the shallow aquifer, but elevation above sea level is used in some circumstances, particularly when constructing transect profiles. To assess the floodplain morphology of sites, and to put groundwater elevations into a floodplain context, LiDAR data were retrieved from http://earthexplorer.usgs.gov. LiDAR data were collected in 2010, and are available for all sites excluding Bobcat. The point data were filtered for ground and surface water, and converted to 1 meter DEMs in ArcGIS, which were used to construct transect elevation profiles at each site corresponding to East, Center, and West BEMP PT wells. Values recorded in the river channel and drains are of the water surface at the time of survey, not ground surface. In some circumstances, and perhaps due to inconsistent elevation datums, the LiDAR DEM reported elevations that were higher than recorded NAVD88 elevations at the sites. In these cases, a correction factor was applied to match the recorded elevations of BEMP wells.

Study Sites

BEMP installed six monitoring sites bracketing the San Juan Chama Drinking Water Project diversion dam operated by the Albuquerque Bernalillo County Water Utility Authority in North Albuquerque, NM. The dam became operational in 2008, and these sites were used to assess the impact on the local ecosystem. Four of the sites, Diversion, Bobcat, Minnow, and Diversion, are equipped with pressure transducers. These are located upstream and downstream of the diversion dam, on both sides of the river (Fig 5). These sites were installed in the early 2000s, and equipped with pressure transducers in 2006 (Eichhorst et al. 2012). After construction of the dam, the area experienced a 9-month disruption in water tables, but soon returned to pre-dam levels (LeJeune 2008).

These sites generally do not experience overbank flooding, and are generally considered hydrologically disconnected from the river. Sediments here are mostly alternating strata of poorly graded sands and clays (LeJeune 2008).

Diversion: The Diversion site is located on the east side of the Rio Grande, just south of the diversion dam, and bounded to the east by the Albuquerque Riverside Drain. It is morphologically characterized by a steep river channel, and relatively high landforms, with an average depth to groundwater of 200+ cm since readings began. The area is sparsely vegetated, with some pole planted cottonwoods, but in general, the area is experiencing a decline in cottonwood canopy and an increase in exotic vegetation (Fig 4). It is one of the few BEMP sites where exotic litterfall is greater than native litterfall. Some flooding occurred here in the spring of 2017, but with low extent and no cottonwood recruitment has been observed since that flooding.

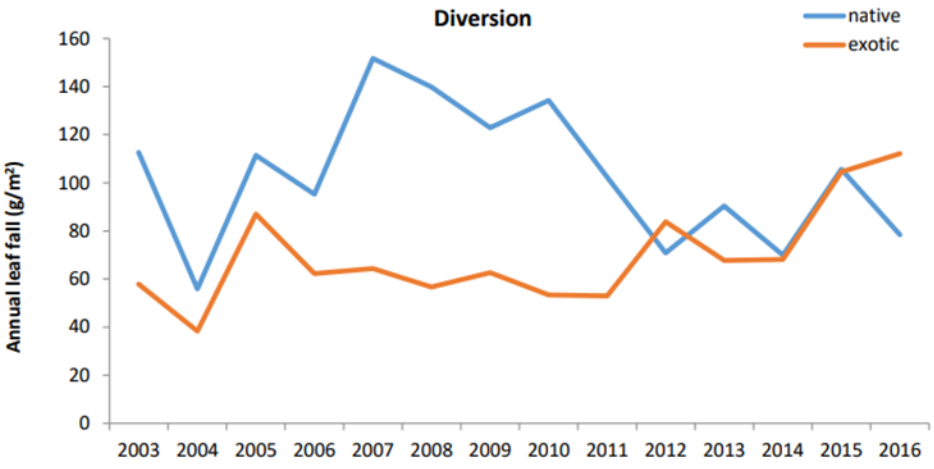
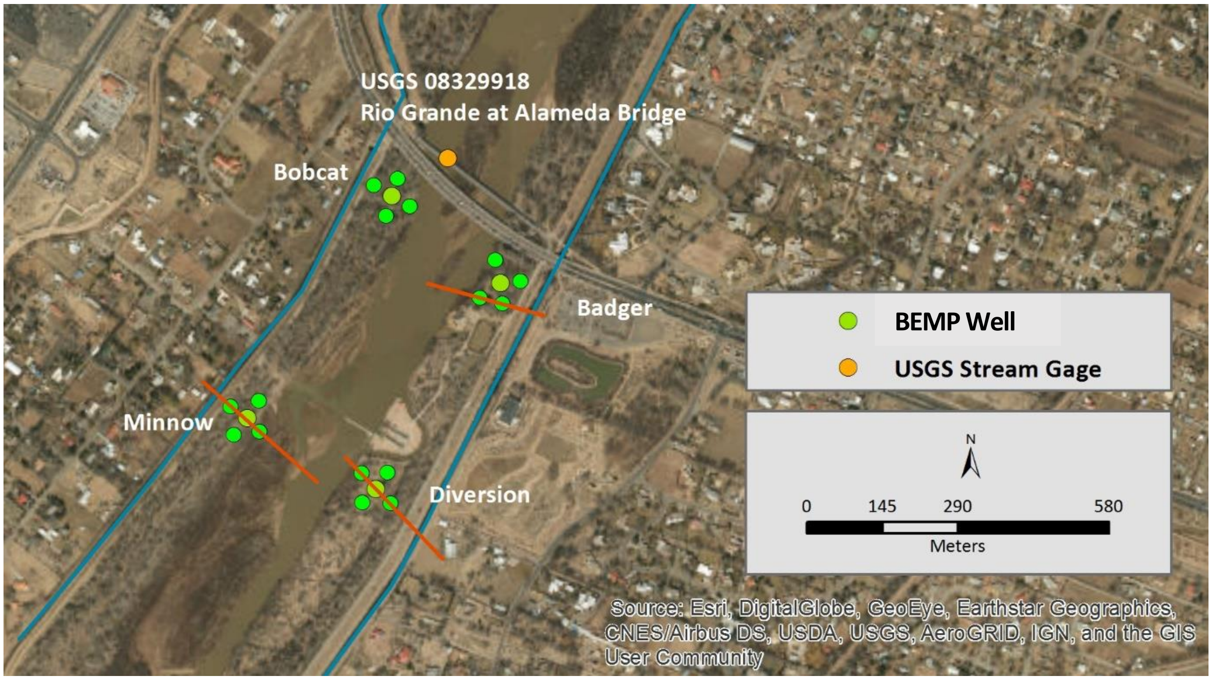


Figure 4. Native and exotic litterfall at the Diversion site from 2003 to 2016. (From Eichhorst et al. 2018).

Badger: The Badger site is located north of the diversion dam, on the east side. Like Diversion, it is bounded to the east by the Albuquerque Riverside Drain. It is characterized by relatively high landforms, a steep channel bank, and average depths to groundwater of ~250 cm. Badger is mostly a cottonwood-dominated forest with some elms.

Bobcat: Bobcat is located north of the diversion dam on the west side of the river, bounded to the west by the Lower Corrales Riverside Drain. In 2004 and 2011, dead trees and exotics were removed and mulched, and the area is today a cottonwood-dominated system with some Goodding willows. This site generally has lower landforms, with an average depth to groundwater of 100-150 cm.

Minnow: The Minnow site is located just downstream of the diversion dam on the west bank, bounded to the west by the Lower Corrales Riverside Drain. This site has lower elevation landforms, and a gentler channel bank. The site is on the edge of what was the active channel before operation of the diversion dam began. The decreased and altered flows downstream of the dam have caused the west area of the previous channel to be exposed most of the time. Average depth to groundwater is 100-150 cm, and the site is characterized by a cottonwood – willow forest. This site has had exotic tree removal, mulching, and pole planting.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5. Map and imagery of North Albuquerque wells and transect lines.

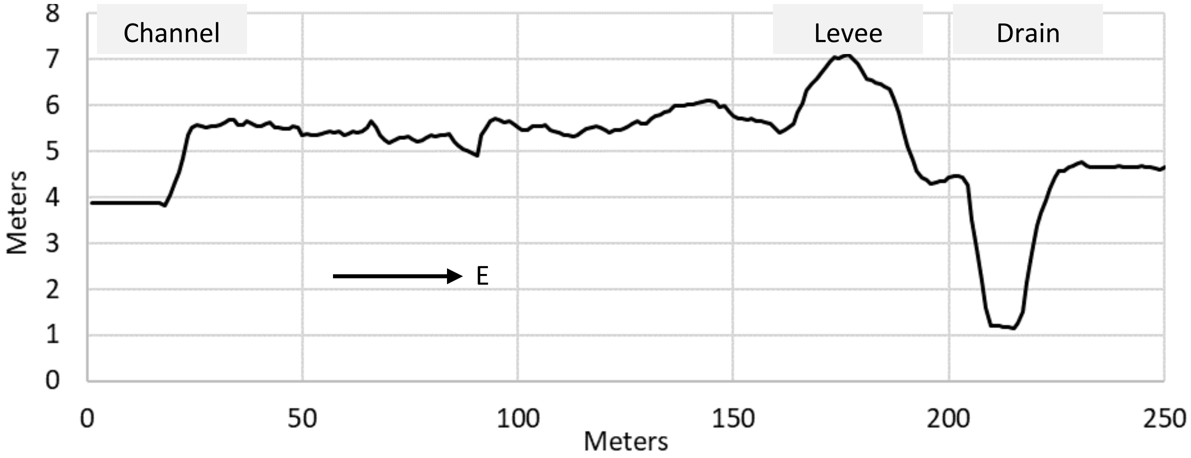


Figure 6. Diversion site E-W transect topographic profile (see figure 5 for location).

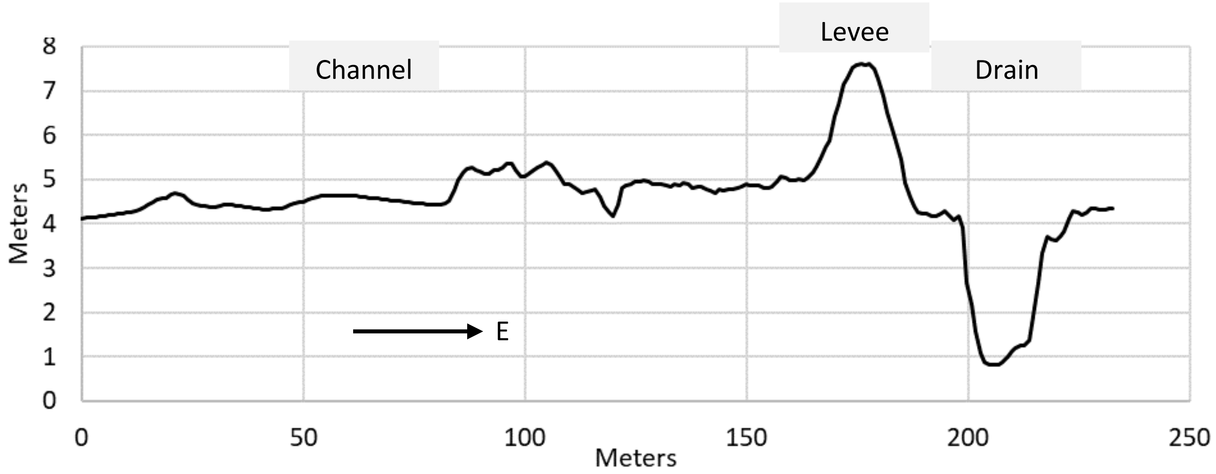


Figure 7. Badger site E-W transect topographic profile (see figure 5 for location).

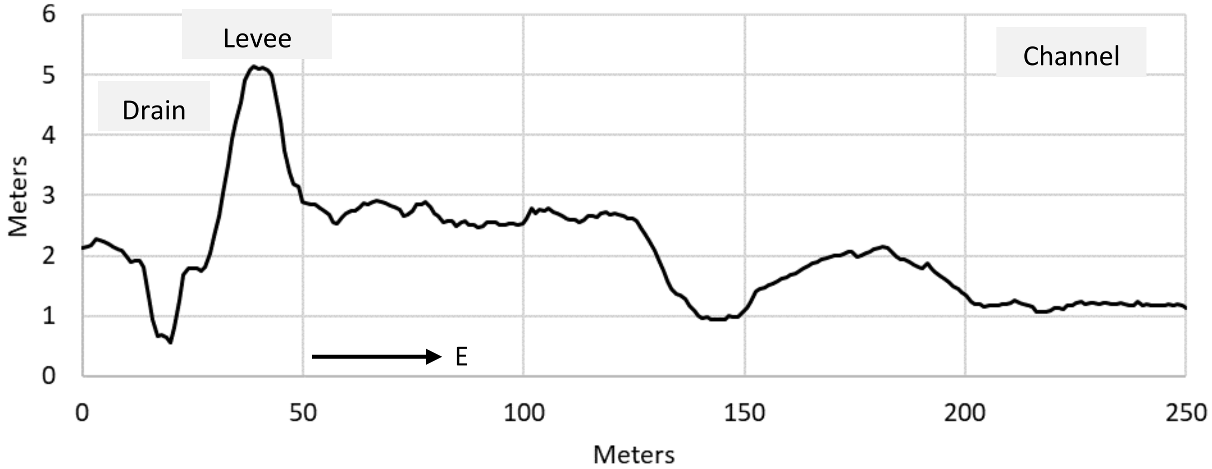


Figure 8. Minnow site E-W transect topographic profile (see figure 5 for location).

Three sites near Belen, NM - Belen, Crawford, and Valencia forest - are located in relatively close proximity, all on the west side of the Rio Grande near the town of Belen, NM (Fig 9). Generally composed of lower terraces and landforms, the sites are considered by BEMP to be fairly well hydrologically connected with the river channel. All three sites are bounded to the west by the Belen Riverside Drain.

Belen: The Belen site was one of the first BEMP monitoring sites, initiated in 1998, and pressure transducers were installed in 2009. Landforms are generally low elevation relative to the stream channel, with an average depth to groundwater of ~100 cm. The site experiences periodic flooding, and is characterized by a relatively young (~20 years) cottonwood forest, with few exotics. The site experienced overbank flooding in 2017.

Crawford: This site was initiated in 2008 as part of the Collaborative Forest Restoration Program, a USGS program for funding forest restoration projects. The site experienced a severe wildfire in 2007 which killed most of the existing cottonwood forest, and it was cleared of exotics afterwards. In 2009, the Interstate Stream Commission lowered a large area of the site's banks and terraces, to create a backwater area designed to flood with river flows > 2500 CFS (Eichhorst et al. 2012). It is bound by both a riverside drain and an acequia ditch on the west side. After flooding in 2009, the new substrate was populated by cottonwoods in lowland areas, and saltcedar in the uplands. The site is considered well connected hydrologically with the river, with water tables generally less than 1 meter deep, and experienced overbank flooding in 2017. This is one of the sites without location or elevation data.

Valencia Forest: Originally composed of a mix of cottonwood, saltcedar, and Russian olive, a 2007 fire and subsequent clearing has left this site mostly dominated by exotic weeds. Generally low lying, the site has average depths to groundwater of ~150 cm.

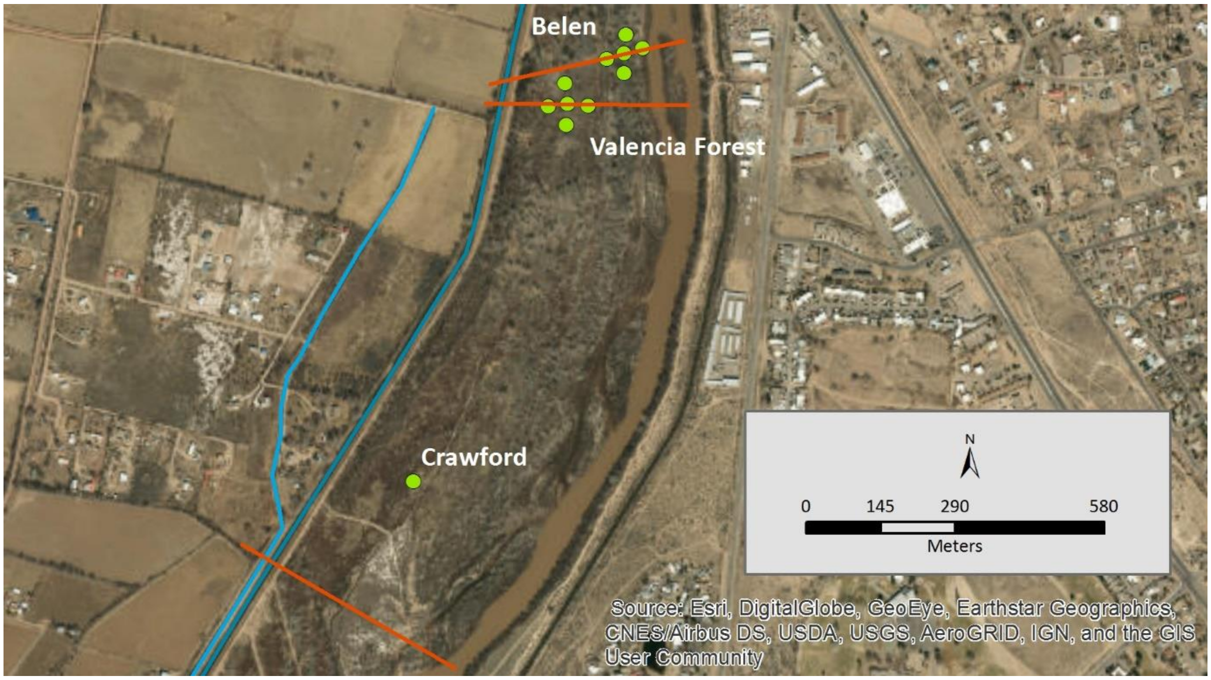


Figure 9. Map and imagery of Belen wells, transect lines, and relevant drains and ditches. Individual Crawford wells at have not been surveyed as of 2018.

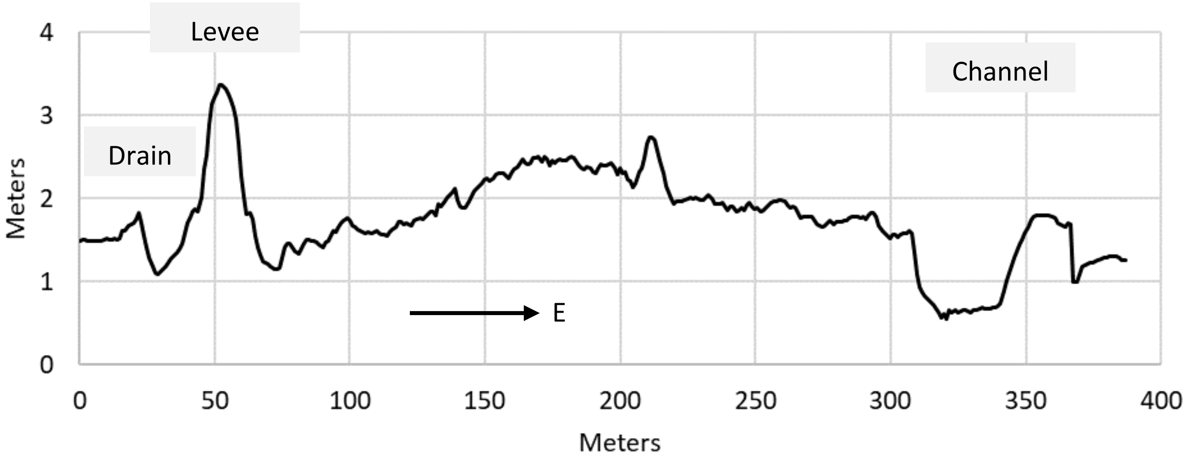


Figure 10. Belen site E-W transect topographic profile (see figure 9 for location).

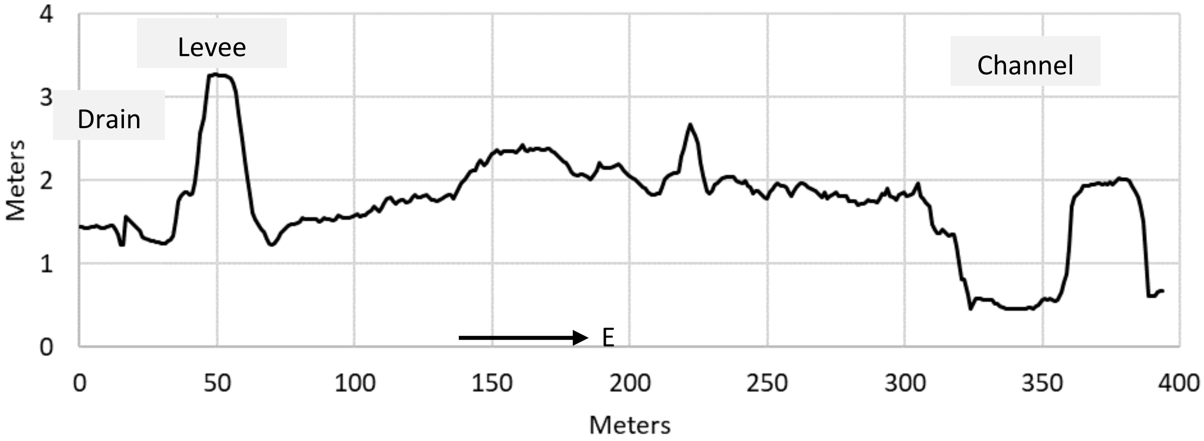


Figure 11. Valencia Forest site E-W transect topographic profile (see figure 9 for location).

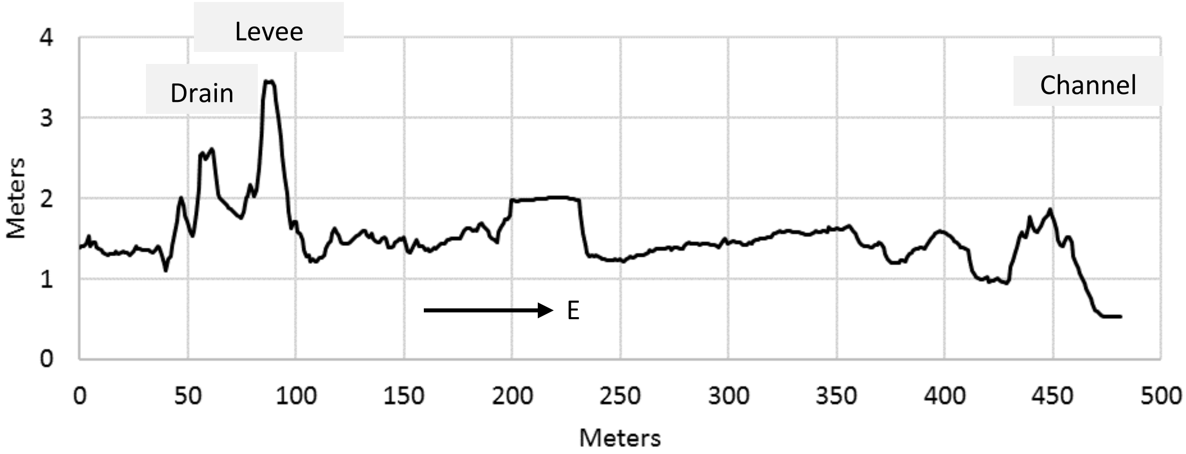
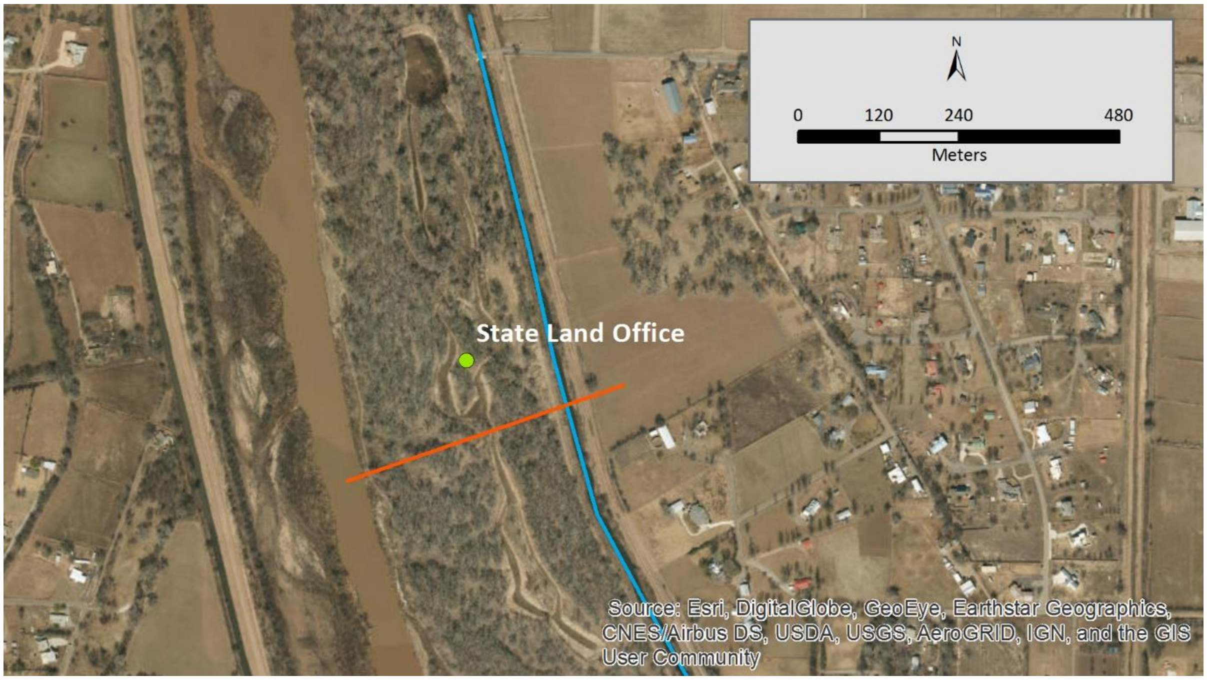


Figure 12. Crawford site E-W transect topographic profile (see figure 9 for location).

State Land Office: One of the most recent BEMP monitoring sties, the State Land Office site was established in 2014 near the Valle De Oro National Wildlife Refuge. The site is on the east side of the river and bounded to the east by the Albuquerque Riverside Drain. The site is predominantly a mature cottonwood forest, with some exotic weeds. Deep channels and pools were dug into the riparian zone in this area to facilitate the creation of wetlands. These channels are not directly connected to the stream channel. Because the restoration occurred after the LiDAR data were collected, the constructed forms are not represented in the topographic profile.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 13. State Land Office site imagery and map. Constructed channels and pools are visible. Individual wells have not been surveyed as of 2018.

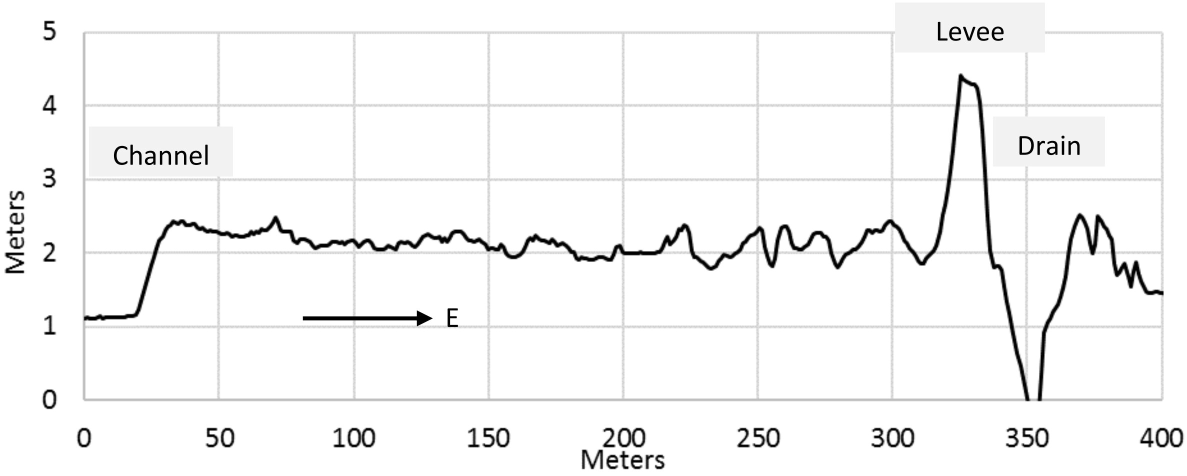


Figure 14. State Land Office E-W transect topographic profile (see figure 13 for location), prior to restoration (see figure 13 for location).

Data Management

Since BEMP's pressure transducer data were last used for study by LeJeune (2008), BEMP staff have collected the data annually each fall/winter. Raw data from each well are manually retrieved and downloaded from the pressure transducer on site. Data are converted from the vender format into Microsoft Excel spreadsheets. Due to evolving staff and other limitations, the format and classification structure of the Excel spreadsheets has often changed from season to season. Likewise, due to time limitations of BEMP staff, the spreadsheets had not been compiled, and remained as separate files for each well and season. Data from prior to 2008 were additionally stored in a unique format by LeJeune. Consequently, by 2018 when this project was started, the raw PT data were split between 250+ Excel spreadsheets of varying format and classification. All of these PT datasets were uncorrected for atmospheric pressure, as barometer readings were stored in separate files. Additionally, all well parameters such as location, elevation, casing height, and cable length were stored in several separate files. The fragmented nature of the data and large number of files made analysis difficult, unwieldy, and prone to user error. Additionally, it was difficult to establish which time periods the data were available for. The raw data had also not been assessed for quality control or accuracy. Manual readings of depth to water table were taken by BEMP staff each time the PT data were collected, with the expectation that the manual readings would be compared to a calculated depth to groundwater. However, this comparison was not done for every season, and if so, wasn't recorded along with the dataset. A single comparison point each season may also not sufficiently gauge the accuracy of a pressure transducer, as readings may fluctuate through the year and can be temperature sensitive. The amount of work necessary to retrieve data, join with well parameters in order to make a useful output, and assess its accuracy inhibits the use of this data. Furthermore, without a proper database or protocol for storing incoming PT datasets each season, the effort needed to create one increases every year. A primary goal for this project was to initiate such a database and assessment of the PT data, for this own project's analysis, and for use by BEMP staff and future students.

The initial task was to determine the ranges that data for each well were available and to create a reference for these timeframes. This was done by plotting each spreadsheet's start and end dates in a timeline (Fig 15). From this, it was evident that there are sizeable time gaps in the datasets, and not all wells were operating the entire period (it had been known to BEMP that some wells had stopped functioning). Besides the most recently installed pressure transducers at the State Land Office, no site had all five pressure transducers still operating at the start of 2018. It is also evident that no PT data were collected for the 2010 and 2012 seasons. The Diversion site is the most complete dataset besides State Land office, with four of its five original pressure transducers still recording data. Badger, Minnow, and Valencia Forest only have one pressure transducer still operating, and the last PTs at Belen ceased operating in 2015. These gaps constrain the time periods and type of analysis that was possible. For example, all three East, West, and Center wells of a site would need to be operating concurrently for a suitable groundwater surface transect to be made. Only the State Land Office and Diversion sites have East, Center, and West wells currently operating, though some sites have data for the three during past years.

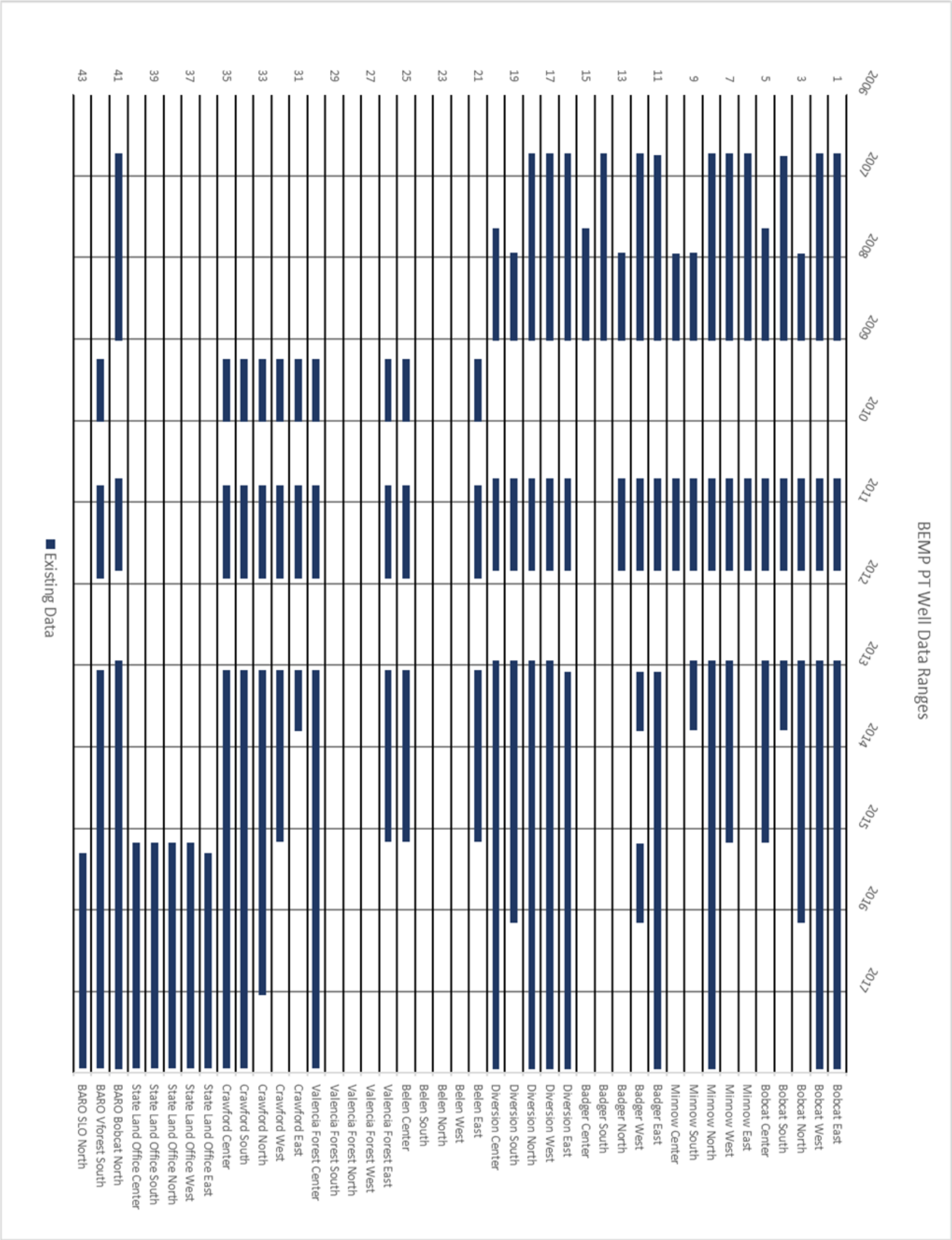


Figure 15. Time ranges of data availability by well.

Prior to this project, the PT data were in separate datasets split by well and season, in a raw format of uncorrected pressure head, and not merged with any well parameters such as casing height or cable length, parameters necessary to extract depth to groundwater or elevation. For this project, a database was built which included all data and parameters in a single archive. The database design had several goals: (1) to be able to output functional data for a user-defined PT well and time range, (2) to automatically correct for barometric pressure and calculate depth to groundwater or groundwater elevation, and (3) to be simple to retrieve data and append new datasets. A long form, relational database was determined to be the best format for accomplishing these goals. Relational databases are comprised of multiple tables, related to each other by selected identifying variables. Because of its ubiquity and relative ease of use, Microsoft Access was chosen as the platform with which to build the relational database.

Wells were assigned a four letter ID, comprised of a three letter abbreviation of the site name and a letter for the well location (E, W, N, S, and C). Each 30-minute recording of pressure head from all PT wells were inputted into a table with a unique pressure transducer ID (PT ID) and timestamp. Barometric logger readings were added as a separate table. Static variables including latitude, longitude, elevation, cable length, and the associated barometer used were compiled in another table, to be related to the pressure recordings by PT ID. Casing-height is a variable that for most wells has fluctuated over time due to maintenance or vandalism, and has been tracked and recorded well by BEMP staff. All casing-heights through time were inputted as a long form table, to be related to other tables by PT ID, year, and month. BEMP's monthly depth-to-groundwater readings for the respective wells were also added as a separate table, using PT ID and timestamp for unique values. Timestamps were entered as separate fields in order to make relationships easier (these can be formed into unified timestamps of any format in the output queries). To conform to the data structure as used in the database, all datasets were transformed before entering using Excel and R. As of summer 2018, the database contains over 6000 BEMP monthly data points, 370,000 barometer readings, and almost 4,000,000 uncorrected pressure head records.

Once all datasets had been imported, several queries were designed for output of user-defined data ranges. These include queries for depth to groundwater, groundwater elevation (for surveyed sites), pressure head and atmospheric pressures, and a query for comparing the PT data to monthly data collected by BEMP. Queries used table relationships to retrieve the appropriate data and well parameters (Fig 16). All calculations and corrections (Fig 17) are written into the queries, so a user only needs to enter the desired well and date range to return ready-to-use data from the selected query. A full description of the database and instructions for its use are in Appendix A.

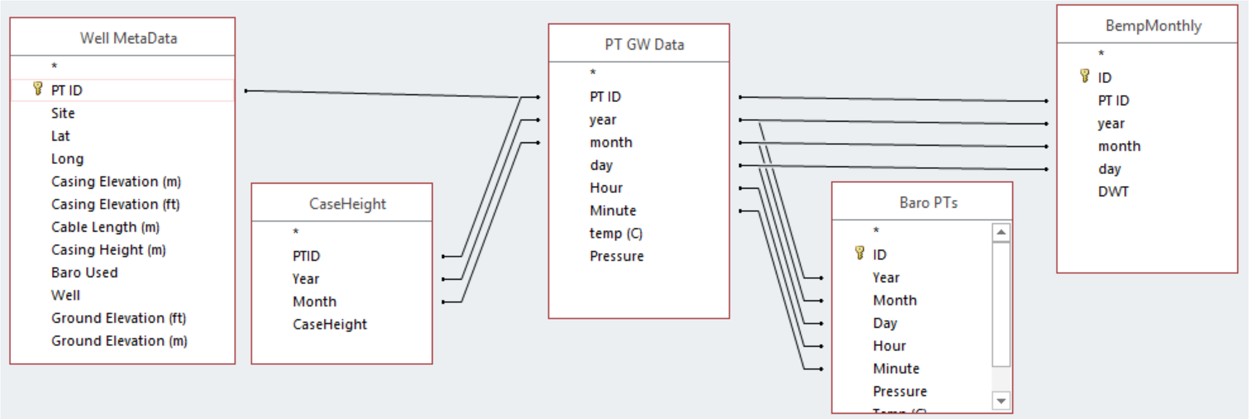


Figure 16. Table relationships used in the query for comparing PT and BEMP Monthly depth to ground water measurements.

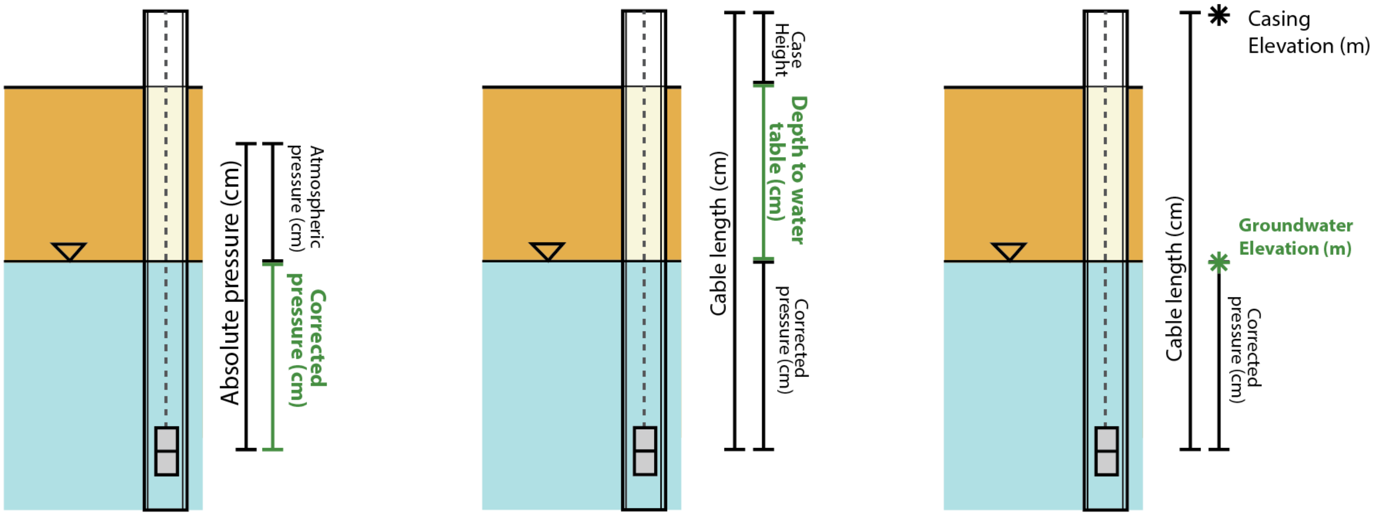


Figure 17. Diagram of corrections and calculations used in the database queries. Outputted values are in green.

Data validation and utility

As the PT data collected since 2008 have not been used or assessed, an examination of the data for accuracy and utility was performed. The PT dataset has not been filtered for quality control, and every PT well includes some spurious values. In most cases, these represent only several 30-minute readings over the entire range, and can be easily identified and deleted on the fly during analysis without significant loss in data resolution. However, for broader assessment of the utility of the PT data, it needed to be verified in some way by manual readings.

BEMP staff collected manual readings of depth to groundwater at each well once a year during data retrieval, but these readings have often not been retained. Fortunately, BEMP includes depth to groundwater readings at all monitoring sites and wells as part of their monthly monitoring. These readings provide for an appropriate dataset with which to compare the PT recordings, and provide higher temporal resolution than the yearly checks would have. The monthly data were retrieved from the BEMP website, and inputted as a table in the PT database. A query was designed to compare the BEMP readings and the calculated depth to groundwater from the associated pressure transducer on the same day as the BEMP measurement, at 12:00 PM. This time was chosen as an approximation of when BEMP staff or volunteers are typically in the field. The query outputs depth to groundwater from both data sources, and the difference between the two. Considering the ranges and behaviors of groundwater measurements in the study area, and the goals of this project, a difference of less than 5 cm is considered a confidently accurate reading.

Comparing time series plots of depth to groundwater from both datasets illuminated how well the two measurements corresponded. Depending on well, the similarity between the two datasets can be characterized as highly similar (Fig 18), dissimilar but correctable, dissimilar and not easily correctable, or unusable. Similarity also often changes over time, for reasons that will be discussed at the end of this section. A time-series of the difference between the two datasets can also indicate whether a dataset is accurate (Fig 18), can be easily corrected (Fig 19), or cannot be easily corrected (Fig 20).

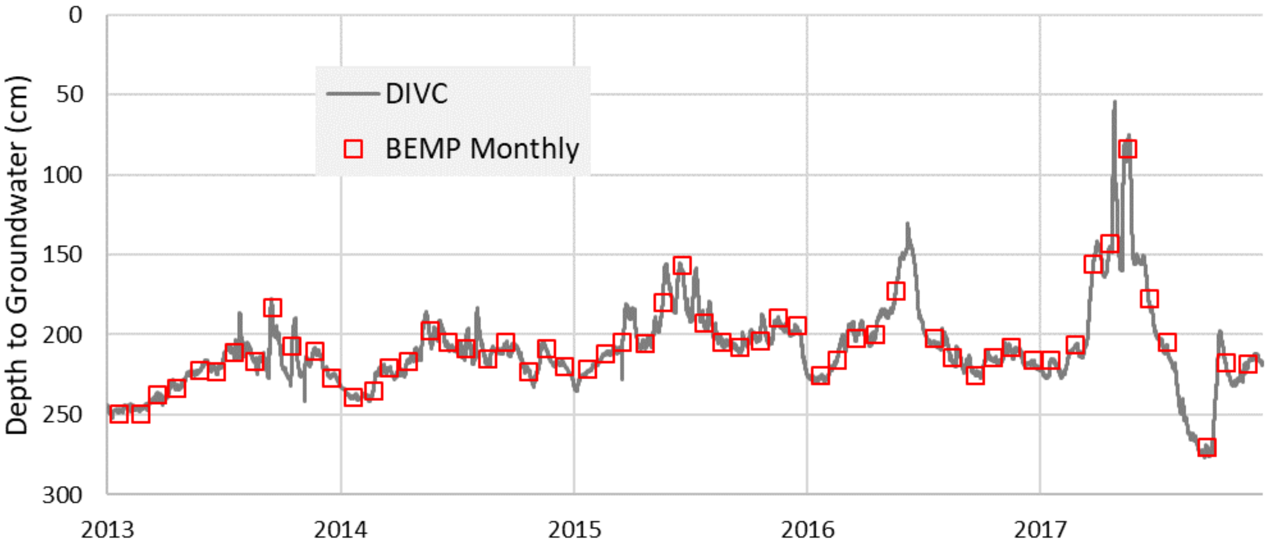


Figure 18. Depth to groundwater at Diversion Center (DIVC), compared with BEMP monthly readings. This dataset has among the highest similarity, and is assumed very accurate.

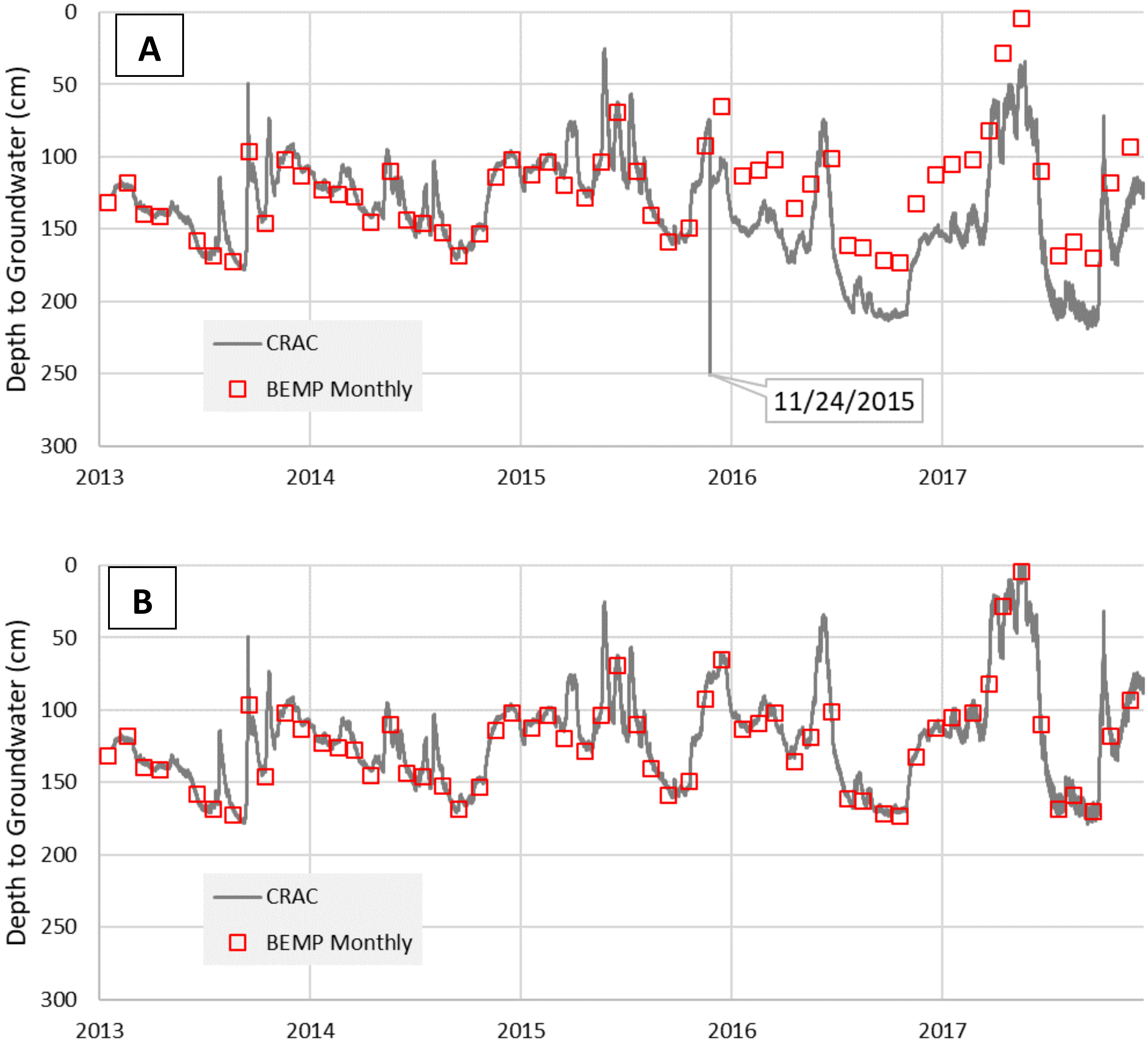


Figure 19. Depth to groundwater at Crawford Center (CRAC), compared with BEMP monthly readings. The original PT data (A) exhibits a discontinuity on 11/24/2015, after which all PT data has been displaced by a consistent amount (40 cm). With a 40 cm correction applied to the PT data after this date (B), the dataset is functional and accurate.

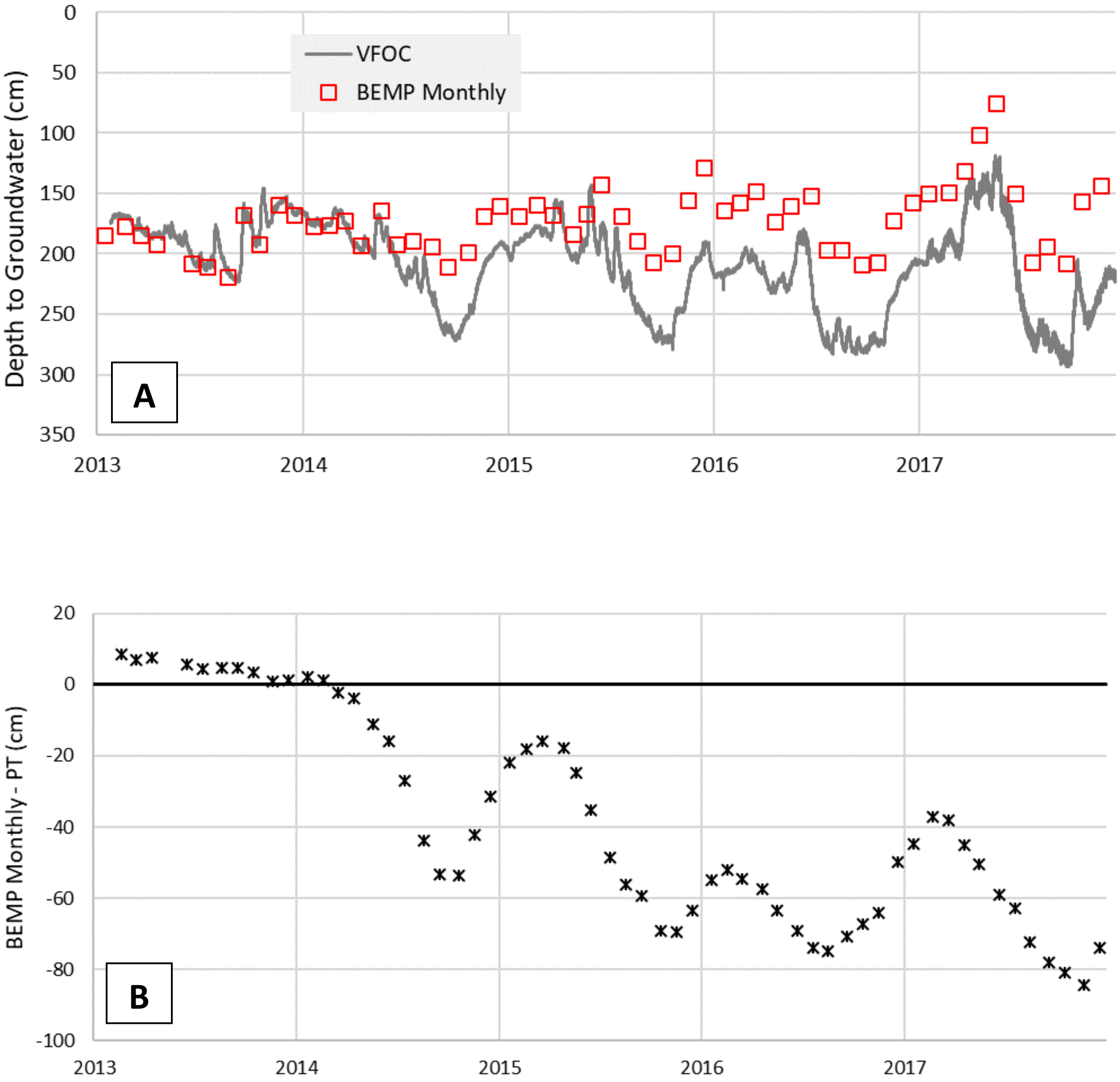


Figure 20. (A) PT recorded depth to groundwater of Valencia Forest Center (VFOC), compared with BEMP Monthly. (B) Difference between the two datasets' recordings. Starting in 2014, the PT dataset begins to drift away from the BEMP monthly values. There is both a steady downward drift, and a seasonal effect. Due to these discrepancies, this dataset was not used for analysis.

Several statistical measures of the difference between PT and BEMP readings were used to further explore and quantify the utility of the PT data. The mean of differences is a logical choice, with the expectation that more accurate datasets will have mean differences closer to zero. The DIVC well, considered in this study to be a highly accurate dataset, has a mean difference of 0.56 cm between the PT and BEMP monthly values. The VFOC dataset, known to be highly dissimilar, has a mean difference of 30.15 cm. Twenty-nine of thirty-five datasets have mean differences under 5 cm. However, the mean can be misleading, as high values on opposite sides of zero will average to zero. Euclidean distance is a common technique for gauging the similarity between two time series. It is expressed as the square root of the sum of squared differences between two associated points. As it is a summation normally meant to compare time series of equal range, Euclidean distance was normalized in this study by dividing by *n,* as in

$$NED = \frac{\sqrt{\sum(x_i - y_i)^2}}{n},$$

where x_i and y_i are depth to ground water measurements for each coinciding measurement, as measured by the PTs and by monthly BEMP readings, and n is the number of matched pairs (constrained by BEMP readings). NED is most useful in comparing datasets to each other, rather than for intrinsic accuracy. For this project, a dataset NED under 0.5 cm was considered suitable.

The standard deviation of differences provides a measure of spread or consistency of the data discrepancy. If a dataset has consistent discrepancy but small deviations, it can be improved with a static correction factor. For example, the Minnow North well from 2010 to 2017 is consistently dissimilar from BEMP monthly readings, but with a small deviation, and can be corrected to more accurately match the manual readings by using a static correction factor (Fig 21). However, this does not account for errors evolving through time or sudden changes in discrepancy, such as observed at Crawford Center.

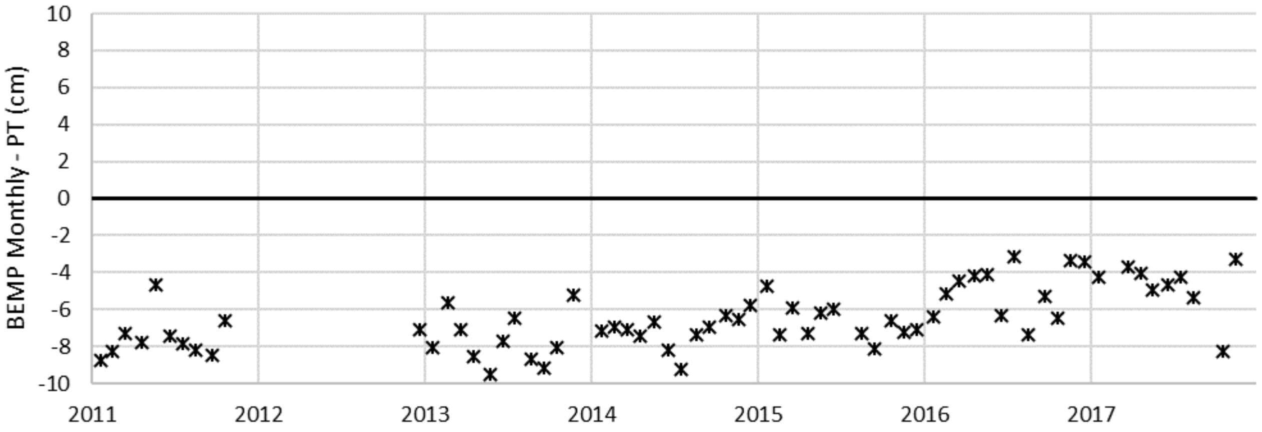


Figure 21. Difference between PT and Monthly data at the Minnow North (MINN) well. While dissimilar, the PT data is stable and with a standard deviation ~3.5 cm, a relatively narrow spread. This indicates that the PT data can be corrected easily by applying a static correction factor.

Both the BEMP monthly and the PT datasets have spurious values that can influence these other statistical measures. Often, these occur for only several matched observations or over a short time. The presence of these outliers does not necessarily indicate the dataset is un-useable, so a fourth metric of data assessment was used, the proportion of matched differences with an absolute value under 5 cm ($P_{<|5|}$). The most similar datasets have $P_{<|5|}$= 1, and the least similar dataset has $P_{<|5|}$= 0.17. The majority of datasets have $P_{<|5|}$> 0.8, and almost half have $P_{<|5|}$> 0.9.

Each statistical measure is valuable, and all together when considered alongside time-series plots of the data discrepancies can inform decisions regarding the utility of the PT datasets. From these analyses, it was concluded by this study that with few exceptions most of the BEMP data are accurate and useable, especially when correction factors are applied when appropriate. Data from after 2010 are generally less dissimilar to BEMP monthly readings than data from before this time (Appendix B).

Potential errors in the PT data can be attributed to several reasons. The spurious values and machine errors of the pressure transducers has been discussed. The pressure transducers are evidently also prone to seasonal fluctuations, as evident in several of the wells. This fluctuation is usually within a few centimeters of expected values. This may be due to temperature changes, though the installed pressure transducers have temperature compensation built in. Some transducers exhibit drift during their operating period, which may have an internal or external cause. When present, this usually manifests as an upward trend in the measurement of depth to groundwater (or a downward trend in pressure reading). In a few cases, transducers exhibit erratic readings just prior to equipment failure.

Human factors also play a role in data accuracy, as the calculated groundwater measurements rely on the accuracy of reported well parameters, such as cable length and casing height (Fig 17). These must be recorded with high accuracy at time of installation and continuously as they change through time from maintenance, failure, or vandalism. Changes in casing height over the operating period have been recorded by BEMP and are included in database queries, but the database and all analysis in this project relies on a single measure of cable length, provided at time of installation. Cable length and transducer depth can be altered from maintenance and vandalism (this is the suspected reason behind the discontinuity in the CRAC well (Fig 19)), and less visibly by root growth and sedimentation at the bottom of the well. The range in values of groundwater measurements can be slight, so small errors in these parameters of the datasets can have substantial effects on observations made from them.

Caveats in the assessment method must also be considered. It is important to note that the BEMP monthly datasets, which the PT data are compared to, are themselves susceptible to human and equipment errors, and high similarity between the two datasets should instill only more confidence, not certainty, as to the accuracy of the PT readings. Differences in measurement time can also have an effect when comparing the two datasets. PT records from 12:00 PM were used to compare to BEMP measurements taken on the same day, to best approximate the time that BEMP's measurements were taken. However, as will be shown in a later portion of this report, groundwater levels can fluctuate rapidly, sometimes over 30 cm in one day. This pace of change is rare, but illustrates that even several hours difference between PT readings and BEMP readings could result in significant discrepancies between the two. There is also a strong diurnal cycle in many of the wells, caused by evapotranspiration by riparian phreatophytes. If BEMP readings are measured consistently at a time other than noon, this could influence the overall comparisons.

Analysis

Methods

Types and ranges of data analysis were constrained by several circumstances in this project. Gaps in data collection and early equipment failure meant that by 2018 only eleven out of the twenty-four pressure transducers installed prior to 2010 were still operating, and no site had the full set of five still operating (State Land Office, installed in 2015, has all five PTs operating as of 2018). Additionally, some dataset accuracy is questionable, either by well or time period. There were also hydrologic constraints. As this project's goal was primarily to assess bank storage and groundwater recessions after high groundwater events, analysis was also limited to years with strong streamflow, particularly during spring. Since PT data collection began, these years have been rare (Fig 22). From the above multi-year hydrograph, it is evident that through the years for which the bulk of the continuous PT data are available - 2011, 2013 to 2017 – the majority have ranged from moderately to extremely dry. Analysis in this study was predominantly restricted to when data availability and high discharge seasons and events coincided.

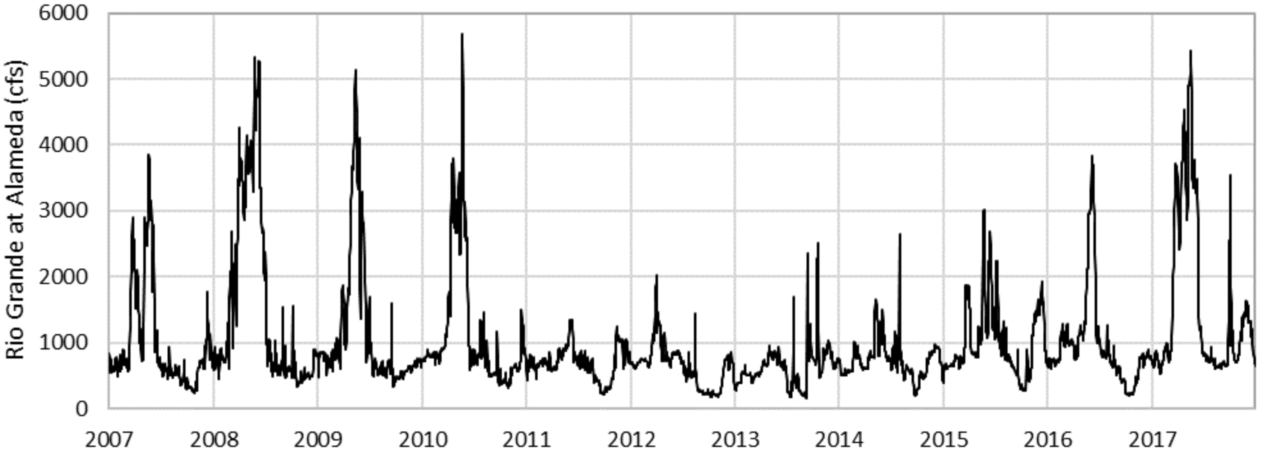


Figure 22. Rio Grande streamflow from USGS 08329918 Rio Grande at Alameda Bridge at Alameda, NM during the operating period of BEMP PTs

Analysis for each site began with plotting depth to groundwater alongside Rio Grande streamflow, as measured by the associated USGS stream gage. Depth to groundwater, rather than absolute groundwater elevation, was chosen for ecological significance. In some cases, precipitation was similarly plotted and compared. These plots allow for general observations of trends, responses, and levels of groundwater. Often, multiple wells are plotted to compare the groundwater behaviors at different distances from the river channel. Time-series of high stage events such as spring snowmelt driven events and late summer monsoons give insight into bank storage and post-event groundwater recession during times when native species such as cottonwoods may be germinating. To better observe and compare rates and behaviors of groundwater recession, several high-groundwater events from the operating period of analyzed wells are chosen and plotted together. Ten days of subsequent PT data were observed, starting from the moment bank storage begins to recede. Day-to-day changes in groundwater depth were derived, using depth to ground water values at each 24 hour period after the recession began. This is done to account for changes due to diurnal fluctuations.

In some cases, where appropriate and when the data allowed it, a transect was constructed using wells that fell along the transect lines as shown in figures 5, 9, and 13. These were plotted alongside respective topographic profiles created from 2010 LiDAR data. In these cases, groundwater elevation was derived as depth to groundwater subtracted by the measured ground surface elevation of the BEMP wells at time of survey. This method accounted for changing casing heights through time. When elevations between the LiDAR data and BEMP surveyed elevations did not coincide, the topographic profiles were normalized to match the BEMP surveys. Time frames were chosen to create transects to either describe post-high groundwater event recessions, or different times throughout the year. Hydraulic gradients were estimated by linear regression between East and West wells in some cases. This section will introduce charts, analyses, and observations for selected sites and periods where data availability and hydrologic suitability coincided.

Diversion

The Diversion site in North Albuquerque is the most complete dataset in the BEMP PT database. Aside from Diversion South, all wells are still operating as of 2018, and all wells have been surveyed. This allows for the broadest range of analysis out of all the sites.

A time series of a long period of continuous data from the Diversion Center well, 2013 to 2017, indicates that water table elevations are highly variable, and strongly tied to discharge (Fig 23). Predictably, the highest groundwater levels occurred in spring of 2017. For this reason, 2017 was examined in more detail in figure 24, figure 25, and figure 26 using data from west, center, and east wells at Diversion. No flooding (DGW = 0) was recorded at this site, but high groundwater events can illustrate typical groundwater behaviors. The 2017 time-series indicates several observations of note:

- Increases in discharge induce almost instantaneous increases in groundwater elevations, for all wells.

- All wells respond simultaneously when the river stage is the only input (absent precipitation). This indicates an extremely fast signal travel time from stream channel to the furthest (east) well, and suitably conductive sediment.
- Groundwater recession likewise begins simultaneously with drops in discharge, though at different rates. While the streamflow drop in mid-May induces a sudden drop in groundwater elevations, a similar drop in early June induces a much slower recession.
- A summer monsoon pulse in late September induces both a high stage event in the stream, and high groundwater levels in the riparian zone, though not nearly as high as during the stream snow-melt event. Groundwater did not respond or recede as drastically during the monsoon event, and peak groundwater was delayed from peak streamflow by several days. In general, groundwater levels during the monsoon event display more a gradual response to streamflow and/or precipitation.
- Diurnal signals as induced by phreatophytes are only present at Diversion when depth to groundwater is less than 100 cm, which in 2017 only occurred at the West and Center wells for several weeks during the spring high groundwater event.

A collection of time series plots following high groundwater events compare recession rates at the Diversion Center well (Fig 27). It is observed that during the dry years preceding 2017, groundwater levels were only marginally elevated, and receded slowly. The spring 2017 event resulted in much higher groundwater levels, and drastically faster recession rates, approaching 20 cm per day for several days after recession began.

As the Diversion dataset included surveyed locations, elevations, and the three wells that correspond to an east-west transect, topographic profiles of the riparian potentiometric surface could be generated. This was done for ten days of groundwater recession following the May 20 high-groundwater event (Fig 28). It is shown by these profiles that even at the highest groundwater mark on record for the site, bank storage does not extend far into the riparian zone, as the groundwater surface is immediately sloped downward. The ten day recession profiles indicate that as river stage drops, groundwater levels near the river recede quickly. At all times during the event, the potentiometric surface is immediately sloped towards the agricultural drain bounding the east side of the floodplain, with a nearly linear shape. A profile of 9/18/2017 represents the low groundwater mark in the year (and the lowest levels on record), and it too is sloped towards the drain. Water tables are elevated about two meters above the low mark at the DIVW well, and about 1.5 meters elevated at the DIVE well. During this event, the strongest discharge event in the PT record in which the stream exceeded 5000 CFS for nearly two weeks, groundwater depths peaked at ~60-70 cm, and only for wells nearer the channel.

Profiles were also constructed for several dates through 2017. The shape of the potentiometric surface remains consistently sloped downward toward the drain, only differing by 1-2 meters in elevation. Hydraulic gradients between the west and east wells through 2017 indicate that it is strongly influenced by river discharge/stage (Fig 30), and ranged from ~0.006 to 0.016, a nearly three-fold difference in gradient throughout this year. Confirming the observations made in the elevation profiles, the gradient is always positive, sloping upwards towards the river channel. The high discharge event in mid-May induced a steep escalation of the gradient, indicating that only the well closest to the river channel was significantly affected by the rise in stage, and this higher gradient may explain why groundwater levels fell so rapidly after the high streamflow subsided.

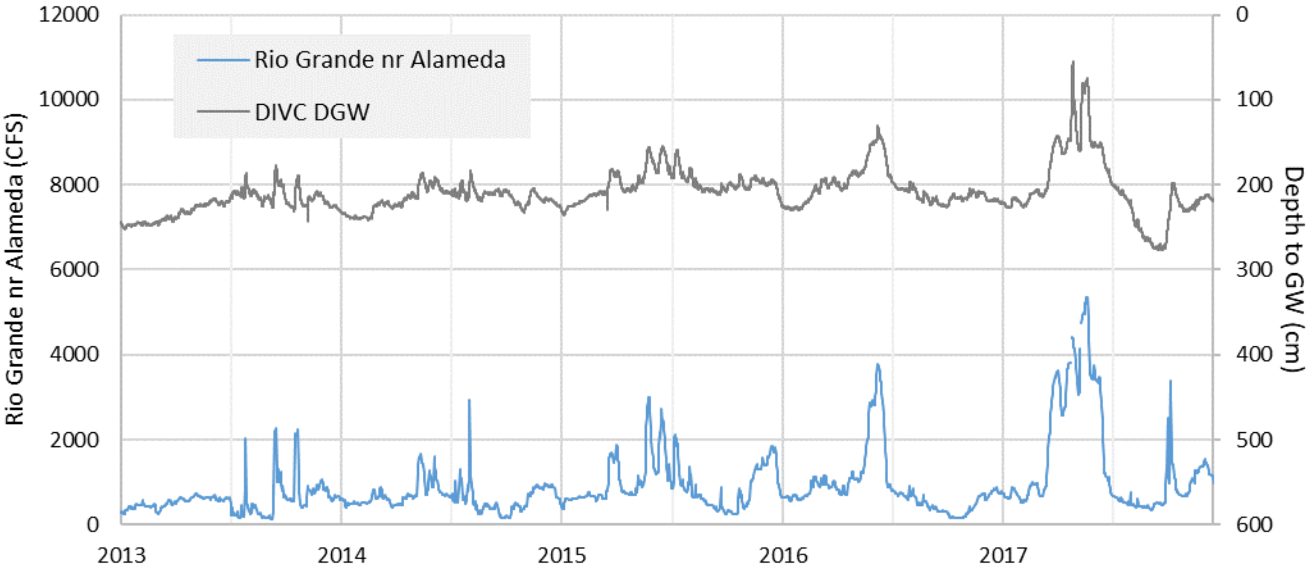


Figure 23. Diversion Center well depth to groundwater (DGW) (Right axis, reversed), Rio Grande discharge from USGS 08329928 Rio Grande nr Alameda, NM, from 2013 to 2017.

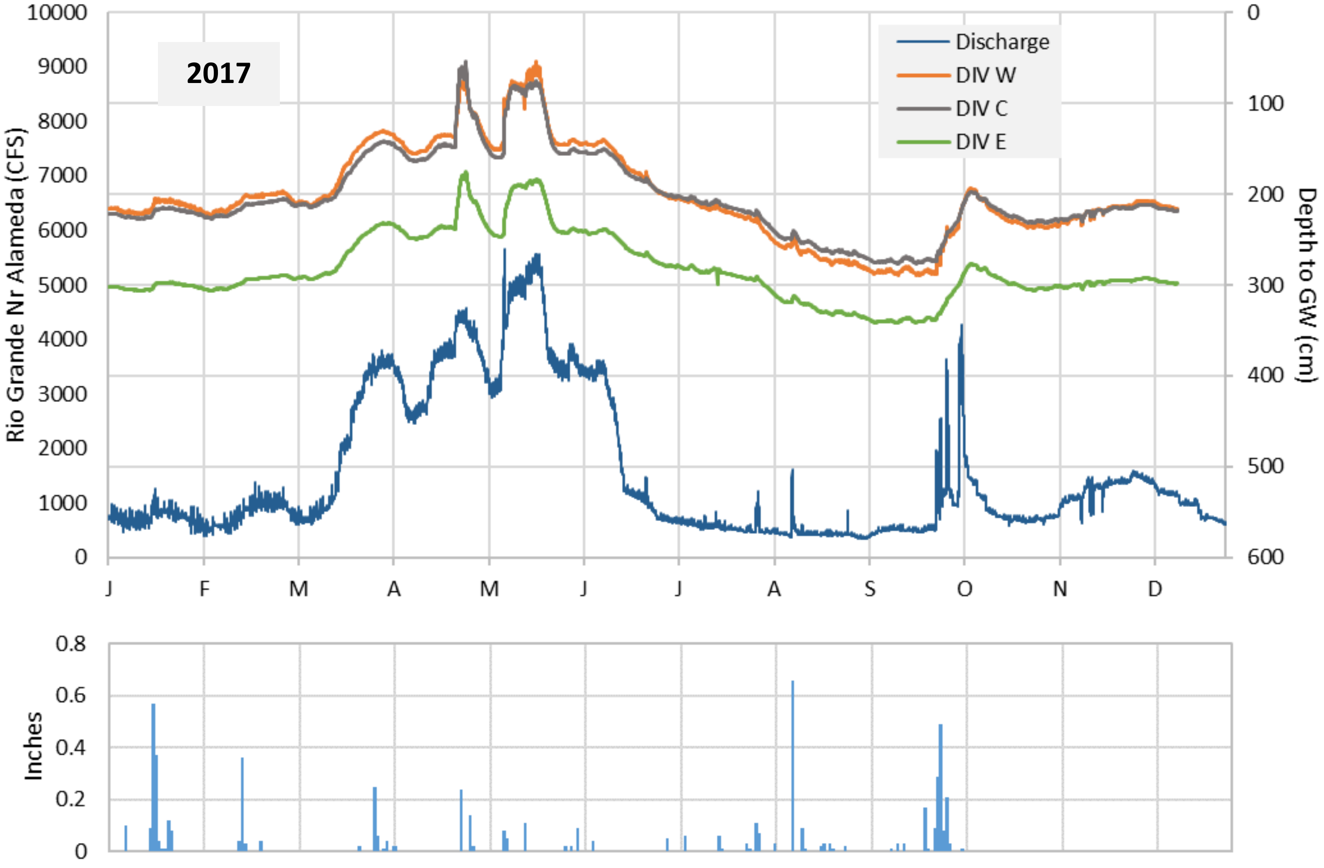


Figure 24. Diversion West, Center, and East wells, 2017. Precipitation (bottom) from Sandia Lakes gauge.

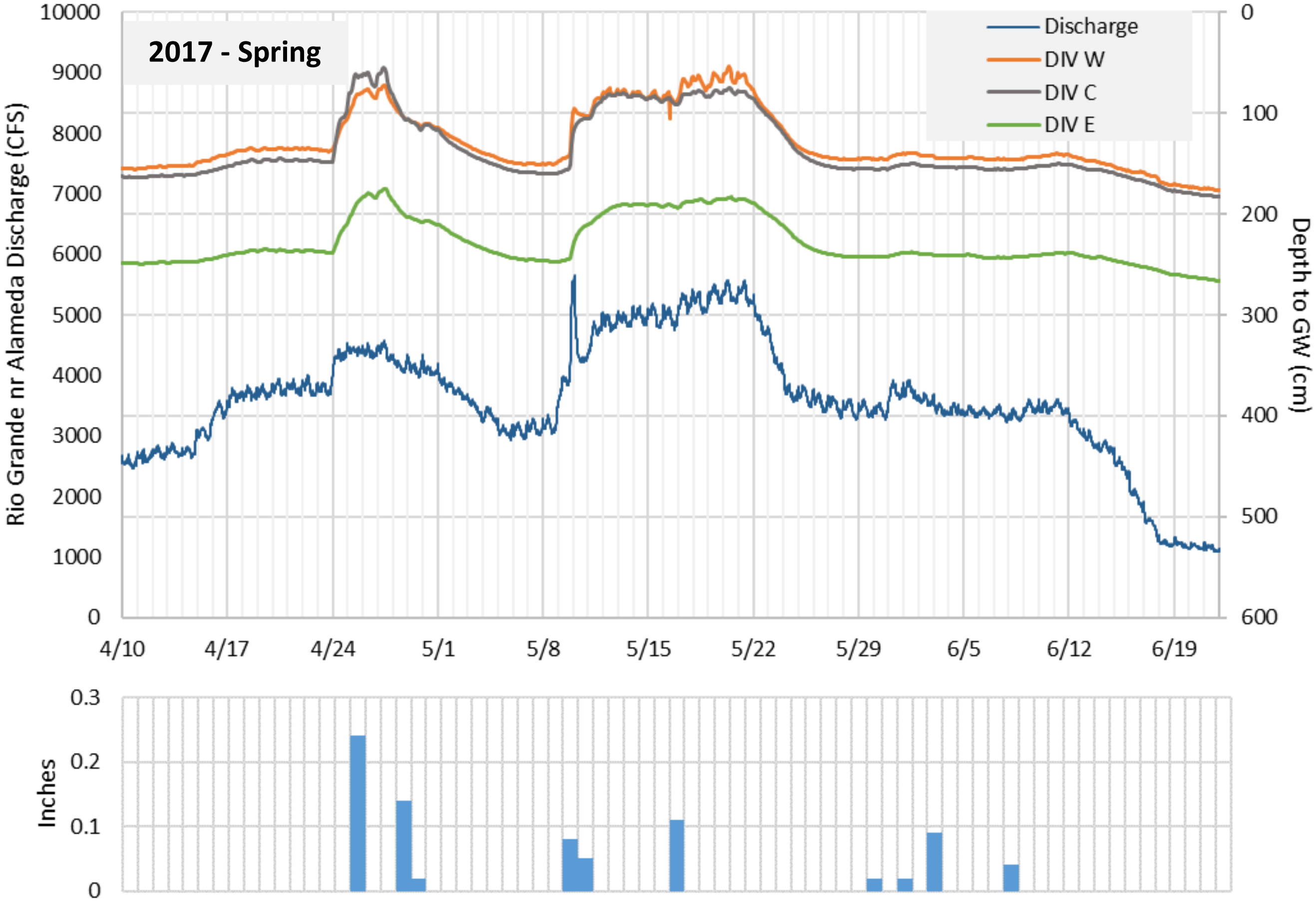


Figure 25. Diversion wells and precipitation during spring event, 2017.

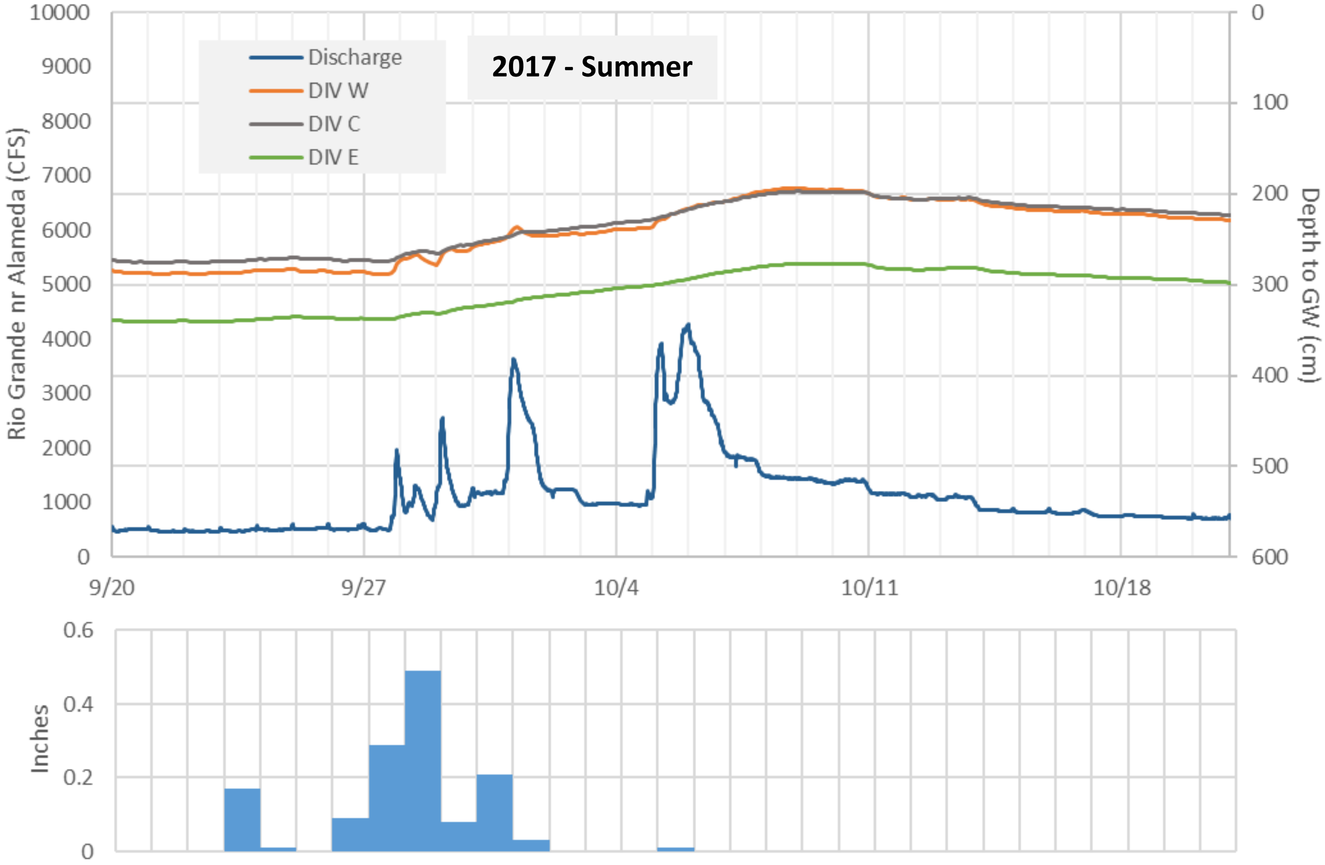


Figure 26. Diversion wells and precipitation during summer event, 2017.

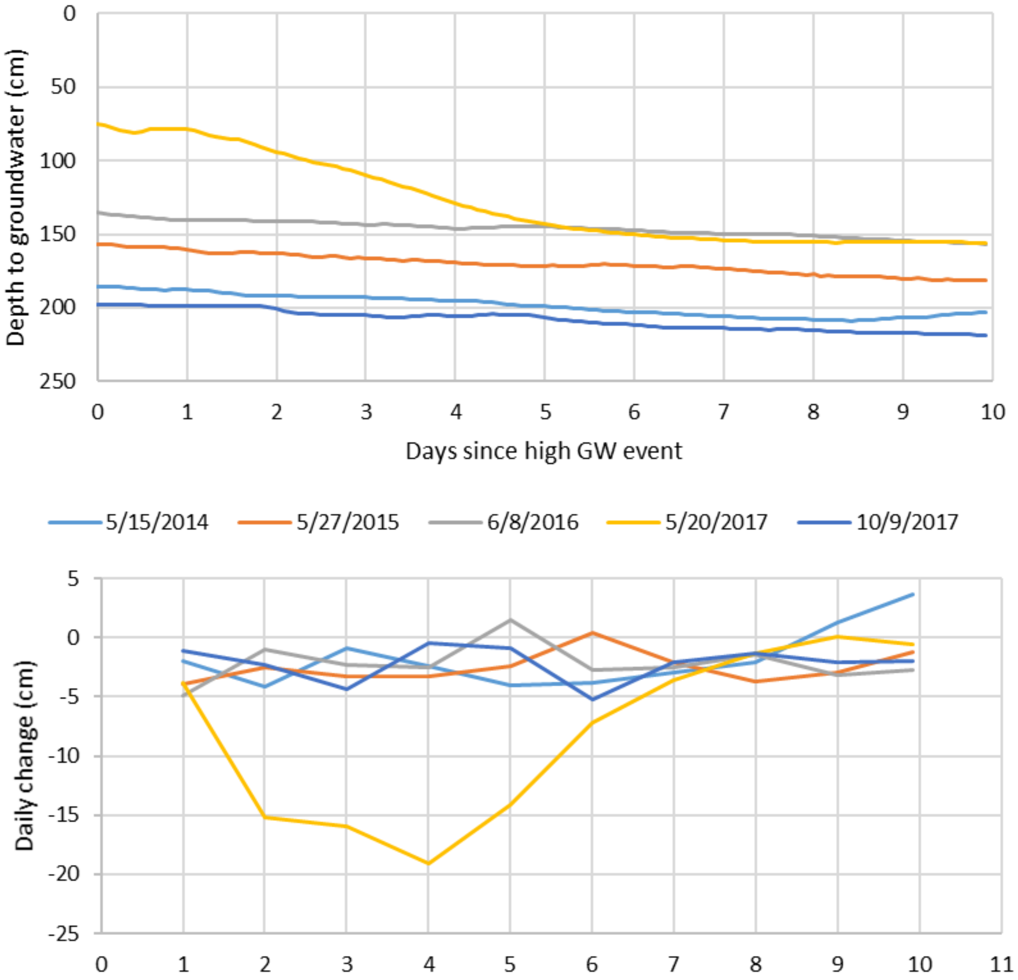


Figure 27. Recession curves of 10-day periods following several high groundwater events at Diversion Center (Top), and day-to-day change in groundwater elevation (Bottom).

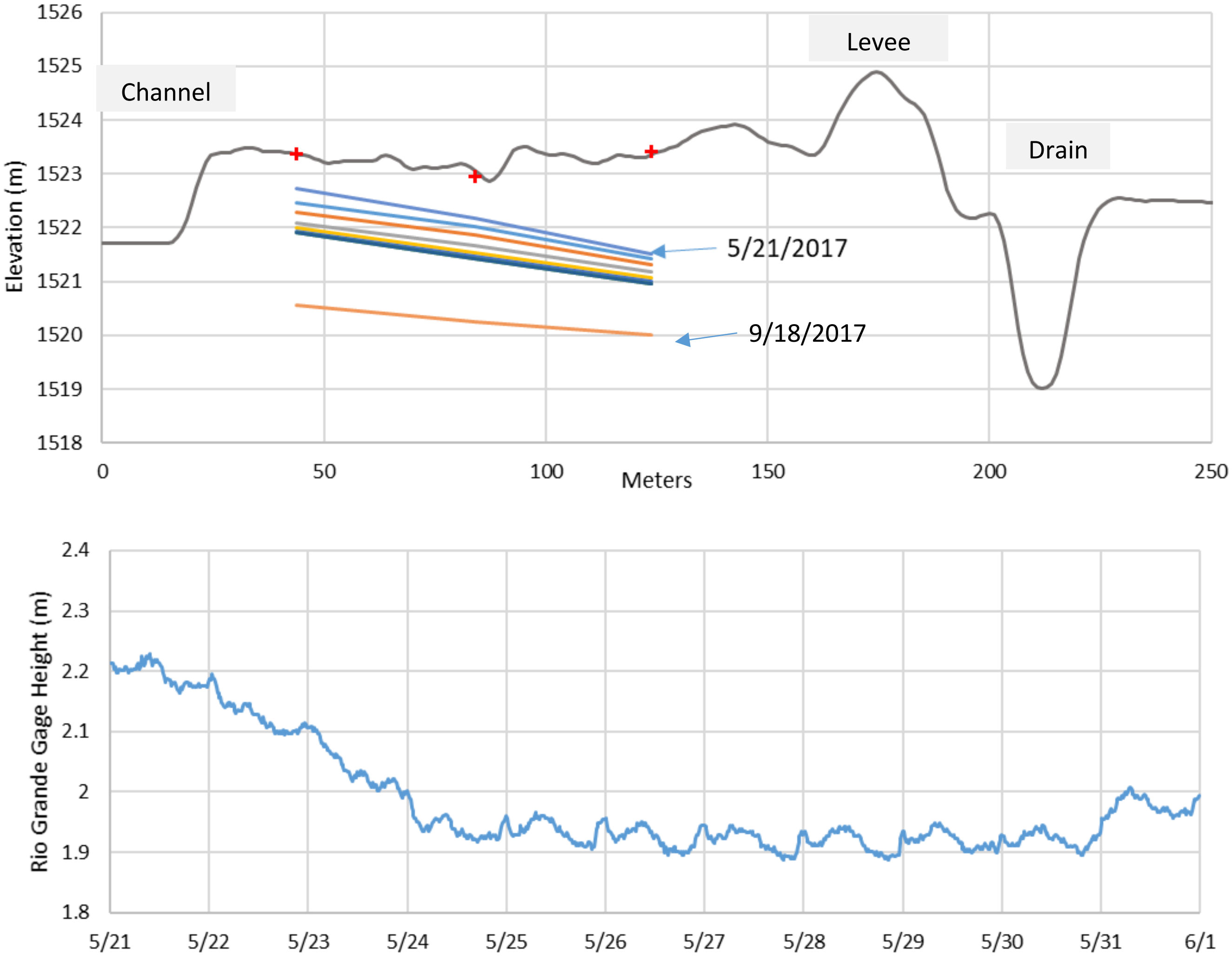


Figure 28. Transect profile of groundwater elevation at the Diversion site on 5/21/2017 and the ten following days (top). Profile of 9/18/2017 is included for low groundwater reference. DIVW, DIVC, and DIVE wells are represented as red crosses. For reference, stage height of the Rio Grande nr Alameda over the same ten day period (bottom).

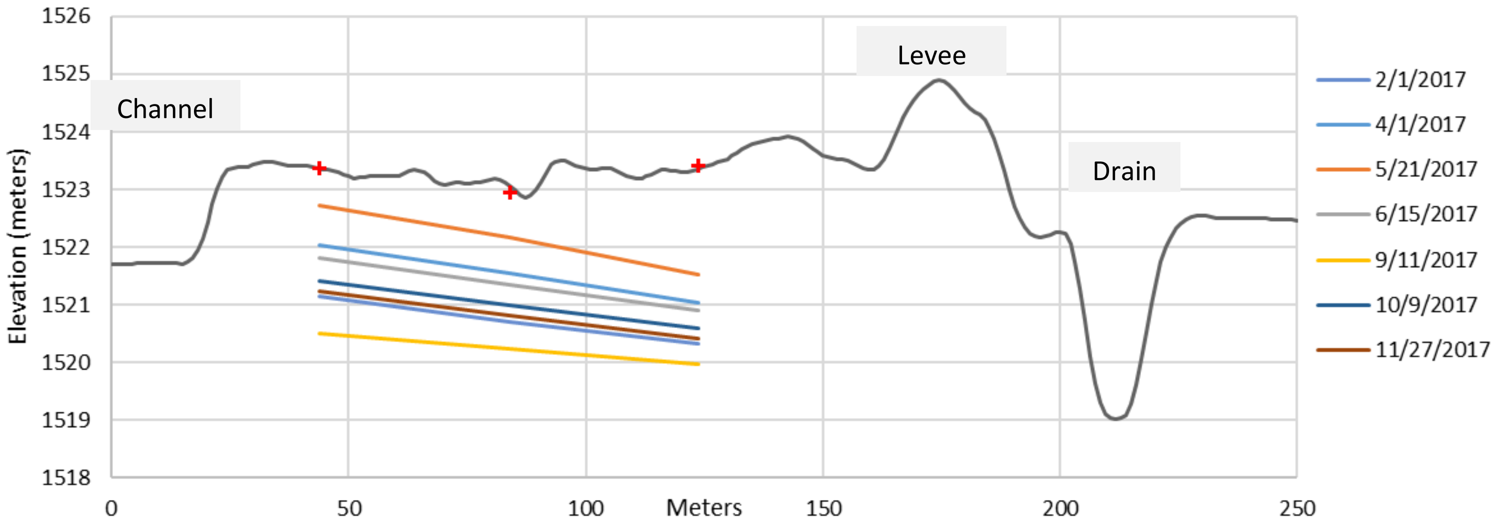


Figure 29. Noon groundwater profiles for several dates at Diversion through 2017.

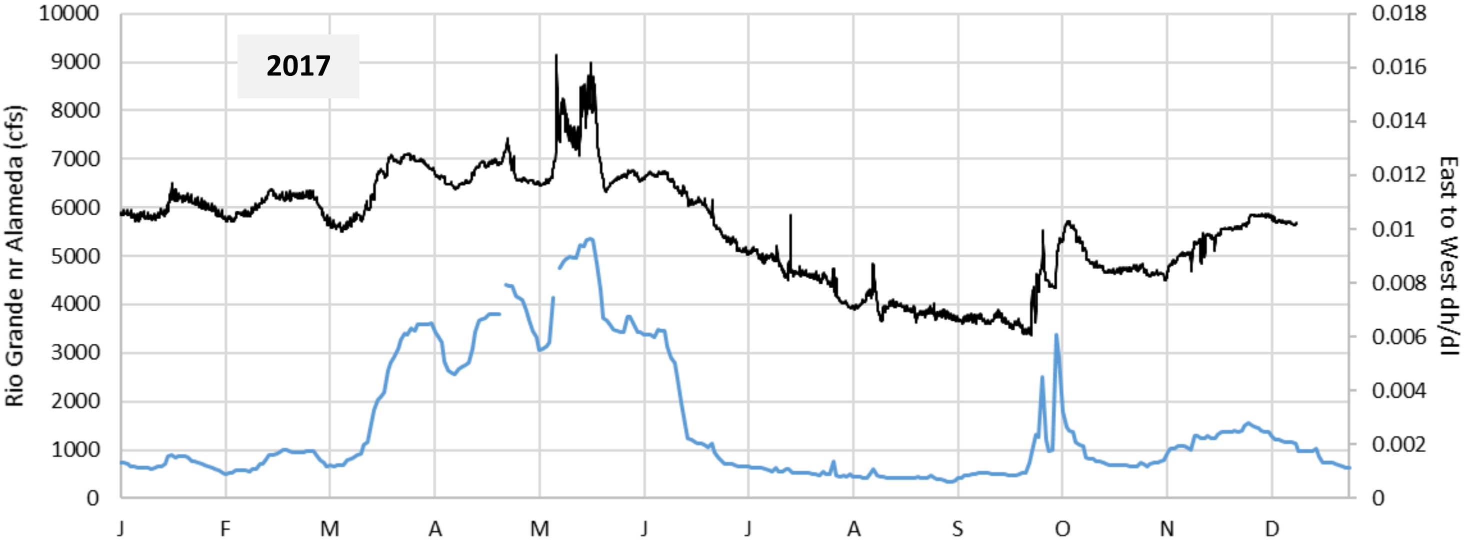


Figure 30. Hydraulic gradient East to West (towards the river channel) for 2017, compared to discharge.

Minnow

The Minnow site unfortunately does not have as complete a dataset as the Diversion site, as only one well was still operating as of 2018. However, it was still chosen for analysis as the site opposite the river from Diversion and downstream of the diversion dam. A long-term time series of this operating well, Minnow North, indicates that groundwater levels at Minnow are, similar to Diversion, highly influenced by stream discharge (Fig 31). All wells were operating during 2008, also a relatively wet year with strong discharge patterns, so this year was chosen for focused analysis (Fig 32). This year did not experience the magnitude of streamflow as in 2017. Again, all wells respond virtually simultaneously. Water tables in this site did have a slight delay after changes in river flow of about one day for the east and center wells and seven days for the western well. This indicates the signal induced by changes in river flows propagate more slowly here than at Diversion. Recession rates following high groundwater events (Fig 24) are also slower when compared to Diversion. However, higher groundwater events are still associated with faster recessions, with some events experiencing recession rates of >10 cm/day after streamflow recedes. The channel morphology may be affecting these differences, as the riverbank is much broader and shallower than at Diversion.

Elevation profiles of the groundwater surface at Minnow demonstrate a similar shape and behavior to Diversion (Fig 35). During a spring high discharge event in 2008, elevations nearer the channel were raised to a higher degree than those away from it, limiting the lateral extent of bank storage. The primary groundwater ridge at Minnow extended about 50 meters from the river channel, and surfaces always sloped towards the drain bounding the west side of the riparian zone here. Profiles throughout 2008 show a similar pattern to Diversion, a surface that appears to terminate opposite the stream channel at relatively stable point in the drain while fluctuating readily with streamflow on the stream end. Reaffirming this, the East to West gradient is again strongly controlled by discharge and always positive (Fig 37). Rainfall events are also shown to affect gradient, even without corresponding effects seen in river discharge, such as is shown in early July. However, the infiltrating rain was not enough to influence the general shape of the groundwater surface.

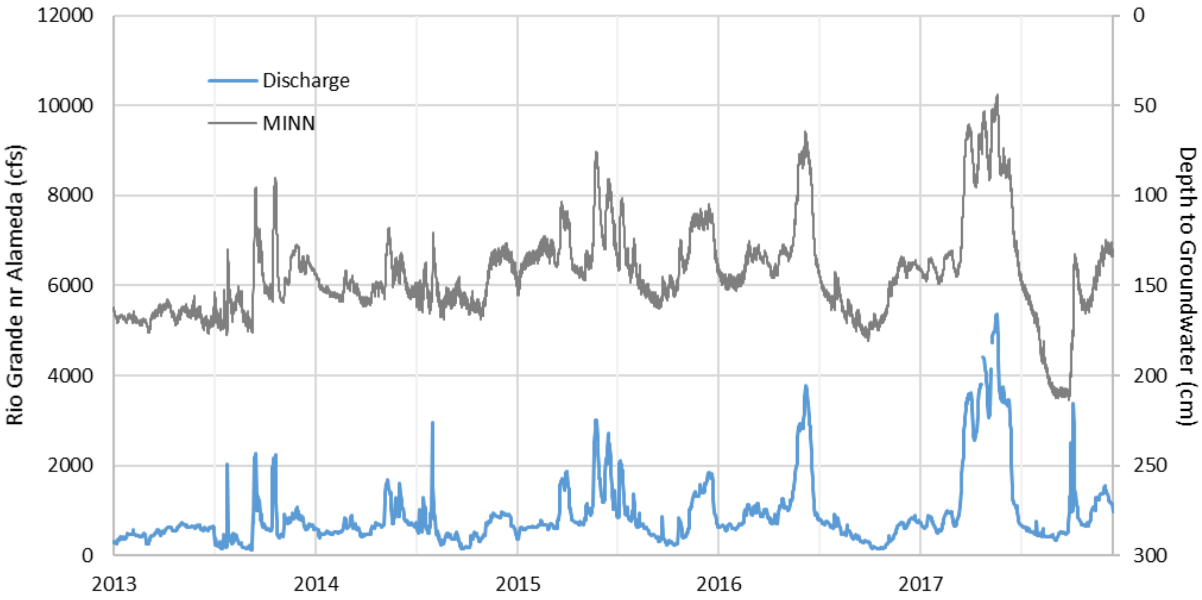


Figure 31. Depth to groundwater at Minnow North, and Rio Grande discharge, 2013 – 2017

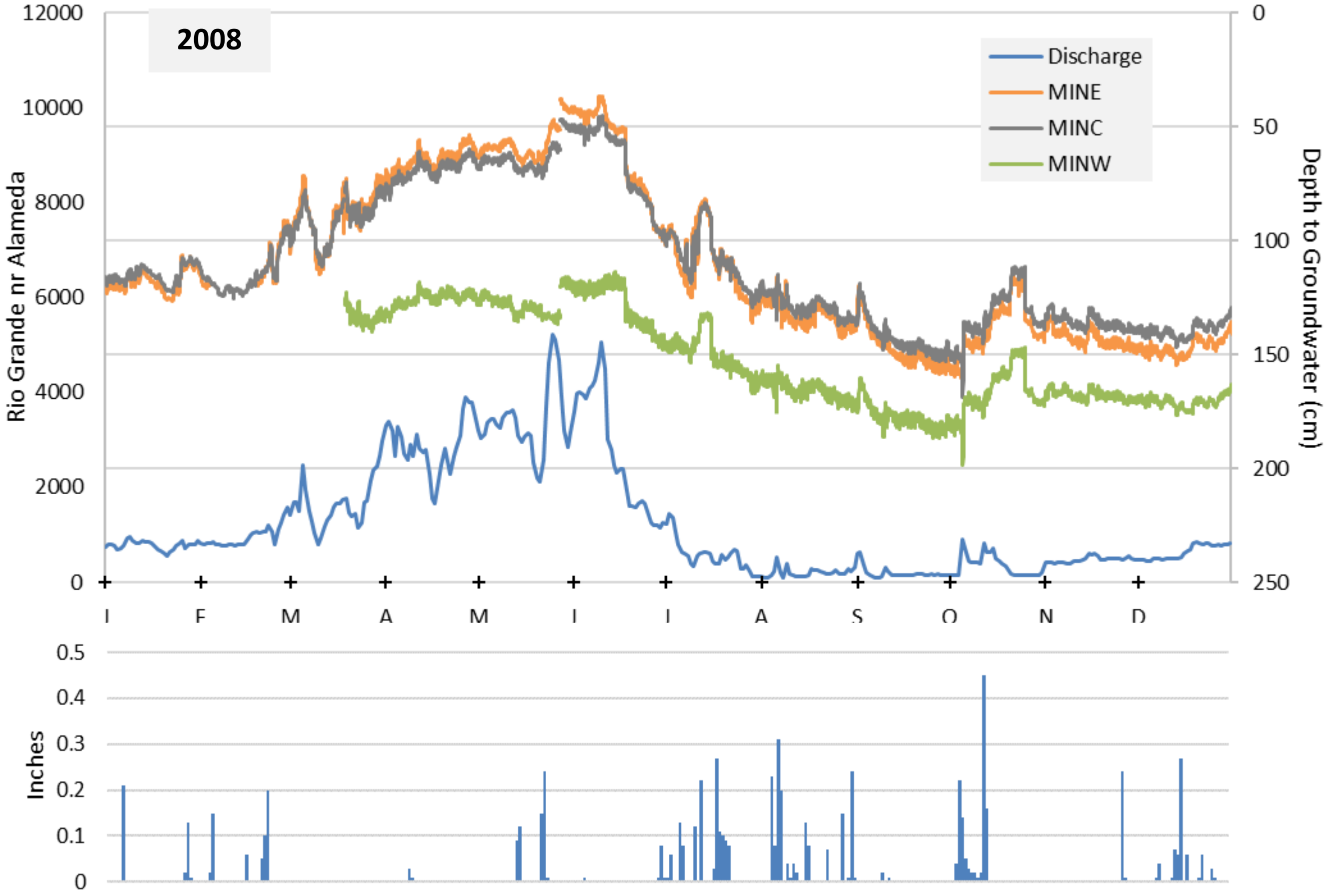


Figure 32. Depth to groundwater at Minnow wells, Rio Grande discharge, and local precipitation 2008. (2008 was chosen to examine because some Minnow wells had ceased functioning by 2017).

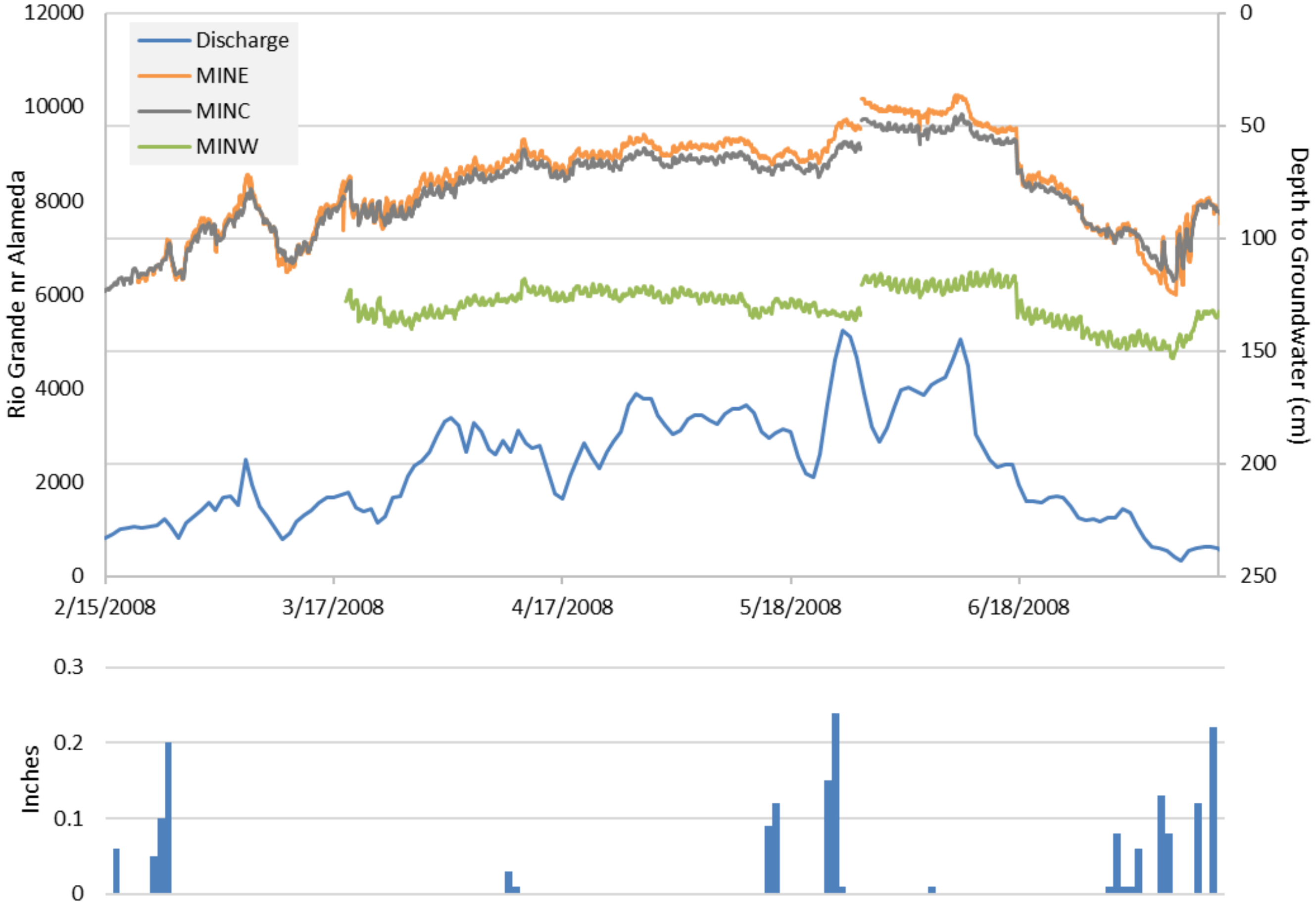


Figure 33. Minnow site depth to groundwater, Rio Grande Discharge, and precipitation during spring high groundwater event in 2008.

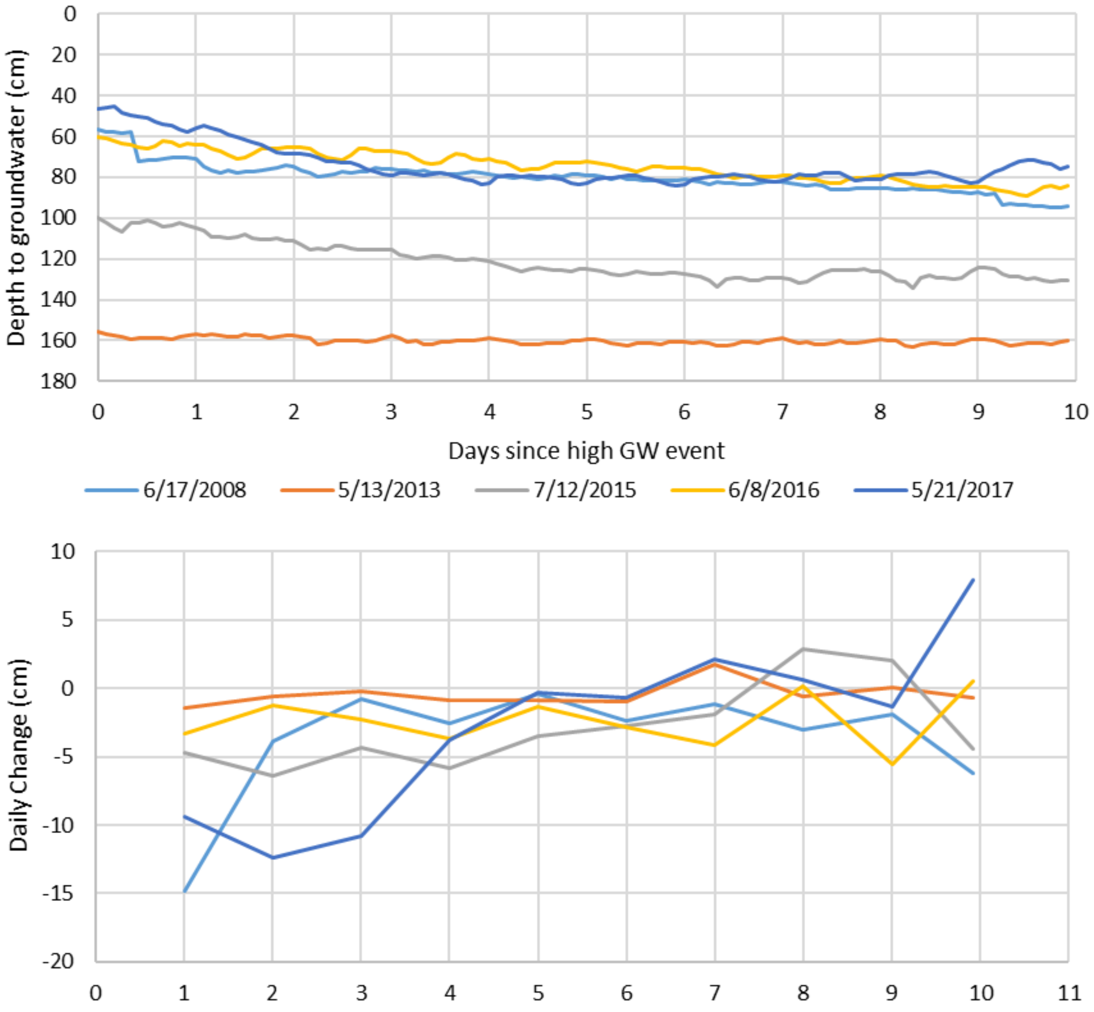


Figure 34. Post-event groundwater recessions at the Minnow North well, and day-to-day change.

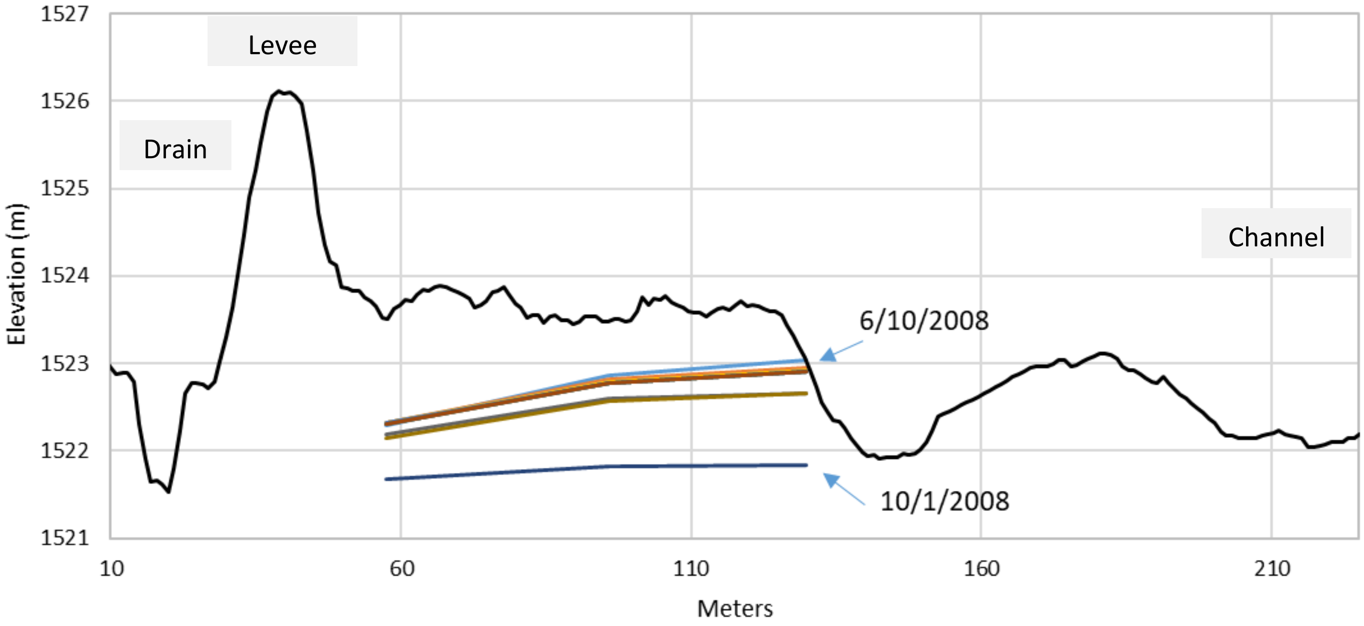


Figure 35. Groundwater elevation profile at the Minnow site during the ten days after a 2008 high groundwater event. Elevations on 10/1/2008 are included as a low reference.

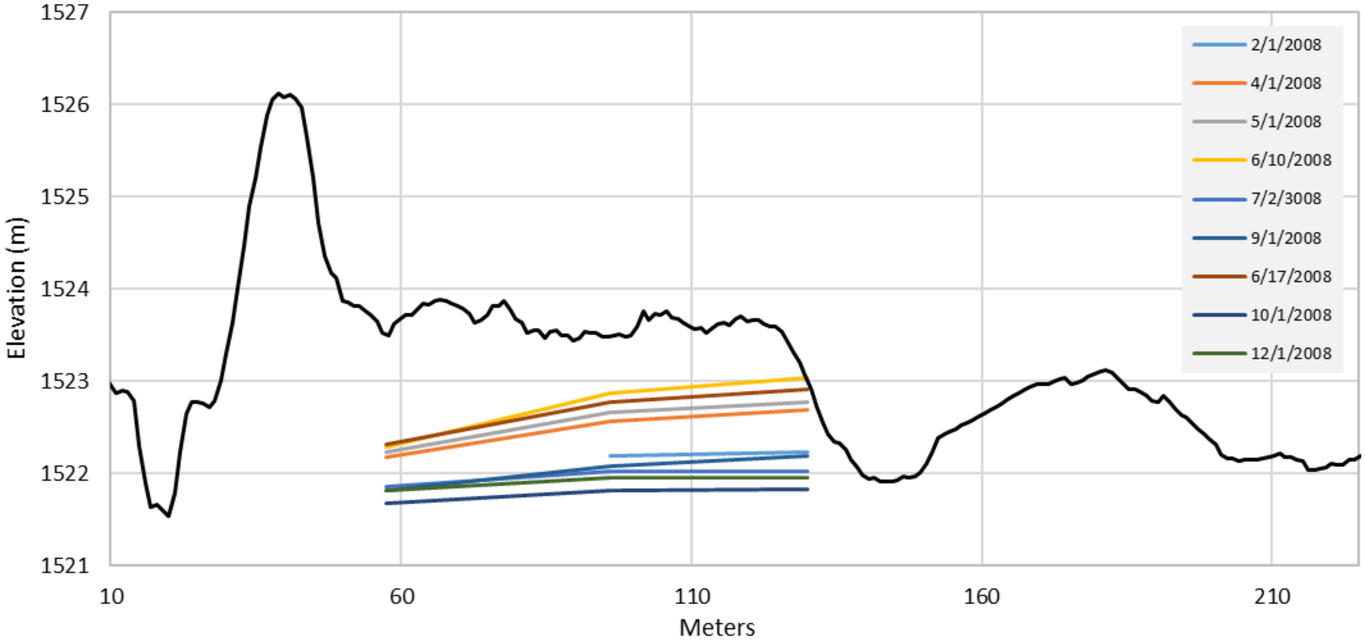


Figure 36. Groundwater elevation profiles at the Minnow site for dates through 2008.

Figure 37. West to East hydraulic gradient (towards the river channel), stream discharge, and precipitation at the Minnow site in 2008.

Bobcat

As of 2018, only two wells at the Bobcat site are still operating. Groundwater levels at Bobcat are similarly influenced by river discharge. Time series of 2017 illustrate that this site experienced similar patterns to Diversion regarding the response to rising and falling discharge during the 2017 spring event (Fig 39). Levels respond almost instantaneously to discharge patterns, and virtually simultaneously between the East and West wells. Depths to groundwater were generally lower here, and diurnal signals were visibly stronger. While groundwater recession recurred immediately after streamflow subsided, the recession rates were much slower than observed at Diversion or Minnow, rarely exceeding 5 cm/day, excluding one event associated with an early fall rainfall event (Fig 40, Fig 41). Though recession rates are for the most part relatively similar, there is an indication that higher groundwater events recede quicker.

Hydraulic gradient between the East and West wells display a similar correlation with streamflow as Minnow and Diversion, but with much less variation (Fig 42). The gradient towards the river was always positive through the year, indicating that during all seasons and events the groundwater surface is sloped away from the river.

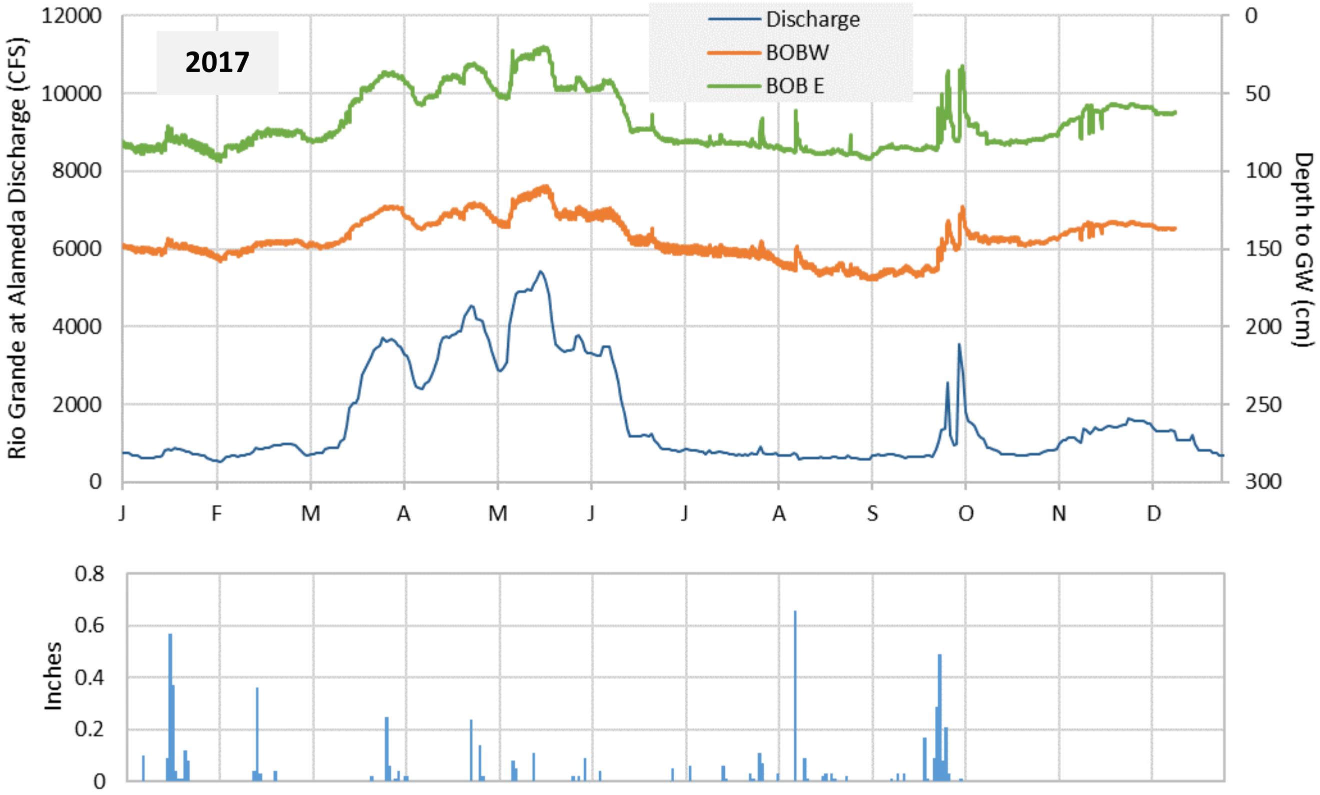
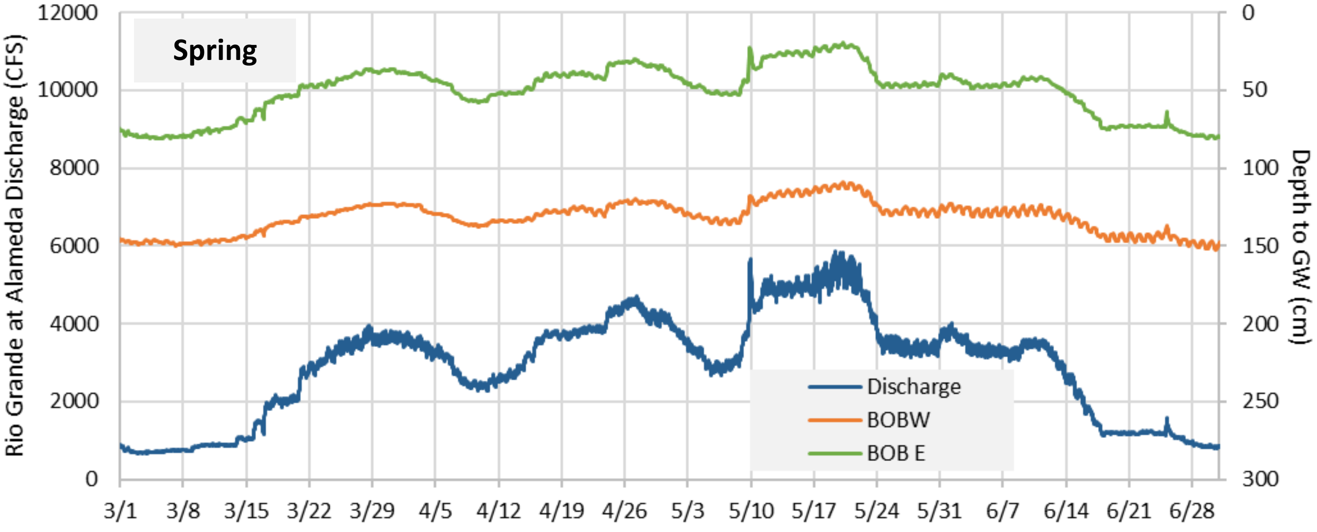


Figure 38. Bobcat East and West wells in 2017 and precipitation, 2017.



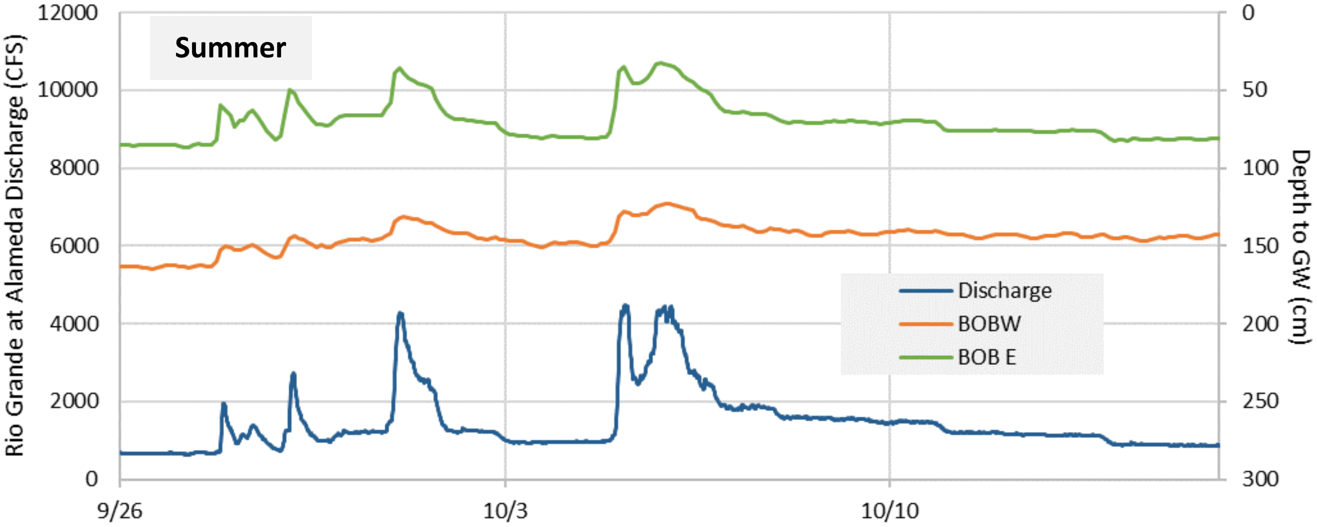


Figure 39. Bobcat W and E groundwater levels and river discharge, spring and summer 2017

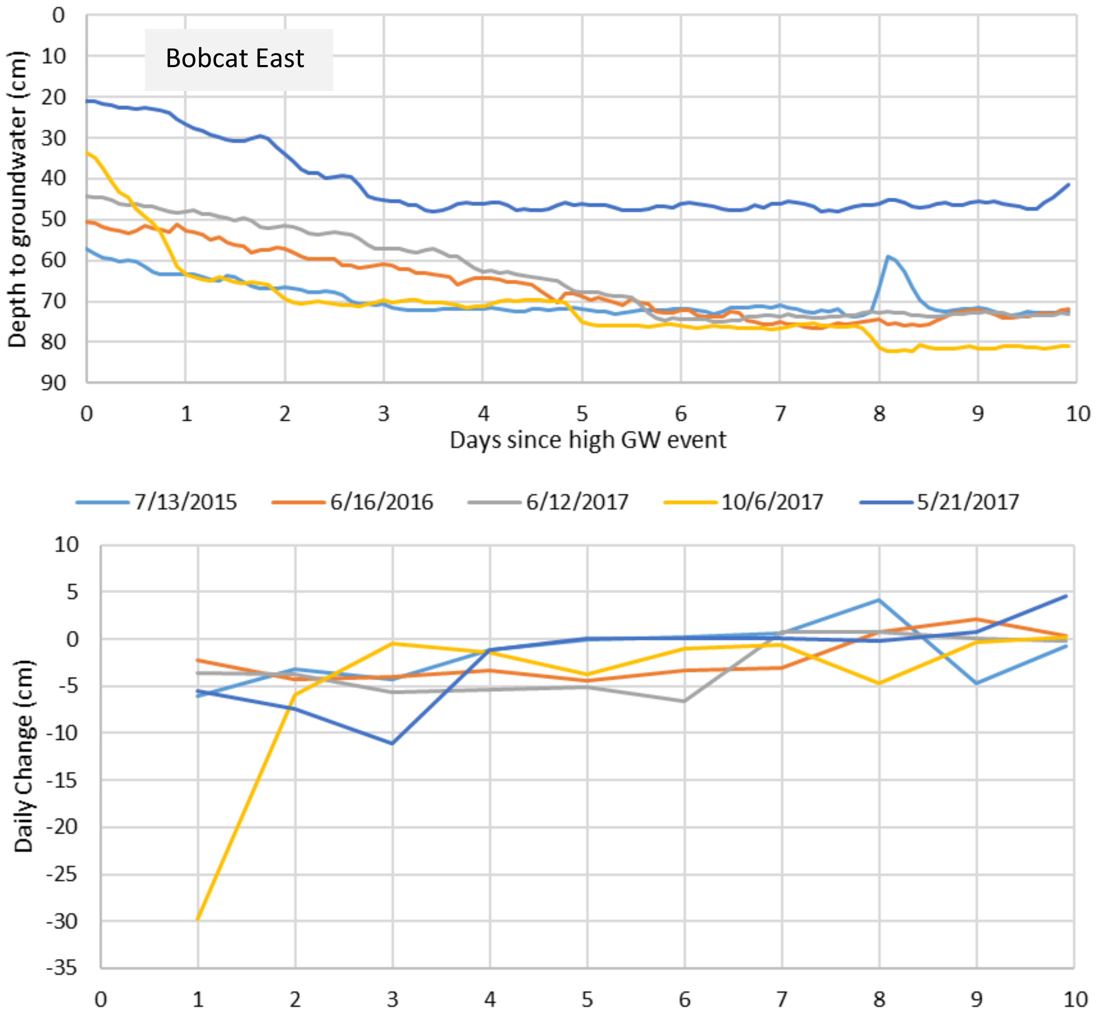


Figure 40. Recessions after high groundwater events at Bobcat East.

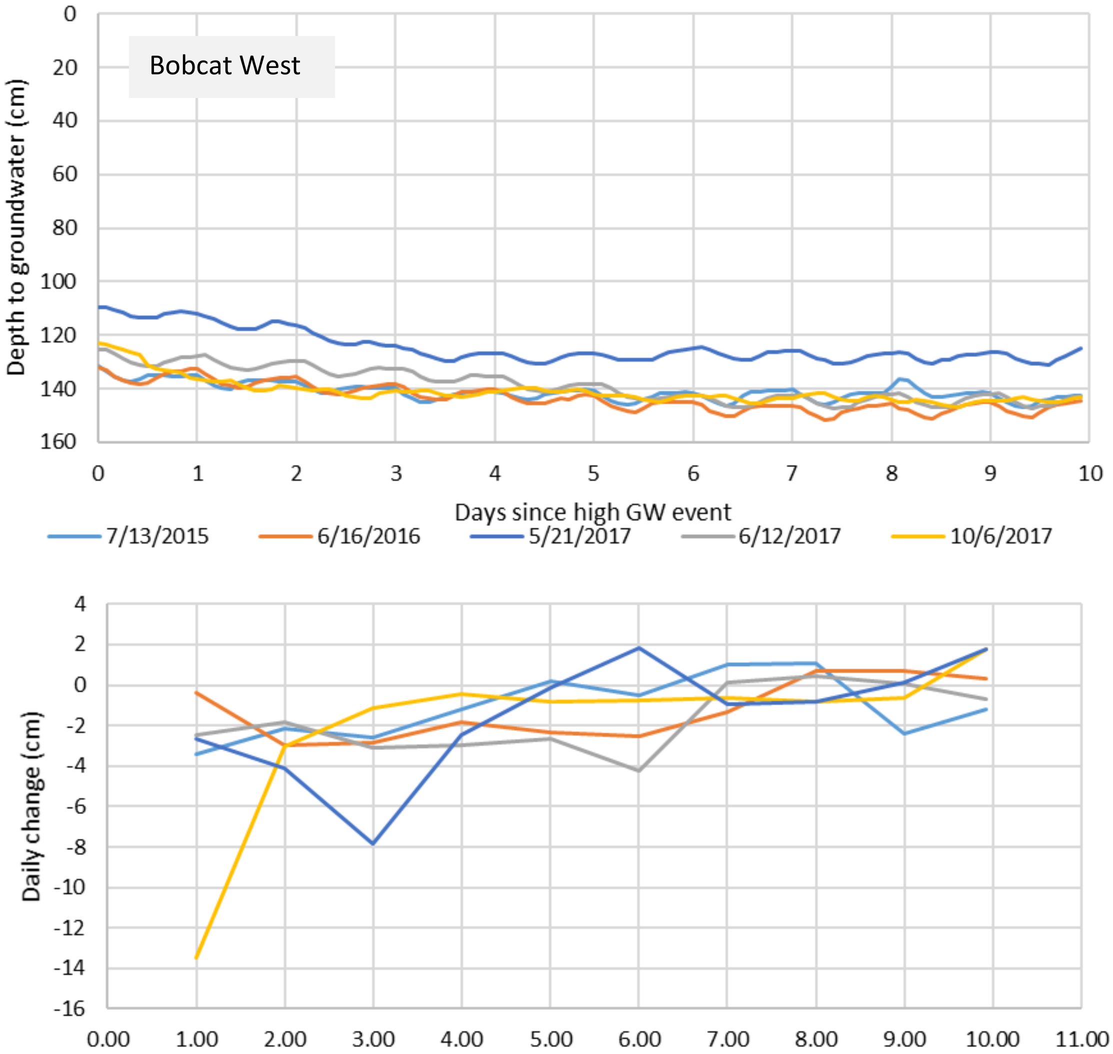


Figure 41. Recessions after high groundwater events at Bobcat West.

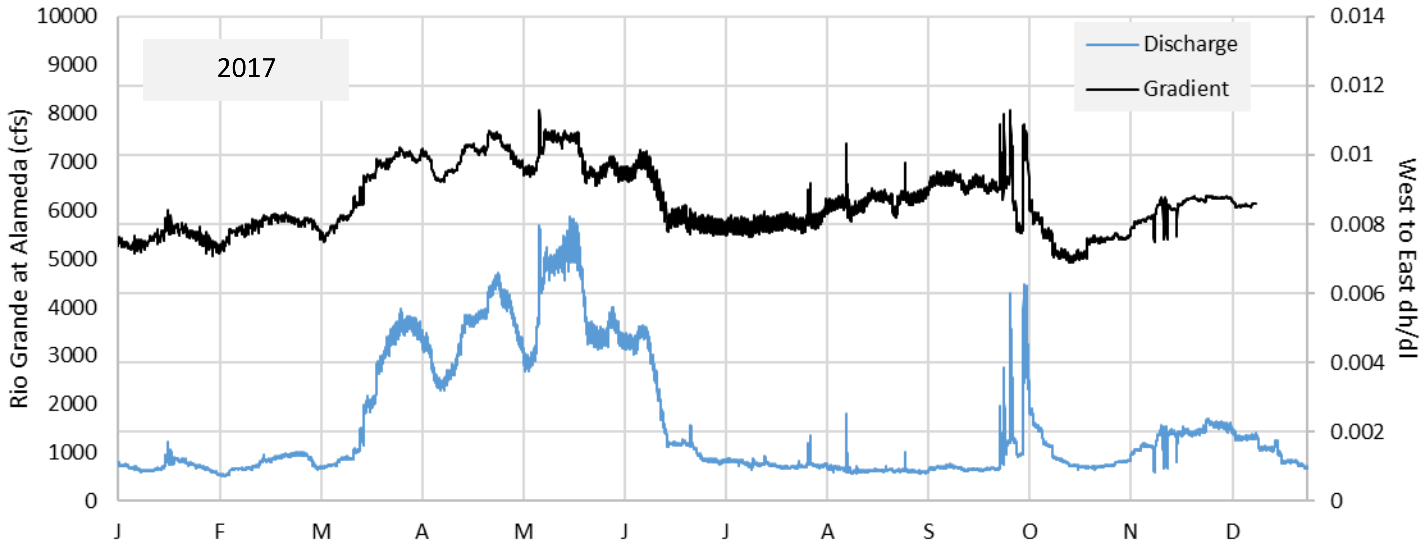
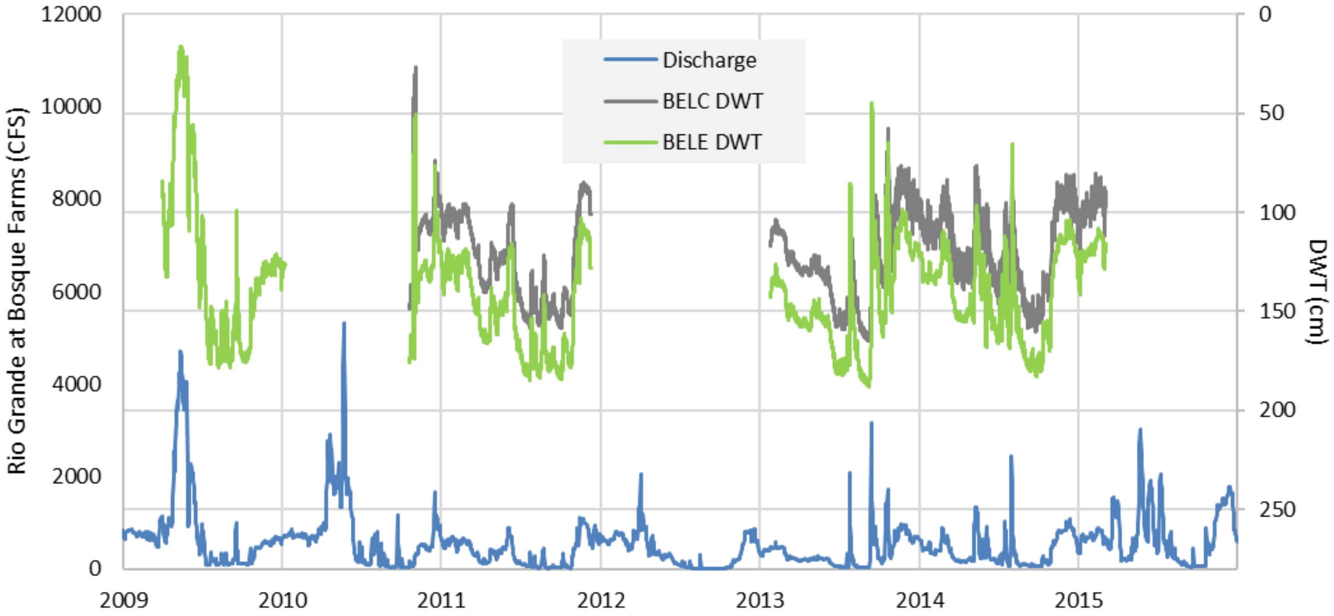


Figure 42. West to East (toward the river channel) hydraulic gradient between the East and West wells at Bobcat, 2017.

Belen

The Belen site PT dataset is quite limited. Only two wells, Center and East, have PT data, and this is spread between three discrete periods prior to 2015 (Fig 43). Depths to groundwater at these two wells ranged from ~20 cm in the spring of 2009 to ~175 cm in the fall of all recorded years. Unfortunately, no flooding events were recorded in the PT data, though the site does experience periodic flooding, including in spring 2017. The wettest year in the Belen record was in 2009, when Rio Grande discharge reached 5000 cfs in the area. Groundwater levels are again tightly correlated with discharge, responding immediately to changes in streamflow. Recession rates after high groundwater events are quite sudden, often exceeding 10 cm/day (Fig 44). In late May 2009, there is a sudden drop in discharge that occurs for several days, before returning to high flows. This pattern is reproduced in the groundwater record, indicating that stage height is the only control on groundwater recession and that there is nothing impeding groundwater recession after streamflow subsides. However, this well is in very close proximity to the stream channel, so it is less surprising to see such drastic responses here. Unfortunately, it was the only well recording at Belen during this event.

Because the East and Center wells are so close together, it was deemed inappropriate in this project to make any analysis or conclusions of the hydraulic gradient based on only these two wells.



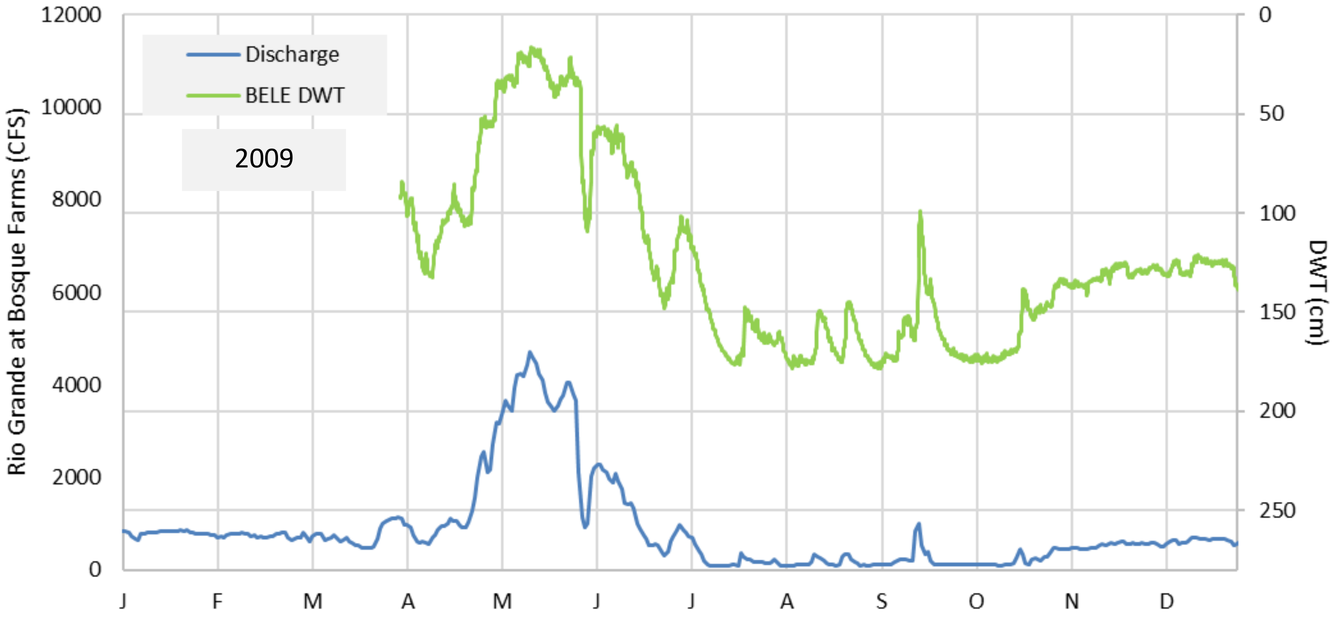


Figure 43. Groundwater levels and discharge at the Belen site for the entire operating period (top), and in 2009 (bottom).

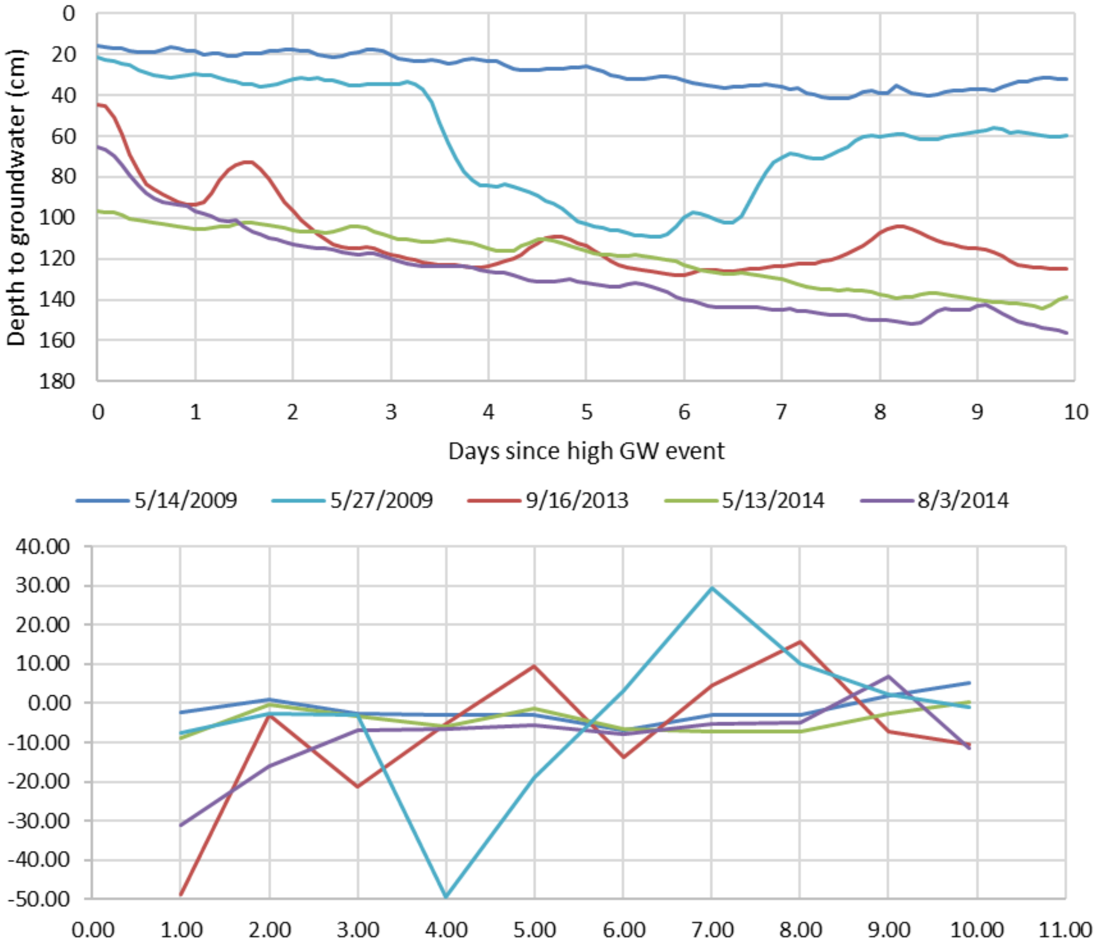


Figure 44. Recessions after high groundwater events at Belen East.

Crawford

Crawford represents the first site in this section that has undergone intensive physical restoration/manipulation of the floodplain. A large portion of the site was lowered to encourage overbank flooding after a certain discharge threshold, about 2500 cfs. It is also the only site that recorded 2017 overbank flooding in the BEMP PT record, indicated by negative depths to groundwater during mid-May at the center well (Fig 46). However, the sharp recession after this time, coinciding with a drop in discharge, illustrates that this site is still susceptible to rapid groundwater recessions, even though it is considered hydrologically well-connected to the river and has relatively shallow water tables on average. After recording the flooding event, both wells experienced water table declines of nearly 50 cm the next several days, simultaneous with the Rio Grande dropping from 4500 cfs to 3000 cfs. Water tables stabilize along with discharge for the following several weeks, before dropping another meter over the subsequent 3 weeks. It is evident again that the only stabilizing influence on groundwater recession is the river stage itself.

A spring event in 2009 presents a rare opportunity. During this year – the first year following bank lowering– the site experienced a successful cottonwood recruitment event in the lowland portions of the site (Eichhorst et al. 2012) after overbank flooding, and the event was captured in the PT record (Fig 48). This spring season serves as one data point regarding suitable groundwater conditions for cottonwood recruitment (Fig 49). Groundwater levels rarely fell by more than 10 cm/day in this period, with several exceptions (the drastic dip in late May observed at the Belen site is repeated here, causing water tables to fall quickly but recover after several days). For the majority of days during this event, the water table did not fall greater than 5 cm/day, and the site never had a period greater than several days in which recession rates exceeded this pace. This may indicate cottonwood seedlings can tolerate some days of fast recession, as long as they are not prolonged or are separated by days with very slow recessions. The sudden drop in discharge/water tables in late May might have been endurable by cottonwood seedlings because levels recovered so quickly afterwards. Sudden drops observed in other years and sites did not have such a recovery and therefore may have been intolerable to cottonwood or other seedlings that depend on bank storage.

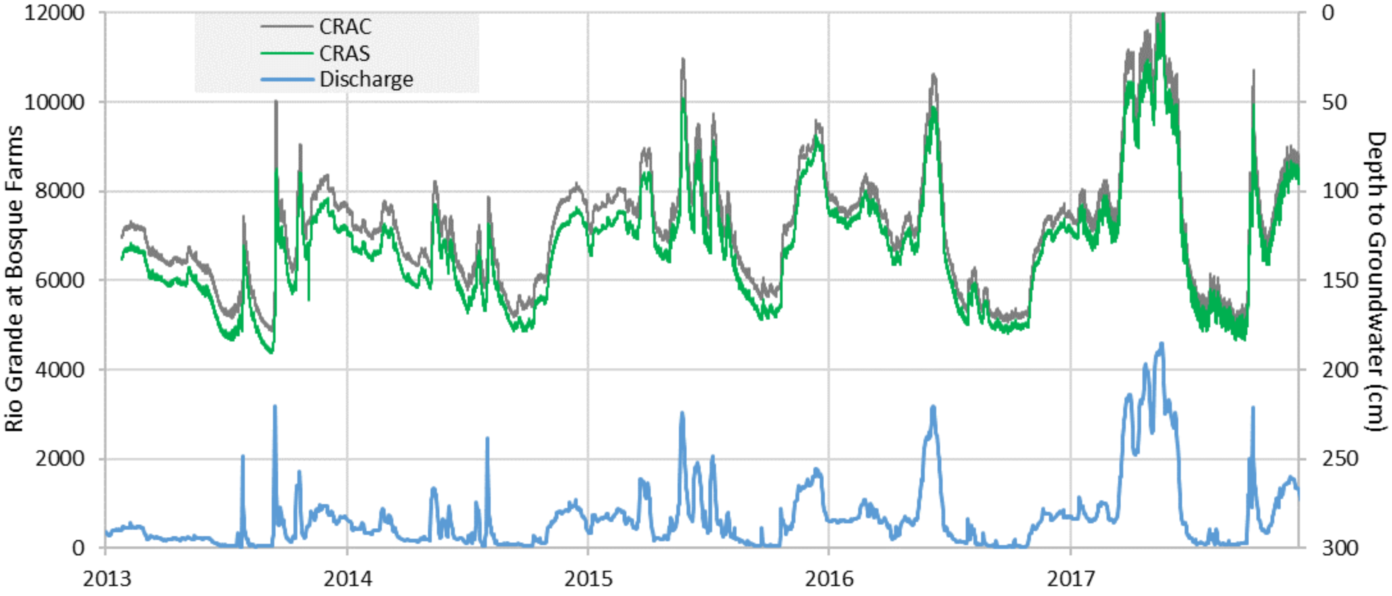


Figure 45. Depth to groundwater at Crawford Center and South, 2013 – 2017

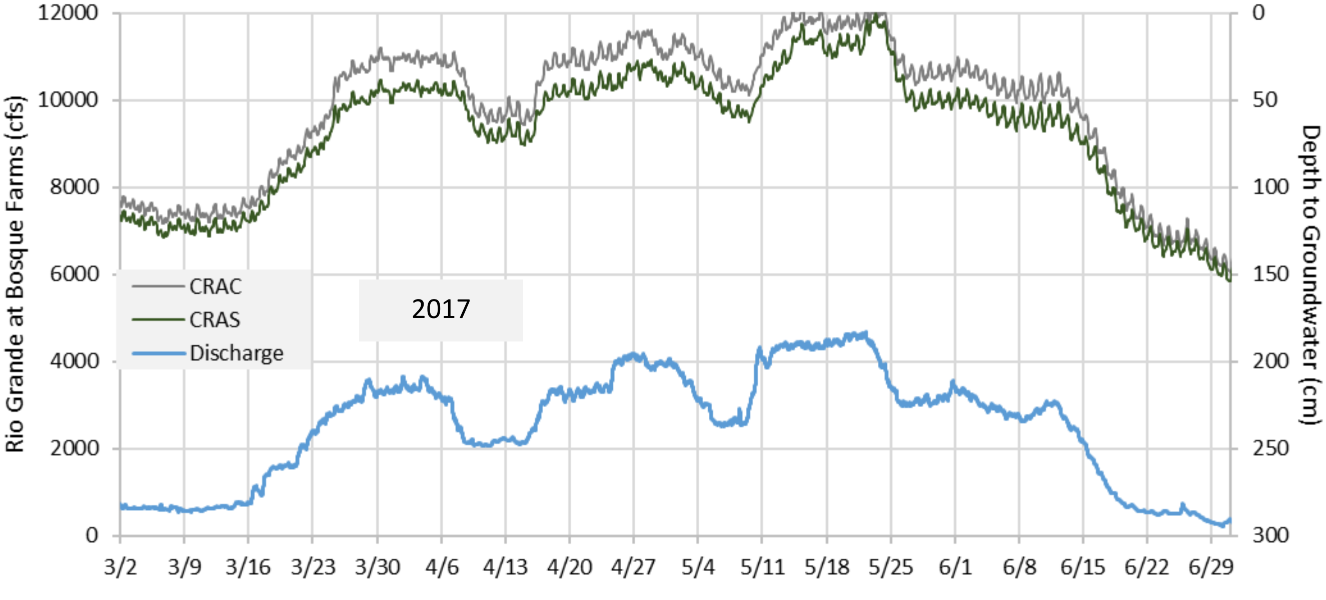


Figure 46. Spring event at Crawford Center and South, 2017.

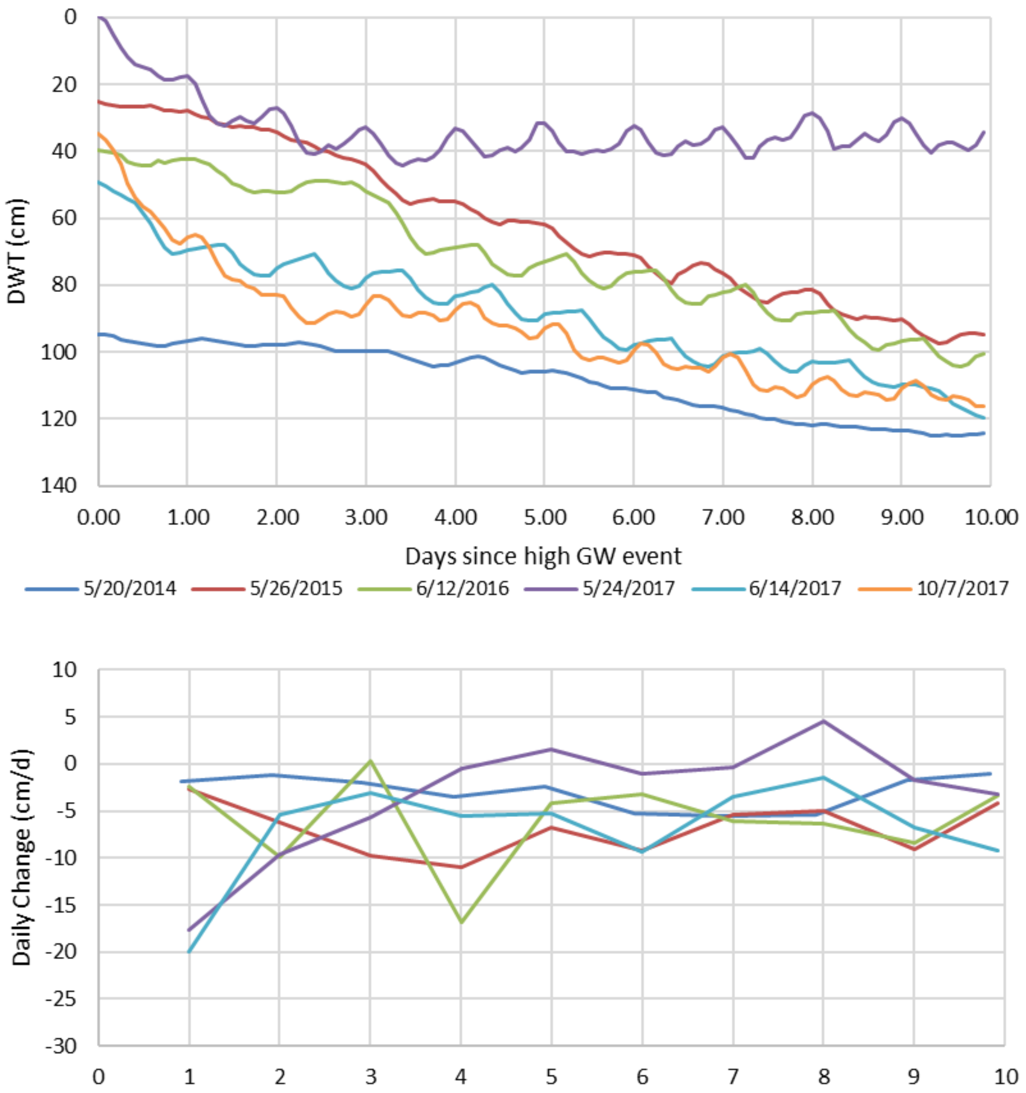


Figure 47. Recessions after high groundwater events at Crawford Center.

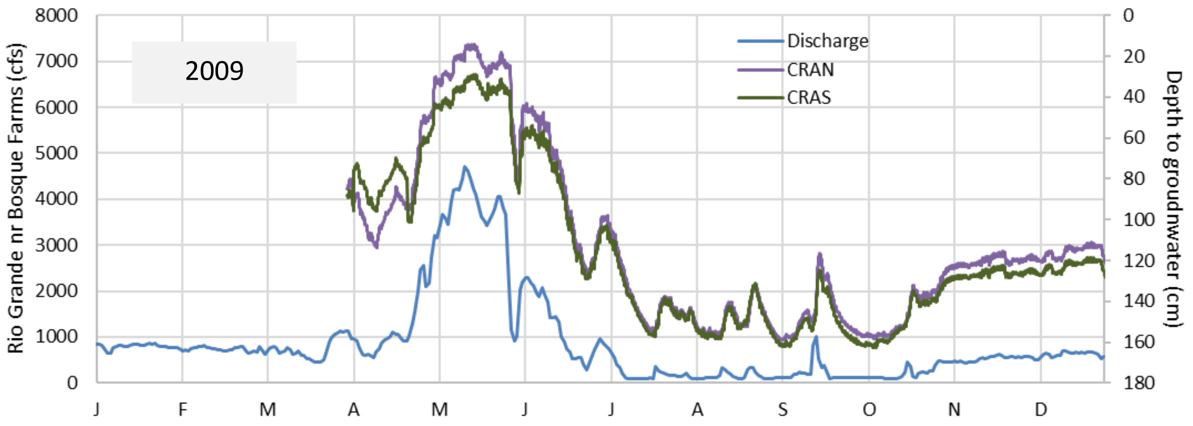


Figure 48. Groundwater levels and river discharge at CRAN and CRAS, 2009.

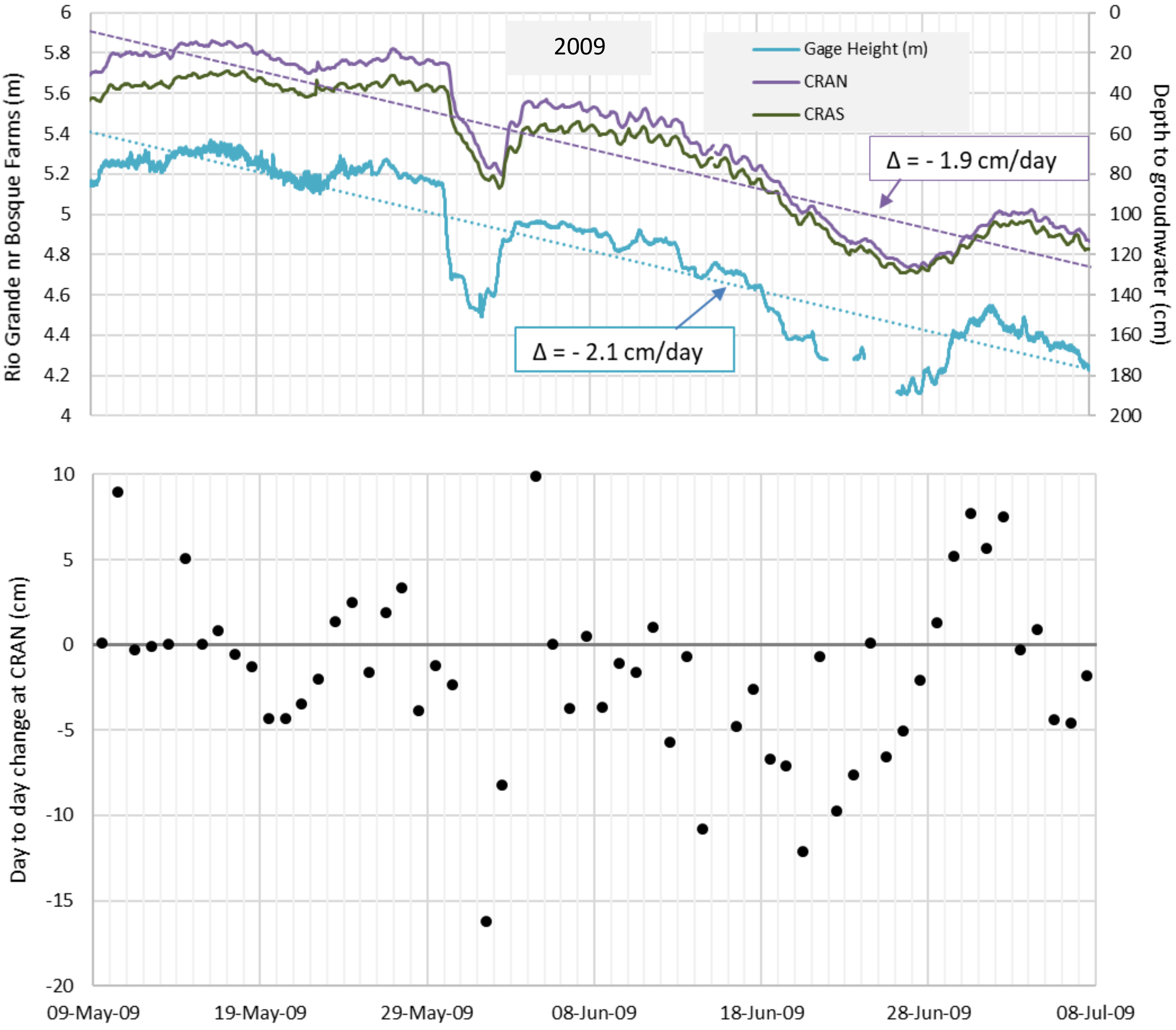


Figure 49. Groundwater levels and day-to-day change in groundwater elevation at Crawford during a cottonwood recruitment event, spring 2009. Average recession rate is included for both stream stage and groundwater levels at Crawford North.

State Land Office

The site at the State Land Office (SLO) in south Albuquerque has also undergone physical restoration. Channels and pools were cut into the riparian zone here to create wetlands. These channels are often wet through the year and experience seep flooding, though they were not dug to be directly connected to the main river channel under normal flow conditions. The SLO Center well is placed in such a channel, and the site experienced seep flooding in 2017. Water tables as captured by SLO West and Center are generally shallow (< 1m), though this site is characterized by a wide variety of landform heights. The SLO South well is placed on such a higher landform, and has average groundwater depths of about 3 meters.

Again, the groundwater levels are strongly influenced by river discharge, but this site more than any other displays a pattern closer to a prototypical natural riparian system. Water tables respond slowly to changes in river discharge, and these responses are more subdued, less erratic than observed at other sites. For example, the sudden drop in discharge in mid-May of 2017 – that at other sites caused water tables to drop by 20-30 cm/day – induced only very slow recessions at State Land Office, never exceeding 4 cm/day. In fact, no groundwater recession event recorded at SLO West and Center exceeded 6 cm/day, by far the slowest and most mediated water table movements observed in this study. Changes in groundwater elevations are also slow to respond after changes in discharge. Peaks and dips in groundwater elevations are delayed by several days from respective changes in discharge.

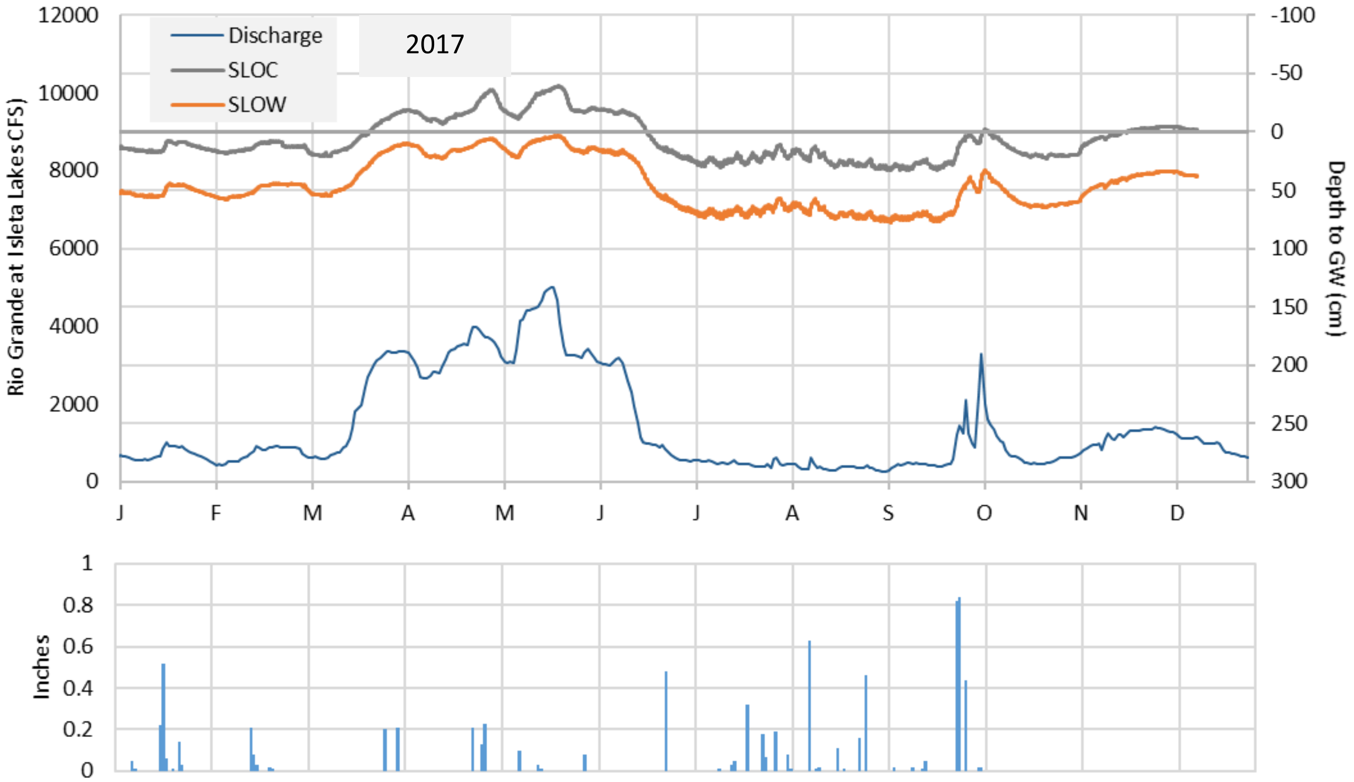


Figure 50. Depth to groundwater at State Land Office, and precipitation at the Albuquerque Airport, 2017.

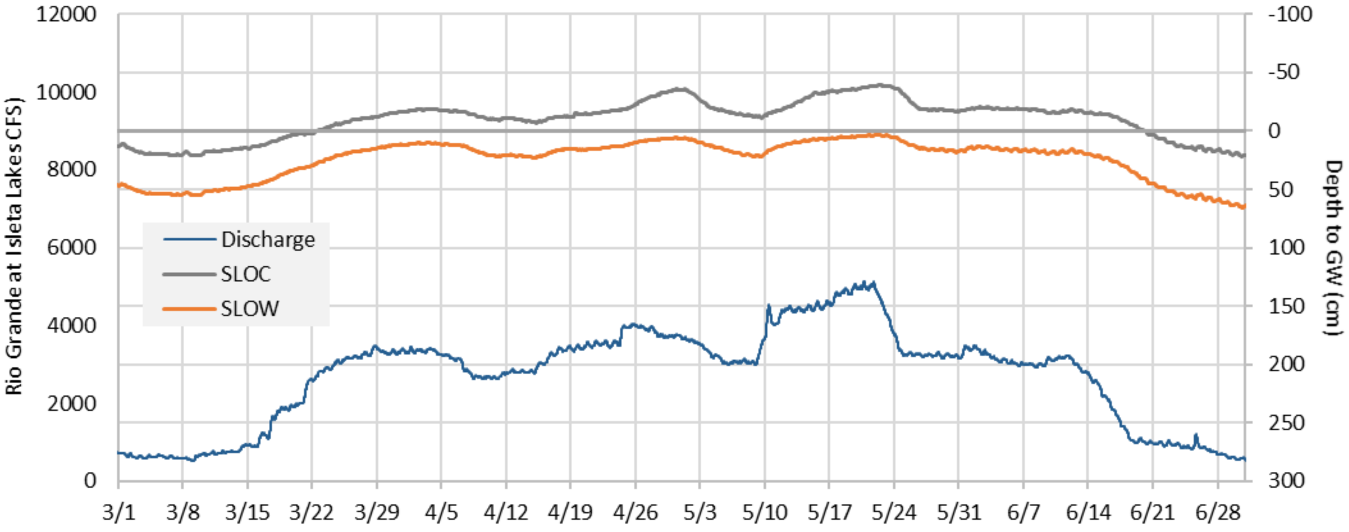
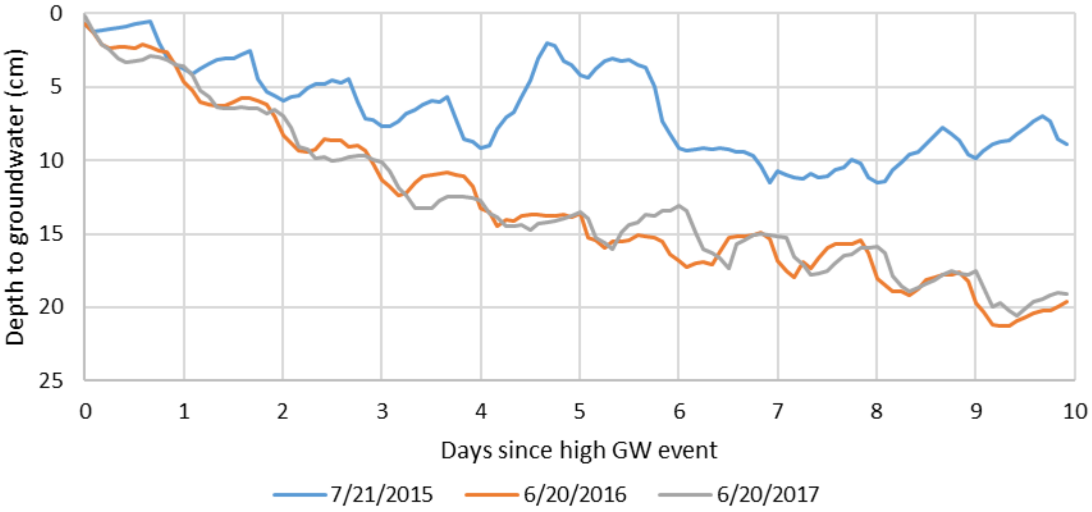


Figure 51. 2017 Spring event at State Land Office.



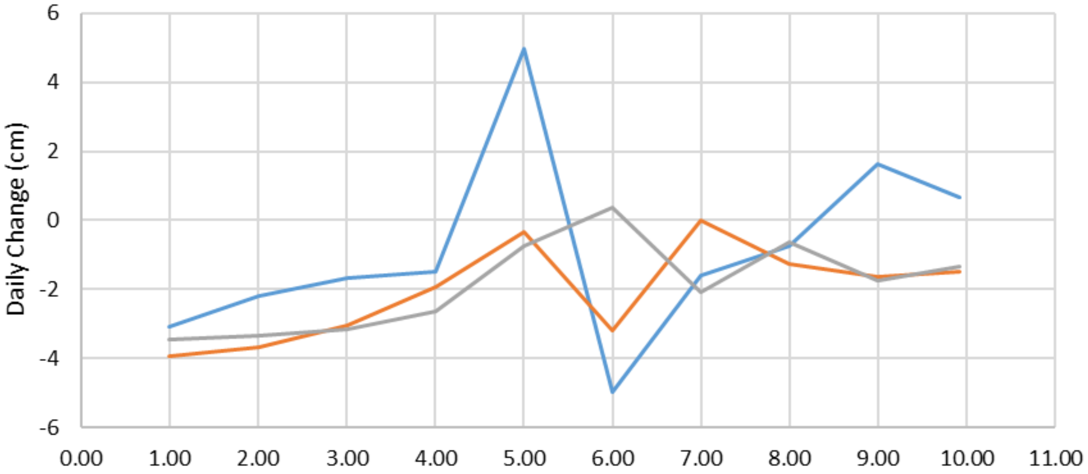


Figure 52. Recessions after high groundwater events at State Land Office Center. Recessions begin when standing water recedes.

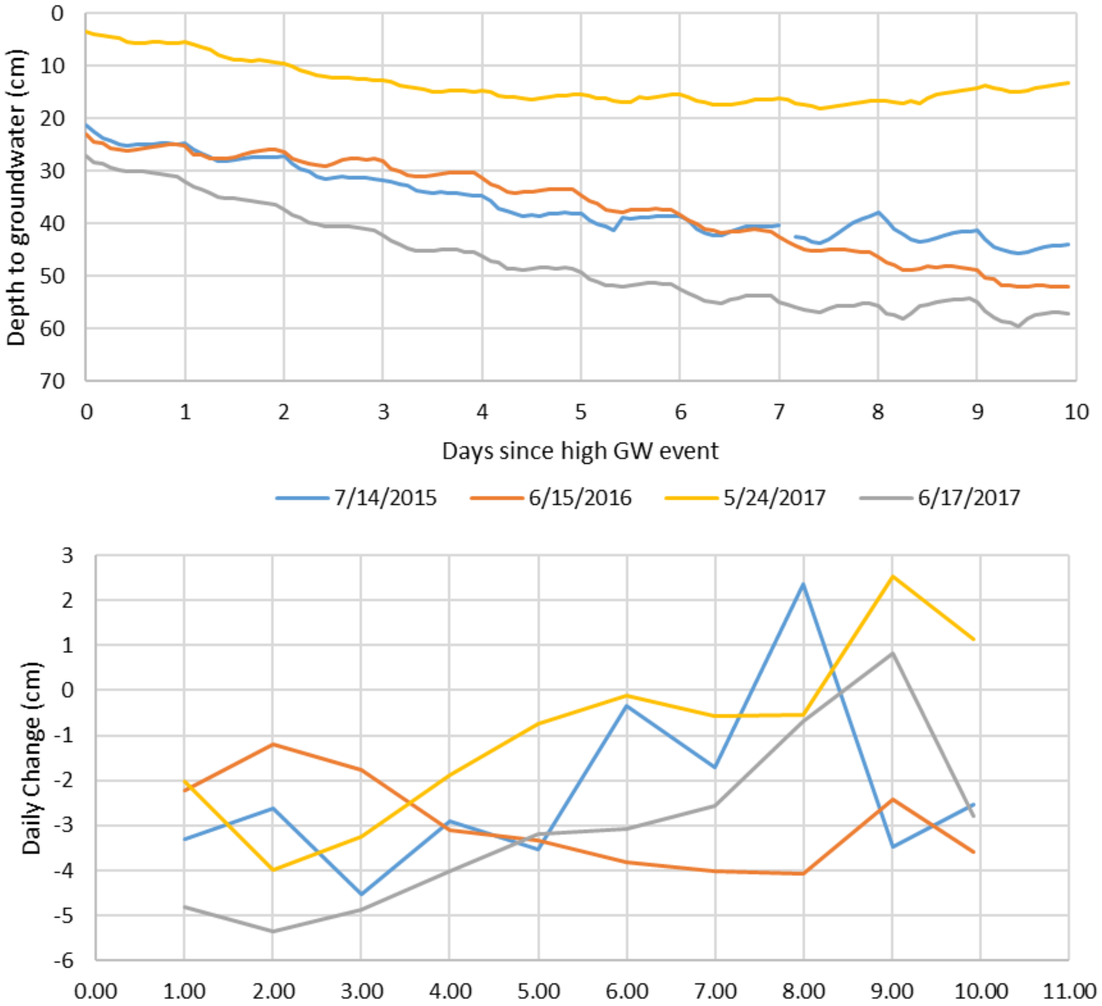


Figure 53. Recessions after high groundwater events at State Land Office West.

Discussion

Throughout the BEMP PT sites, a consistent observation is the high variability of water table levels, and the strong correlation to streamflow. With the exception of State Land Office, groundwater levels respond quickly to changes in discharge, on both the rising and falling ends of discharge events. In many cases, this response occurs virtually simultaneously. By far the strongest driver of groundwater behavior is high discharge events associated with spring snowmelt. Even though summer monsoon events can provoke river discharges with similar magnitudes, spring season events cause the highest and most prolonged elevated groundwater levels. Precipitation events directly and indirectly influence groundwater levels, but with a slightly different and muted response pattern when compared to influences from river discharge alone. Responses during these events are delayed and more gradual when rainfall is the primary forcing.

Bank Storage

Because of the tendency of groundwater levels to respond instantly and considerably to subsiding discharge, bank storage after high discharge events is observed in this study to be transient and with a narrow extent. Groundwater recessions often exceed 10 cm/day, and are observed to at times reach >30 cm/day. Recessions almost always exceed a benchmark rate of 4 cm/day, the experimentally derived maximum tolerable rate of groundwater decline of cottonwood seedlings. The Rio Grande hydrograph is characterized by sudden surges and drops in discharge, especially during spring events. In the midst of the spring 2017 event, Rio Grande discharge at the North Albuquerque sites declined over 2000 cfs over a period of several days in mid-May, and then again dropped a similar amount over the period of a week in early June. Because of the high responsiveness of groundwater levels to river discharge, this coincided with sharp, immediate recessions of groundwater tables at all observed sites, with the exception of State Land Office. These patterns of sudden, fast recessions indicate that groundwater dynamics in the MRG are highly removed from the natural, pre-development state, when cottonwood recruitment – and respective suitable groundwater conditions – occurred periodically.

When applicable, observations of three wells that fall along a transect across the floodplain can illustrate the extent of bank storage in the MRG. While all wells experienced some increase in water table levels during high discharge events, the most significant gains were only observed in the wells closest to the channel, throughout the event. At Diversion, during the spring 2017 snowmelt, the largest groundwater event in the PT record, the water table at 20 meters from the stream channel rose nearly two meters from previous conditions, while elevations at 100 meters from the stream channel only rose close to one meter during the same event. At the Minnow site directly across the stream channel, the pattern is similar. Tables along the stream channel rose over a meter during spring 2017, but only <50 cm rises were observed 75 meters from the channel. Considering the terrestrial floodplain extends about 150 meters from the channel on the east side and about 50 meters on the west side, the profiles indicate that high discharge events significantly raise groundwater levels over only less than half of the riparian zone.

The groundwater recordings during the 2009 cottonwood recruitment event at Crawford indicate that seedlings can in fact tolerate recession rates faster than have been observed experimentally. However, rates during this event were markedly slower than observed at other sites or years, and the faster rates were not prolonged, and were interspersed with periods of slower and/or negligible recession rates. Groundwater levels at Crawford and the other Belen sites are on average shallower than in North Albuquerque, another condition that makes recruitment more likely. Shallower average water tables mean that taproots have to endure receding groundwater for a shorter time before reaching the normal level of water tables, and may lead to slower recession rates due to shallower hydraulic gradients. It is more likely, however, that groundwater here is still so highly tied to streamflow that the groundwater conditions observed during the recruitment event were more due to an uncharacteristically slow reduction in streamflow, rather than inherent morphological or hydrologic characteristics. During the 2009 event at Crawford, it took nearly two months for discharge to return to normal levels after peaking in early May, and the decline was relatively consistent (besides the sudden depression, which was followed by a quick recovery). This corresponds to an average drop in river stage of 2.1 cm/day. In comparison, a 2017 spring event that reached similar magnitudes in streamflow took less than a month to return to normal levels following the peak in discharge, and the decline was characterized by two sudden drops for which there was no recovery. Streamflow, an external control, determines groundwater rates, and the pattern of slowly subsiding discharge observed in spring 2009 may not be the norm.

It is unclear why the groundwater movements at State Land Office are subdued when compared to other sites. It may be a factor of the generally shallow water tables, or a result of the restoration efforts there. Because of data issues such as the lack of survey information, or that the East well often goes dry, little can be said at this point regarding the shape of the groundwater surface here or its relationship to floodplain morphology.

Impact of agricultural drains

The agricultural drains bounding both sides of the Middle Rio Grande are perhaps one of the most directly impactful modifications made to the riparian groundwater system. Their effect on groundwater levels are clear from surface profiles at Minnow and Diversion. At all times throughout the year and during high discharge events, water table surfaces very quickly separate from being parallel to the surface, slope away from the river and converge near a consistent point at the bottom of the drain. This deep incision of the groundwater surface so close to the stream channel is in contrast to natural systems and to the estimated surface of the MRG in pre-development eras (Fig 54). Before the effects of pumping and construction of the drains, the aquifer surface was estimated to have sloped upward regionally, semi-parallel with surface topography (McAda, 2002). In the immediate floodplain / riparian zone, this likely manifested as a broad, shallow, and flat surface. Some areas of the Middle Rio Grande may even have been gaining reaches.

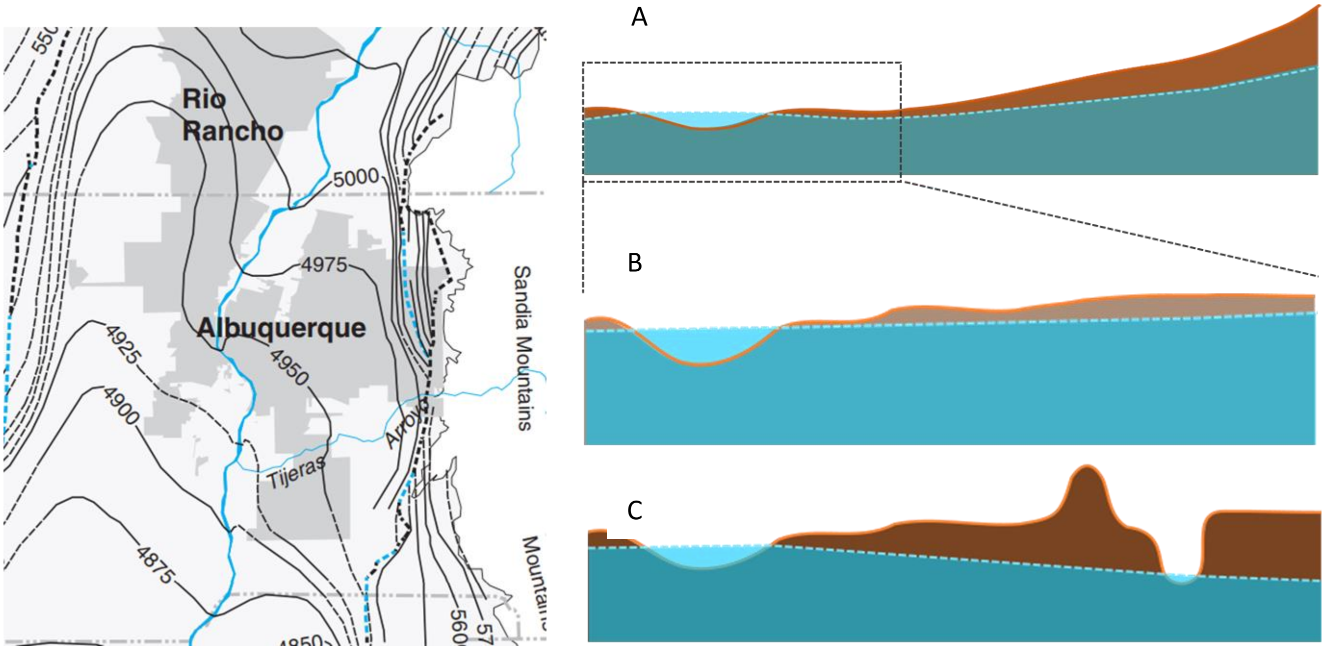


Figure 54. Map of estimated elevations of the pre-development groundwater surface in the Middle Rio Grande (left) (McAda 2002). Generalized profile of the pre-development regional aquifer (A). Detail of pre-development groundwater surface of the riparian area (B). Conceptual model of current day riparian groundwater surface as affected by the deeply excavated agricultural drains, based on observations at Diversion and Minnow.

The primary effect of the drains was to considerably lower the local water table, which was their intended purpose. While successful in lowering water tables in the agricultural portions outside of the drains, it is evident that water tables were also permanently lowered in the immediate vicinity inside/river side of the drains. In dry periods with low stream stage, this has the effect of lowering water tables across the entire riparian zone, as evident by the early October and September 2017 water table surface at Diversion and Minnow (Fig 28, Fig 35). During periods of high-streamflow, such as Spring 2017, the drains keep water tables subdued in areas farther from the channel, even while tables closer to the channels rise drastically. It is evident that the drains have permanently detached many areas of the riparian zone from the shallow, fluctuating groundwater regimes that characterize natural systems.

A secondary effect of the drains is due to their functioning as static boundary conditions in the riparian potentiometric surface, several meters below where it is expected. While stream stages and near-stream groundwater levels fluctuate, sometimes by several meters, the opposite side of the riparian groundwater surface remains comparatively stable, bound by a point located near the bottom of the drain. The stability of this boundary condition is illustrated by the fact that groundwater surface profiles appear to be converging on a singular area in the drain, throughout high discharge events and throughout the year. It is also demonstrated by BEMP's monthly readings of depth to water in the drains, which show that water surfaces in drains remain consistent throughout the year, never deviating by more than 50 cm (Fig 55).

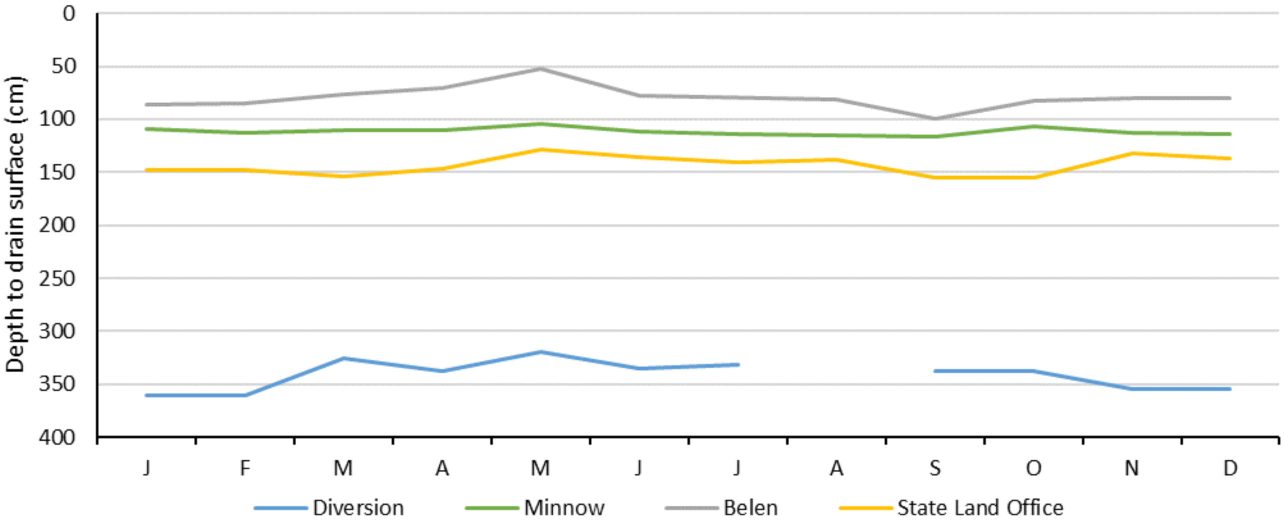


Figure 55. BEMP monthly readings of depth to water surface at the drains of several BEMP sites, 2017. (Data from BEMP 2017)

This static boundary condition induces a permanent hydraulic gradient away from the river, which increases in steepness as stream stages rise. The correlation between discharge and gradient is demonstrated in figures 30, 37 and 42. Not only does the gradient induce a consistent flux from the stream channel itself, it may be part of the reason groundwater recessions are so rapid and unencumbered, and why bank storage so transient. In the natural riparian system of the pre-development MRG, high discharge events would similarly raise water tables adjacent to the stream channel, but because water tables were already shallow and supported by the upward sloping regional aquifer, induced gradients may not have been severe. Likewise, with no drain to intercept the groundwater, bank storage would propagate outward during high stage events, before slowly dissipating after streamflow recedes, restrained by the relatively small differences in hydraulic head between bank storage peaks and regional aquifer levels. Presently, raised water tables near the stream can only be sustained by consistent high stream stage levels, and bank storage cannot propagate because of interception by the drains and the associated induced gradient. Because the immediate water tables near the drain have been lowered by such a degree and made permanent, the elevated water tables near the stream rescind immediately and quickly after stream stage subsides.

Depth and morphology of the drains are likely important in their effect on riparian water tables. The drains at the North Albuquerque sites are uncharacteristically deep, in order to drain the low-lying exterior areas. Drains in the Belen area, however, are relatively shallow and the agricultural areas they service are of generally the same elevation as the riparian zone. It was shown by Isaacson (2009) that in some areas in the MRG, riparian water tables converge at elevations *below* the drains, as possibly influenced by drawdown of the regional aquifer by municipal pumping. It was Isaacson's conclusion that location and morphology of the drain and floodplain determines whether riparian area groundwater surfaces converge to the drains or not.

The impact of the drains after overbank flooding cannot currently be ascertained from the BEMP dataset, as only one site experiences significant overbank flooding during the PT record, and lack of spatial information there hinders analysis.

Past conditions

To assess the deficiencies of the MRG concerning the recruitment and support of native species, it is useful to compare present day conditions to previous times when recruitment did occur. The 1940s were a likely era for recruitment events occurred, based on the general age of mature stands of cottonwoods in the MRG, and the fact that the decade was characterized by several years of high streamflow, including a large flood event in 1942. Drains and levees were in place at this time, but this was before the construction of Cochiti Dam. The effect of the dam is evident when comparing hydrographs from wet years of the 1940s with 2017, the wettest year in the BEMP PT record (Fig 56). Peak annual discharge exceeded 10,000 cfs five times in the decade, a threshold not experienced in the MRG since the construction of Cochiti Dam in 1973. The stream in the 1940s was wide and braided, whereas in 2017 it was a mostly singular, narrow, deepened channel (Fig 57).

There are several possibilities as to why groundwater behavior in 1940s was conducive to cottonwood recruitment even while under the influence of the drains, which would have been exerting similar forcings on the potentiometric surface as in 2017. Drain stage is observed to fluctuate slightly during high discharge events in 2017 (Fig 55), but still functions as a constant head boundary relative to stream stage changes. Floods in the 1940s may have been great enough to overcome the constant head boundary condition normally produced by the drains, as the drains may have filled due to seepage or spillage through or over the levee. Secondly, the spring event hydrographs recede at a slower rate than what is observed in the modern record, limiting the rate of groundwater recession, as the two are highly linked as observed in this study. Lastly, the Crawford event of 2009 demonstrates that recruitment can occur successfully even without perfect groundwater conditions, as long as the other variables of flooding, prepared substrate, and seedfall coincide. All of these speculations allude to the fact that the natural flow regime is still the master variable of native recruitment, and its disruption with the construction of Cochiti Dam is the primary change.

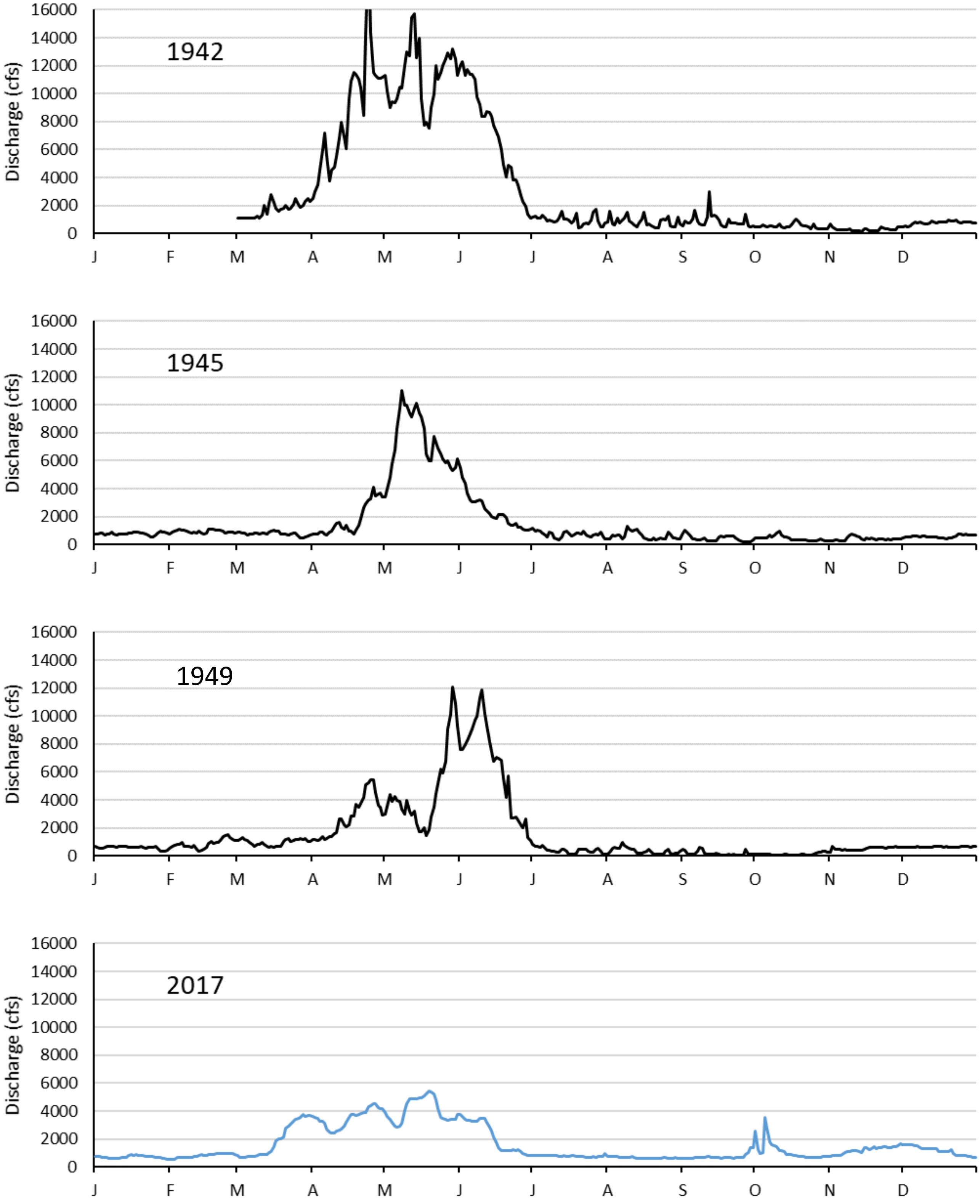


Figure 56. Hydrographs of the Rio Grande at Albuquerque, NM for three selected years in the 1940s, compared to discharge at the same gage in 2017 (Data from USGS).

Figure 57. Aerial imagery of MRG reach containing the Diversion, Minnow, Bobcat, Badger BEMP sites in North Albuquerque, 1949 and 2016 (Imagery from cabq.gov).

Conclusion

The goal of this project was to compile a functional database of BEMP's pressure transducer datasets, assess their accuracy and utility, and demonstrate the use of the data in attempt to evaluate the behavior of groundwater in the MRG riparian zone and potential impacts on native species. A relational database was constructed, and BEMP's data were found to be accurate with few exceptions. Study of the data indicated that groundwater levels are highly tied to streamflow, and groundwater recession is almost solely controlled by the rate of streamflow decline. Bank storage is almost negligible, as only the water tables near the stream channel are elevated during high discharge events, and these elevated tables recede rapidly after streamflow subsides. Drains are believed to have a large impact on these recessions, as they induce a steep gradient away from the river, increasing flux away and down from the stream channel, intercepting the propagation of bank storage ridges, and causing rapid declines in groundwater levels.

There are several ramifications of these observations when considering the future of native riparian systems and potential restoration efforts. It is shown that physical restoration efforts have been successful, in inducing overbank flooding at Crawford, and possibly by encouraging beneficial groundwater behavior at State Land Office. Overbank flooding is still the most important variable for improving the chances of native recruitment, and can be encouraged with bank cutting or experimental flows. However, observations from this study indicate that for both of these strategies, post-flood streamflow reductions should be considered, because of the direct correlation between stage and groundwater recessions. Under current river management, streamflow subsides too rapidly to encourage the slow groundwater recession normally characterized by riparian bank storage. If managed streamflows are to be used in restoration, the falling limb of the hydrograph must be tapered slowly until water tables reach their average level. There is some flexibility though, as the 2009 event at the Crawford site indicates that cottonwoods can tolerate some short-term volatility in the falling limb of the hydrograph, as long as the long-term rate remains gradual.

The effect of the drains poses another consideration for restoration efforts. Observations from this study indicate that they are quite impactful on groundwater behaviors in the riparian zone, by decreasing average groundwater levels in their immediate area and by contributing to the rapid recession rates observed after high discharge events. Negating or removing the effects of the drains could be part of comprehensive planning regarding riparian restoration.

It is also evident from this study that there are many areas in the MRG that are no longer hydrologically appropriate for native recruitment or integrity. This is already well known regarding flood occurrence, as many elevated terraces in the MRG are not likely to experience overbank flooding under current management practices. Observed deficiencies in groundwater behavior may further limit the reaches of the MRG that could be considered suitable for native systems. Areas further from the stream channel have permanently lowered water tables due to the bounding agricultural drains. These areas will likely experience increased desertification without the enhanced soil moisture caused by the capillary fringe of shallow water tables. These areas are likely in transition between that of a riparian wetland to an arid system, more closely resembling the regional environment. This effect is compounded by the changes made to the stream channel, which has limited opportunity for lateral migration and has been deepened flood control measures. Similarly, other areas experience such rapid groundwater declines, even near the stream channel, that native systems may not be successful in regenerating even after overbank flooding.

It is clear that the hydrologic system of the riparian zone has changed, and barring any drastic changes in climate or policy, our expectations for it may need to change as well. There certainly are areas in which the historic system may be preserved, but this study indicates that these areas are rare, and might only be possible through intensive, expensive restoration efforts. That being said, cottonwood forests are not the only system that can provide ecosystem services, habitat, recreation, and general societal utility in the MRG. In some areas, it may be more hydrologically appropriate to replace them with similarly desirable systems, or be allowed to transition to the next successional stage.

The efforts of organizations such as BEMP are integral to the success, health, and sustainability of the invaluable MRG riparian zone, in whichever form it may be. Not only does BEMP provide an extensive amount of study, insight, and advocacy for the MRG ecosystem, the benefits of their inclusion and education of local students is incalculable. It is hoped that the analysis and contributions of this study will help further their goals.

Future work

In the course of this project, some ideas, questions, and hypotheses were developed for which there was not enough time to explore. The datasets collected by BEMP are rich and growing, and – now compiled in a database – there are many avenues for possible future work. Several of these ideas for future work are listed here.

- *Continue the study with a completed, larger dataset*. Spatial data for the currently un-surveyed sites will give more insight as to the shape and nature of MRG groundwater. The sole record of a cottonwood recruitment event (Spring 2009 at the Crawford site) could be better examined with survey data, so that water tables can be placed in context with the floodplain and drain morphology. The distinctive groundwater patters at the State Land Office site could also benefit with spatial context.
- *Quantify or model the relationship between Rio Grande streamflow and observed groundwater behavior.* This could be used to create "ideal" hydrographs within the limits of current climate and policy, which would be helpful when considering restoration projects and possibilities.
- *Comparisons to natural riparian systems.* This project made only speculations as to how the current MRG groundwater regime may be different from natural systems. Ideally, groundwater data from a similar but unregulated stream system could be used in studying these differences. A challenge would be finding a suitable analog to the pre-development MRG, and modeling could be an alternative method for comparison.
- C*omplete the riparian groundwater transects with river channel and drain surface elevations.* Elevations of the river channel at the same temporal resolution as groundwater readings would give better and more detailed insight into the response of local water tables to changes in local changes in stage, rather than the broader interactions as explored in this study based on discharge or nearby gage height. Installing additional pressure transducers in the stream and

drain would be ideal for measuring the water surface elevations, but these could maybe be estimated accurately enough with modeling.

- *Investigate the relationship between water table depth and soil moisture in the MRG.* How much of an influence do changes in groundwater elevation have, and what is the effect we see on ecological diversity and integrity on the surface.
- *Explore policy considerations.* What is the feasibility, risk, and implications of enacting restoration policies that consider the observations made in this project? Namely, experimental flows to encourage slow recession rates after flooding and removing the effect of the riverside drains.

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Appendix A

Pressure Transducer Database
Tables and queries

Tables and fields

Well Metadata: All parameters that the database uses to select or append data from designed queries. This table is still incomplete, as some sites have not been surveyed. The database is primarily in metric units, but imperial unit fields are included here in the case that surveyed elevations or lengths are measured in feet.

Field	**Type**	**Description**
PT ID	Short Text	A four-letter unique identifier for each well (three-letter site abbreviation + well location)
Site	Short Text	Full site name as used by BEMP
Well	Short Text	Specific well (East, West, Center..)
Lat	Double	Decimal degree
Long	Double	Decimal degree
Casing Elevation (m)	Double	Surveyed elevation at the top of the casing
Casing Elevation (ft)	Double	Surveyed elevation at the top of the casing
Cable Length (m)	Double	Length of cable the transducer is suspended from, length from top of casing to the transducer
Casing Height (m)	Double	Length from ground to top of casing, at time of installation or survey. Only to be used to calculate ground or casing elevation from the time of survey, not for depth to groundwater and other queries.
Baro Used	Short Text	The nearest barometric logger ID, which will be used to correct from absolute pressure to water pressure. Three loggers are used in the dataset, also given unique IDs
Ground Elevation (ft)	Double	Surveyed elevation at the ground surface of the well
Ground Elevation (m)	Double	Surveyed elevation at the ground surface of the well

PT GW Data: The repository of all pressure transducer readings, in long form: each record is a single pressure transducer reading. A separated field format for timestamp is used so that (1) records are simpler to relate to other time-based fields such as barometer readings and casing heights, (2) periodic data can be more easily queried, and (3) standardized or proprietary timestamp formats can be more easily built within queries for when data is to be extracted for use in other platforms. All times recorded as Mountain Standard Time (MST UTC -7).

Field	**Type**	**Description**
PT ID	Short Text	
Year	Double	
Month	Double	
Day	Double	
Hour	Double	
Temp (C)	Double	Temperature (C) as recorded by transducer.
Pressure	Double	Absolute, uncorrected pressure head (cm) as recorded by transducer.

Baro PTs: Same format as the PT GW Data table, but for recordings from the three barometric loggers, at the same 30-minute intervals as the groundwater pressure transducers. This allows for correction of the absolute pressures as recorded by the submerged pressure transducers. Barometric loggers are suspended above the water surface in their respective wells.

Field	**Type**	**Description**
PT ID	Short Text	A unique barologger ID, denoted as the same four-letter ID of the well it is housed in, followed by "_b". -BOBN_B for North Albuquerque sites -VFOS_B for Belen sites -SLON_B for State Land Office wells
Year	Double	
Month	Double	
Day	Double	
Hour	Double	
Temp (C)	Double	Temperature (C) as recorded by transducer.
Pressure	Double	Atmospheric pressure head (cm) as recorded by transducer.

CaseHeight: A long-form, monthly data table of casing height at each well over the operating period, compiled from a timeline of casing height changes observed by BEMP staff.

Field	**Type**	**Description**
PT ID	Short Text	
Year	Double	
Month	Double	
CaseHeight	Double	Measured length from ground surface to casing top (m)

Case Height Timeline: The same data as in CaseHeight, but in wide form. In this table each record is only a unique time, and each well's casing height is an individual field. Either format can be used, depending on computer power. The CaseHeight table is referenced in the designed queries so that the relevant casing height is automatically related, but this can be demanding on the host computer. If needed, references to the CaseHeight table in queries can be replaced with the relevant field in the Case Height Timeline table. This reduces the number of fields that need to be indexed and related, and results in faster processing. However, this introduces more sources of human error, so care should be taken in choosing the correct Case Height Timeline field.

Field	**Type**	**Description**
Year	Double	
Month	Double	
BOBE	Double	Casing height at BOBE (cm)
BOBW	Double	Casing height at BOBW (cm)
BOBN	Double	Casing height at BOBN (cm)
…continued for all wells		

BempMonthly: Monthly depth to groundwater readings from BEMP staff and volunteers, as made available on the BEMP.org website. These recordings have been transformed to long-form and assigned the same PT ID. In this way, BEMP's monthly readings can be queried alongside queries of depth to groundwater as measured by the PTs, as a check for accuracy and utility.

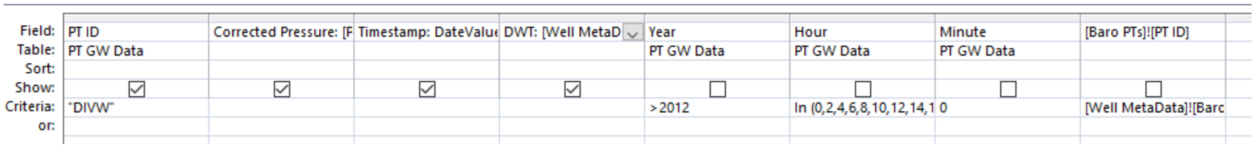
Field	Type	Description
PT ID	Short Text	Same IDs used throughout the database
Year	Double	
Month	Double	
Day	Double	
BEMP DWT	Double	Depth to water table from the ground surface (cm)

Queries – extracting data

<u>PT Data Extract – Depth to Water Table:</u> This query outputs depth to water table in cm, based on user defined PT IDs and time ranges (Fig 1). Tables PT GW Data, CaseHeight, Baro PTs, and Well MetaData are related by PT ID and separated timestamp fields. A field that creates a merged timestamp is included for easier post-output analysis.

The depth to water table for the respective PT ID is calculated from related tables as:

*(Cable Length*100) – (CaseHeight*100) – (Absolute Pressure – Barometric Pressure).*



Field:	PT ID	Corrected Pressure: [F	Timestamp: DateValue	DWT: [Well MetaD	Year	Hour	Minute	[Baro PTs]![PT ID]
Table:	PT GW Data				PT GW Data	PT GW Data	PT GW Data	
Sort:								
Show:	☑	☑	☑	☑	☐	☐	☐	☐
Criteria:	"DIVW"				>2012	In (0,2,4,6,8,10,12,14,1	0	[Well MetaData]![Barc
or:								

Figure 1. An example query of Depth to Water Table in design view for extracting depth to groundwater every two hours at the Diversion West well, for years after 2012.

The default is for the query to automatically use the appropriate barometric logger based on the user-defined groundwater PT ID. For slower computers, the query performs faster when instead the user also defines the correct barometric logger. However, this a source of human error, so care should be taken to select the correct barometer PT ID.

<u>PT Data Extract – Depth to Water Table – SLO:</u> This is an identical query only for using State Land Office PT data, as raw pressure readings at this site need a correction factor applied. The use of this query is the same.

<u>PT Data Extract – GW Elevation:</u> This query outputs elevation (NAVD88) of the groundwater surface in meters, based on user defined PT IDs and time ranges. Tables PT GW Data, Baro PTs, and Well MetaData are related by PT ID and timestamp fields. The groundwater elevations are calculated as:

(*Casing Elevation) – (Cable Length/100) + (Absolute Pressure – Barometric Pressure)/100*

Note: This query may result in erroneous values, as it does not account for changing casing heights. An alternative method for determining groundwater elevation is to use the Depth to Water Table query and subtract the output from the surveyed ground surface elevation.

<u>PT Data Extract – Pressure and Parameters</u>: This query makes no calculations or corrections, but outputs all relevant readings and parameters for the defined PT ID and date ranges. This can be used for checking raw recordings and measurements, or for manual calculations post-output. Outputted fields include separated date and time fields, absolute pressure, barometric pressure, casing height, and cable length. The user must specify the correct barometer logger ID.

<u>PT Data vs Monthly Data:</u> A query used for comparing depth to water table as measured by BEMP staff and volunteers during monthly monitoring, and as calculated by the PT readings. Based on a user submitted PT ID, the query outputs monthly readings of depth to groundwater from BEMP, and depth to groundwater from the PT record at 12:00 PM on the same day as the BEMP reading, and a field of the difference between the two, in cm.

Appending New Data

Incoming pressure transducer data can be appended to the main repository table “PT GW Data” either by importing directly into the table (if the raw data is in table form), or by importing into a new table and appending to PT GW Data by a query. If importing directly, all incoming fields must match those in the PT GW Data table. These include segregated timestamp fields, and a PT ID field, which must be populated previously to import. If importing to a new table to be appended, fields can be created during the append query with the appropriate criteria. The simplest way to append a year’s worth of PT data would be to assemble and transform all of the year’s datasets into one using a more flexible data manipulation platform such as R or Excel, then appending the assembled dataset into the database with a single import or query.

The “Location” field in the raw PT data collected for each site could be used to relate to the PT IDs used in the database, so that PT IDs don’t need to be added manually, which introduces a source of error. This was not done for this study, as many of the BEMP datasets did not have a location field, but the field should be included in future press transducer data retrievals to make addition to the database easier.

Appendix B

Data validation and utility

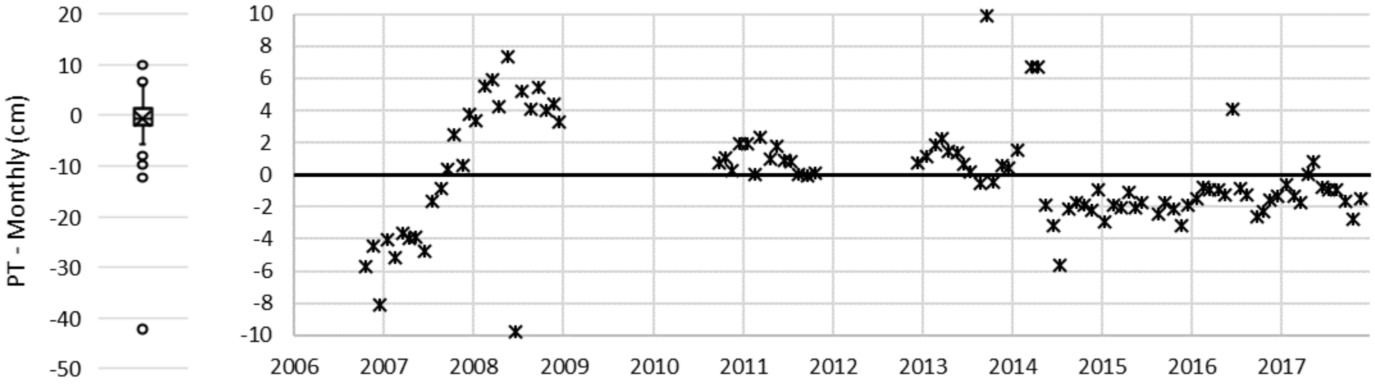
Measures of depth to water table (DWT) are compared between BEMP's monthly measurements (Monthly) and those calculated by the PT database (PT). Discrepancies in DWT between the two samples of each site were analyzed by mean (μ), standard deviation (std), normalized Euclidean distance (NED), and the proportion that were within 5 cm of difference ($P_{<|5|\text{cm}}$). Discrepancies are measured as (PT) – (Monthly).

As these metrics alone don't give a comprehensive understanding of the accuracy and utility of the PT dataset, the differences are additionally plotted in a boxplot and timeseries. Boxplots include the full range of measured differences. Timeseries plots have y-axis ranges of -10 cm to 10 cm, in order to make small details over time more visible. In two cases, wells VFOC and CRAE, a wider axis range in the timeseries is used to display anomalies in those datasets.

Statistical measures, boxplots and timeseries plots of (PT) – (Monthly) for all wells in the BEMP PT database are listed here.

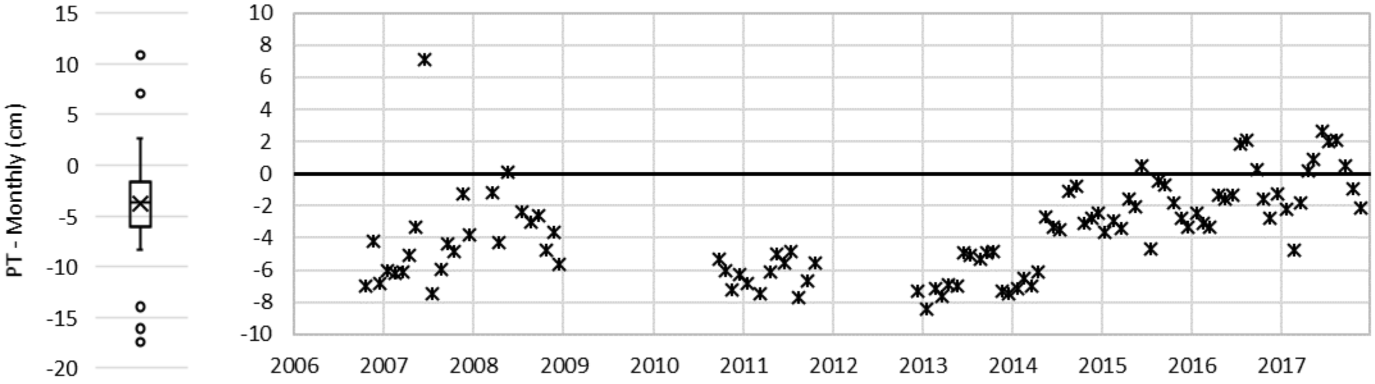
Bobcat East (BOBE)

μ = -0.68 cm std = 5.39 cm NED = 0.53 cm P $_{<|5|cm}$ = 0.85



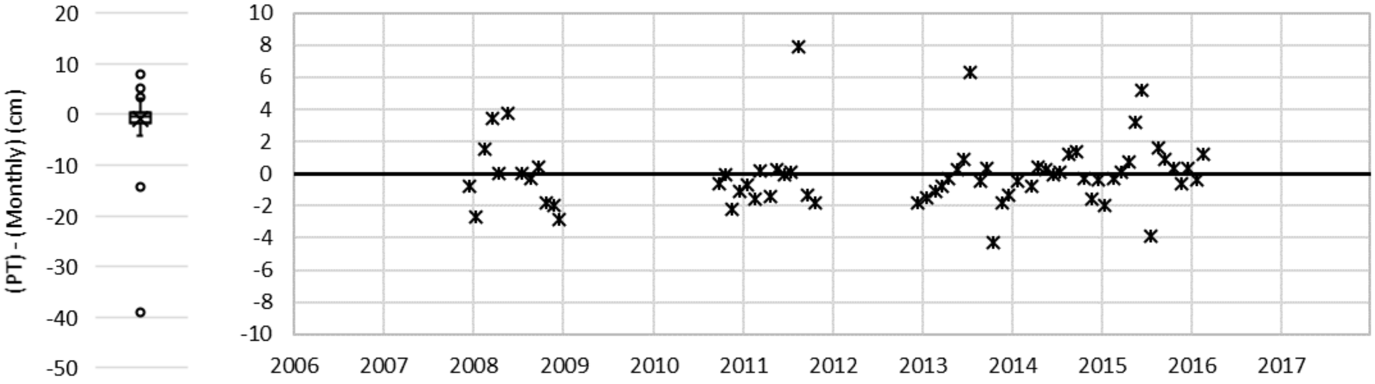
Bobcat West (BOBW)

μ = -3.81 cm std = 3.84 cm NED = 0.54 cm P $_{<|5|cm}$ = 0.61



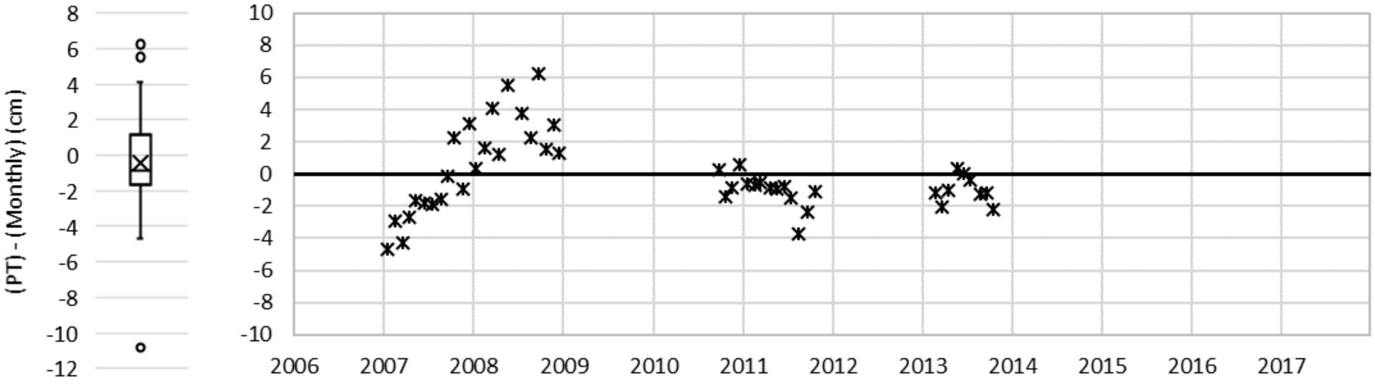
Bobcat North (BOBN)

μ = -0.85 cm std = 5.48 cm NED = 0.68 cm P $_{<|5|cm}$ = 0.92



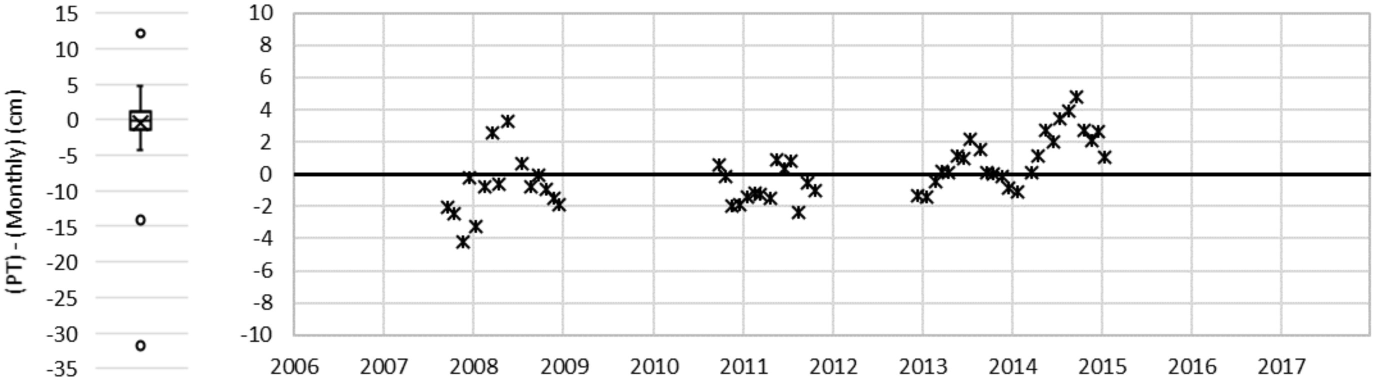
Bobcat South (BOBS)

μ = -0.43 cm std = 2.79 cm NED = 0.41 cm $P_{<|5|cm}$ = 0.94



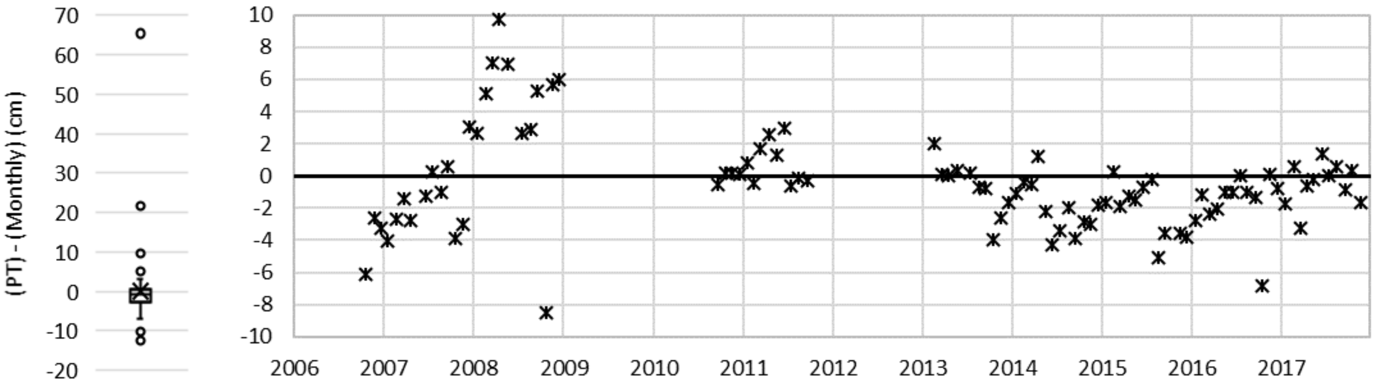
Bobcat Center (BOBC)

μ = -3.31 cm std = 5.22 cm NED = 0.54 cm $P_{<|5|cm}$ = 0.61



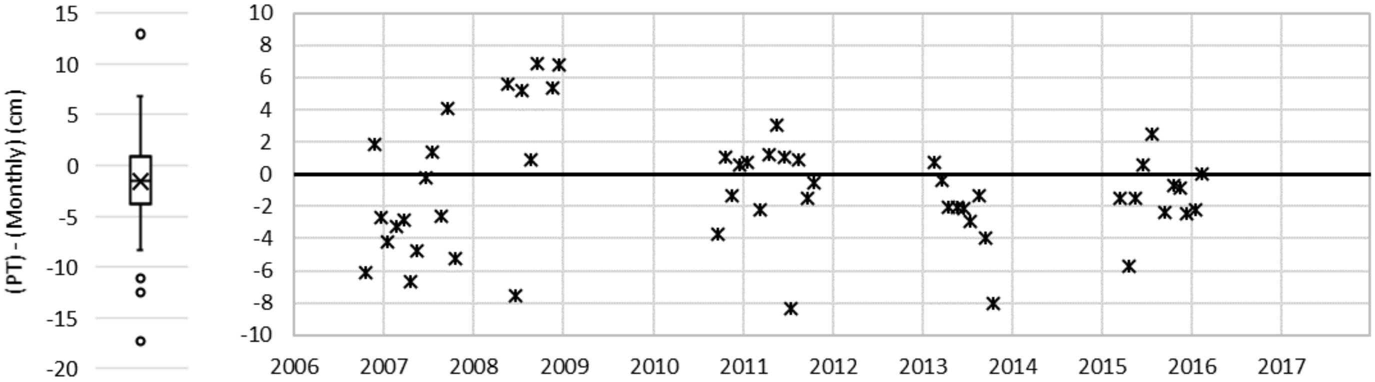
Badger East (BADE)

μ = 0.10 cm std = 7.75 NED = 0.78 cm P $_{<|5|cm}$ = 0.85



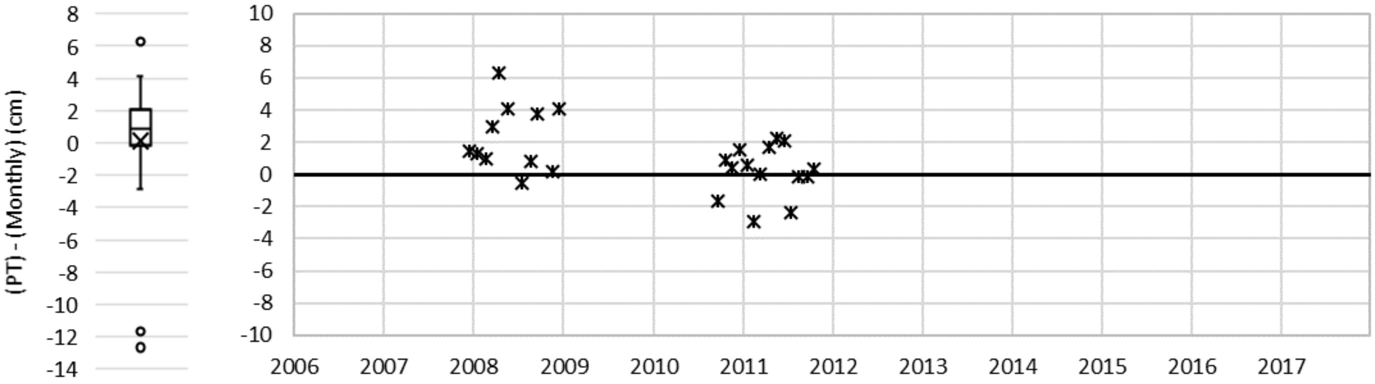
Badger West (BADW)

μ = -1.60 cm std = 5.01 cm NED = 0.68 cm P $_{<|5|cm}$ = 0.71



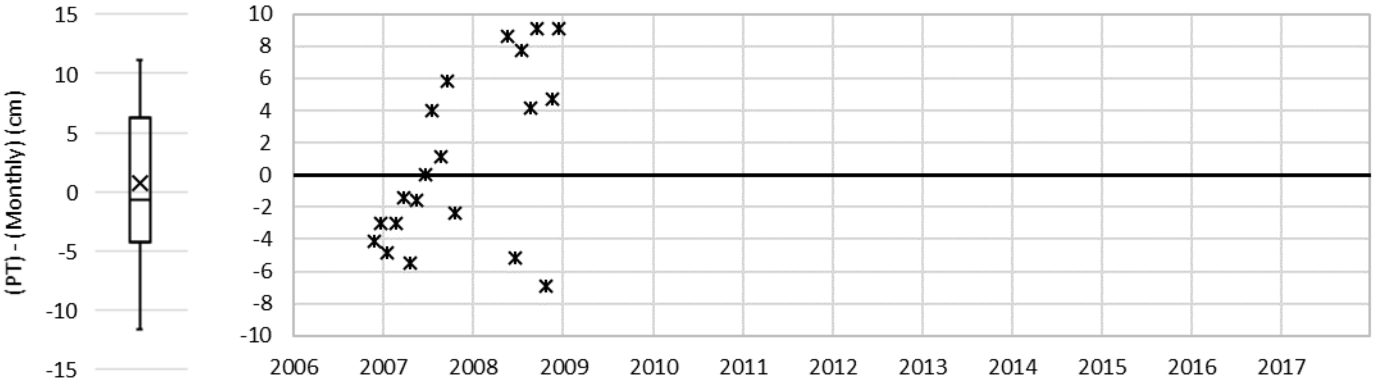
Badger North (BADN)

μ = 0.13 cm std = 4.07 cm NED = 0.80 cm P $_{<|5|cm}$ = 0.89



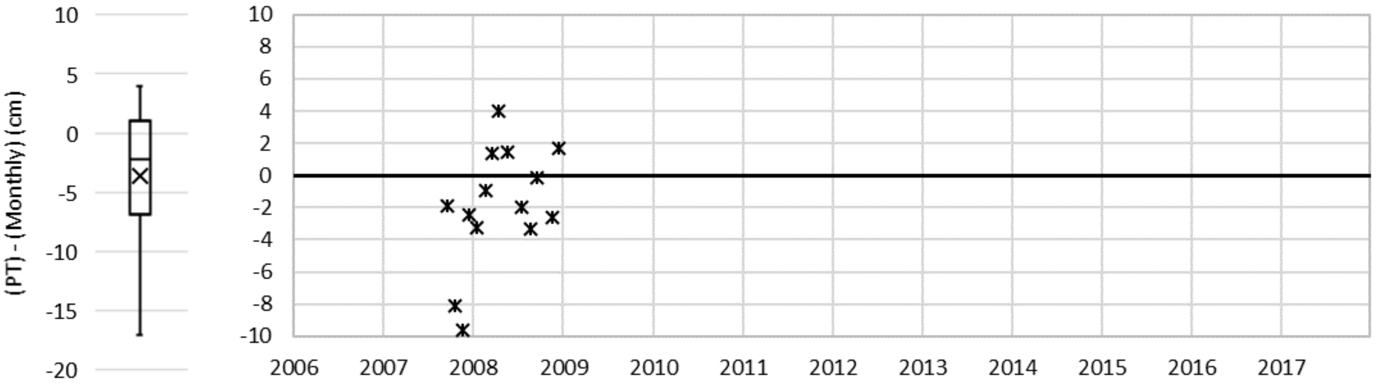
Badger South (BADS)

μ = 0.72 cm std = 6.20 cm NED = 1.30 cm $P_{<|5|cm}$ = 0.55



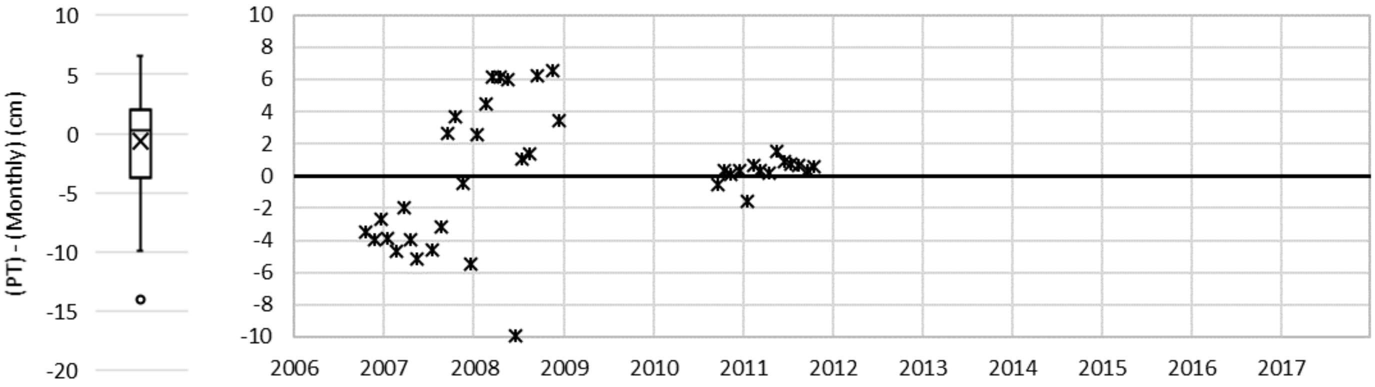
Badger Center (BADCC)

μ = -3.60 cm std = 5.92 cm NED = 1.69 cm $P_{<|5|cm}$ = 0.75



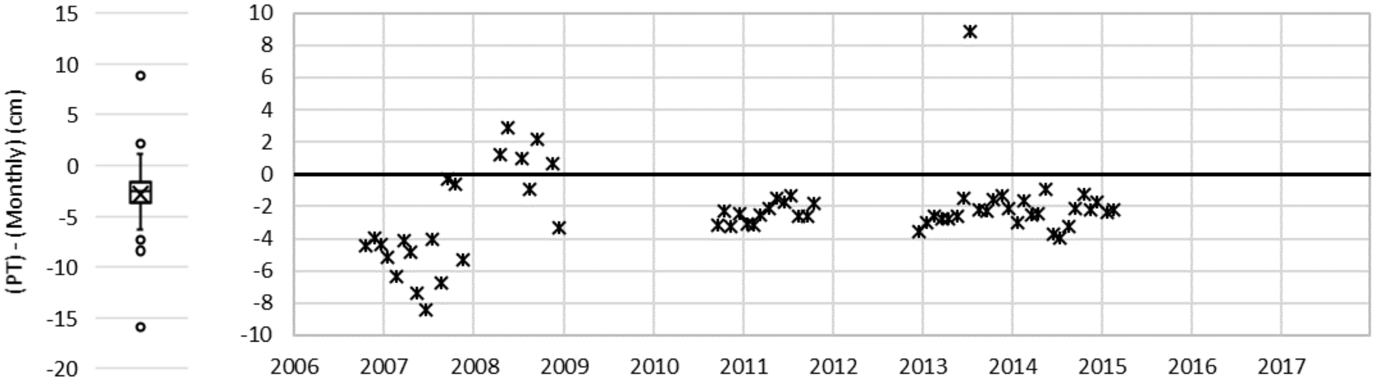
Minnow East (MINE)

μ = -0.64 cm std = 4.75 cm NED = 0.74 cm $P_{<|5|cm} = 0.76$



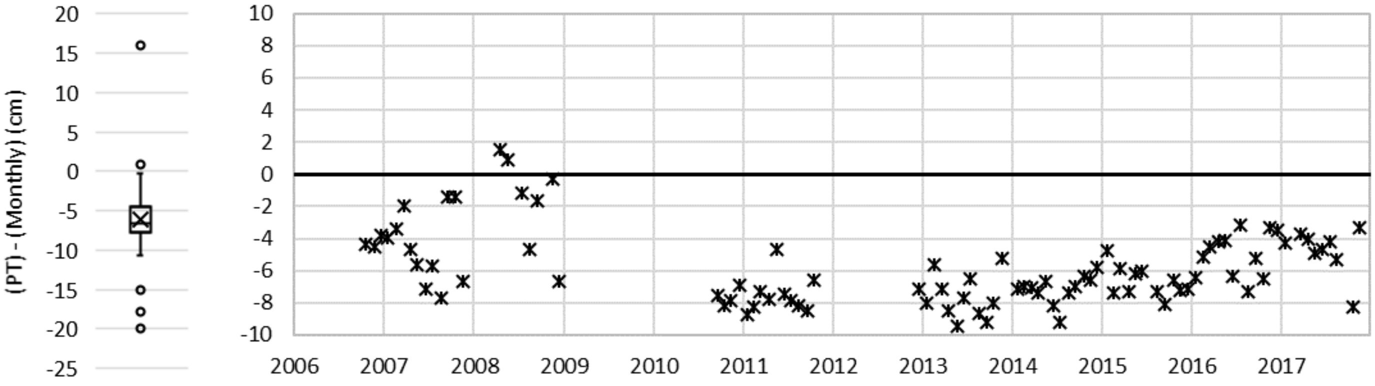
Minnow West (MINW)

μ = -2.82 cm std = 3.39 cm NED = 0.55 cm $P_{<|5|cm} = 0.86$



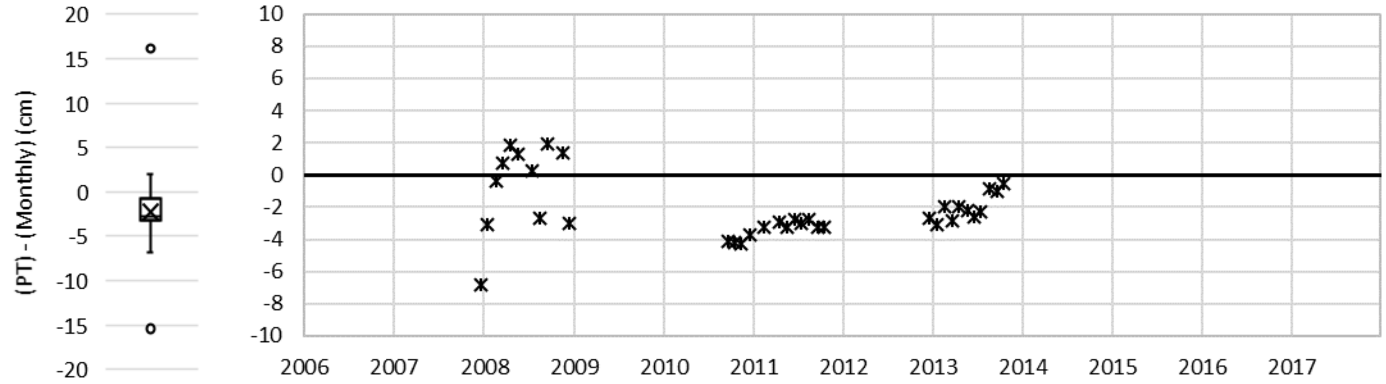
Minnow North (MINN)

μ = -6.16 cm std = 3.95 cm NED = 0.74 cm $P_{<|5|cm} = 0.31$



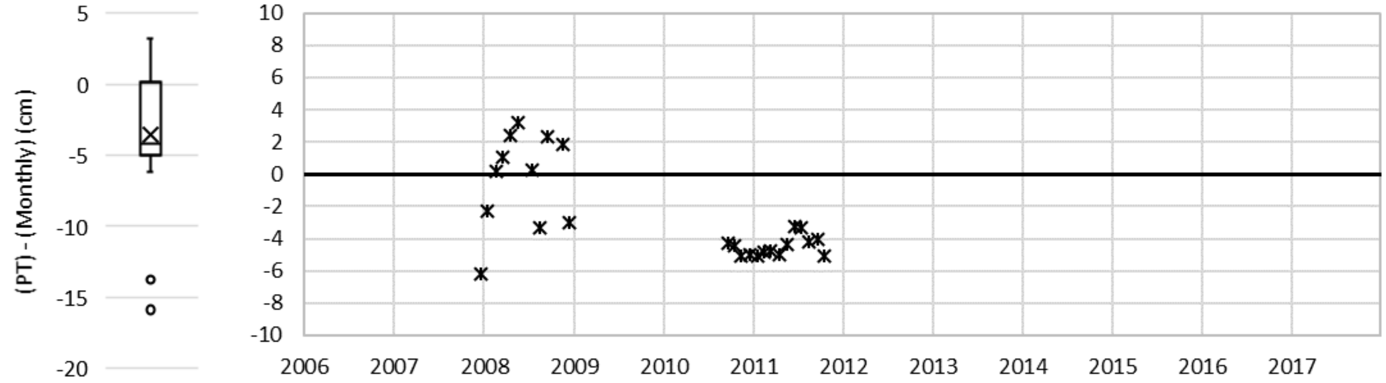
Minnow South (MINS)

$\mu = -2.30$ cm   std = 4.69 cm   NED = 0.85 cm $P_{<|5|cm} = 0.89$



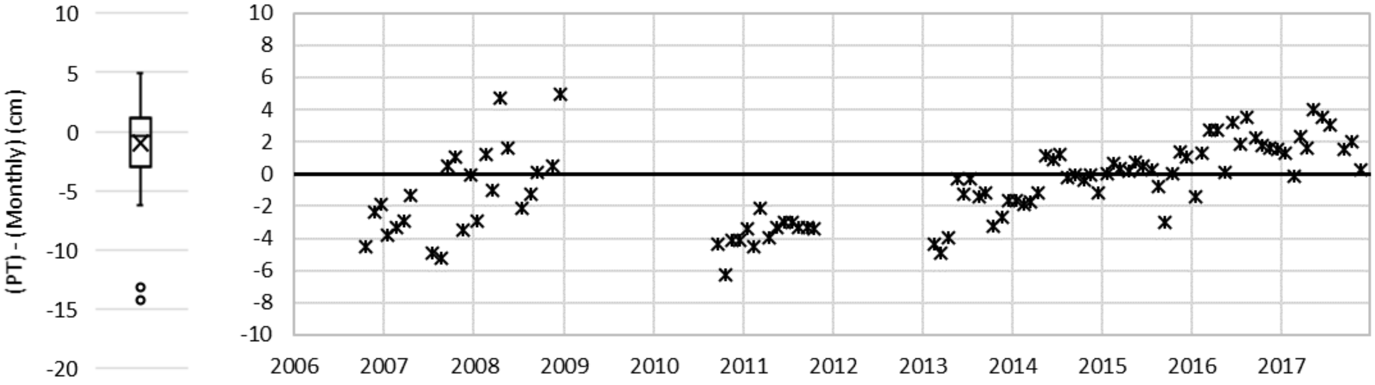
Minnow Center (MINC)

$\mu = -3.54$ cm   std = 4.28 cm   NED = 1.06 cm $P_{<|5|cm} = 0.74$



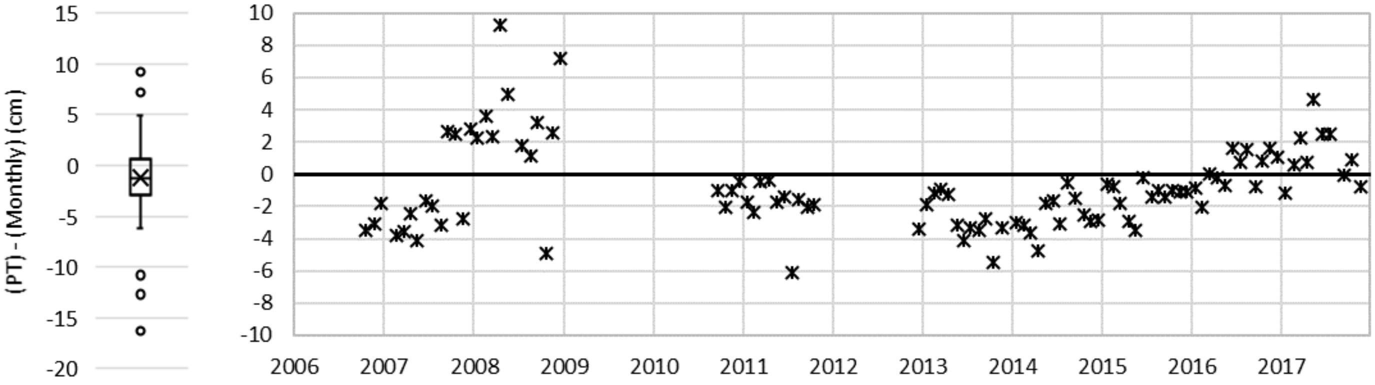
Diversion East (DIVE)

μ = -0.98 cm   std = 3.10 cm   NED = 0.33 cm $P_{<|5|cm}$ = 0.96



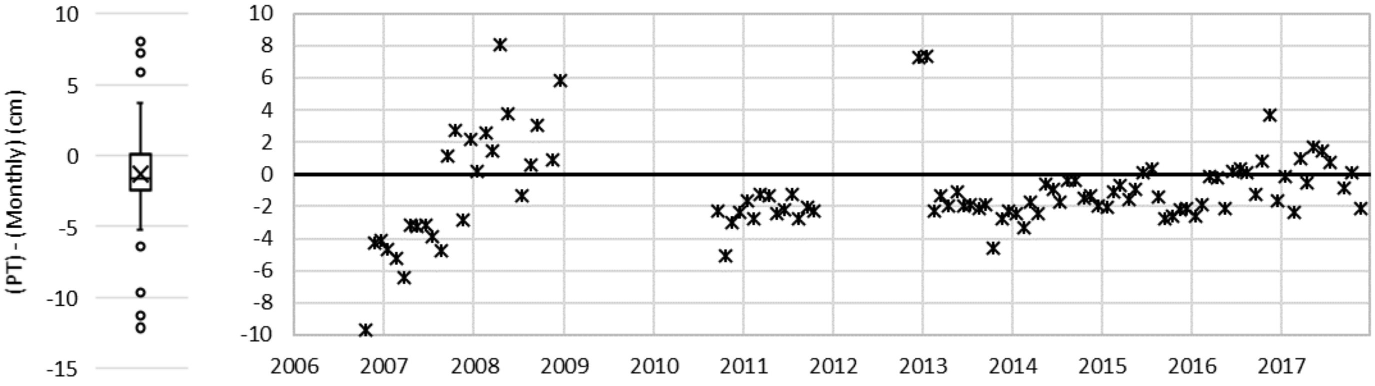
Diversion West (DIVW)

μ = -1.22 cm   std = 3.36 cm   NED = 0.36 cm $P_{<|5|cm}$ = 0.93



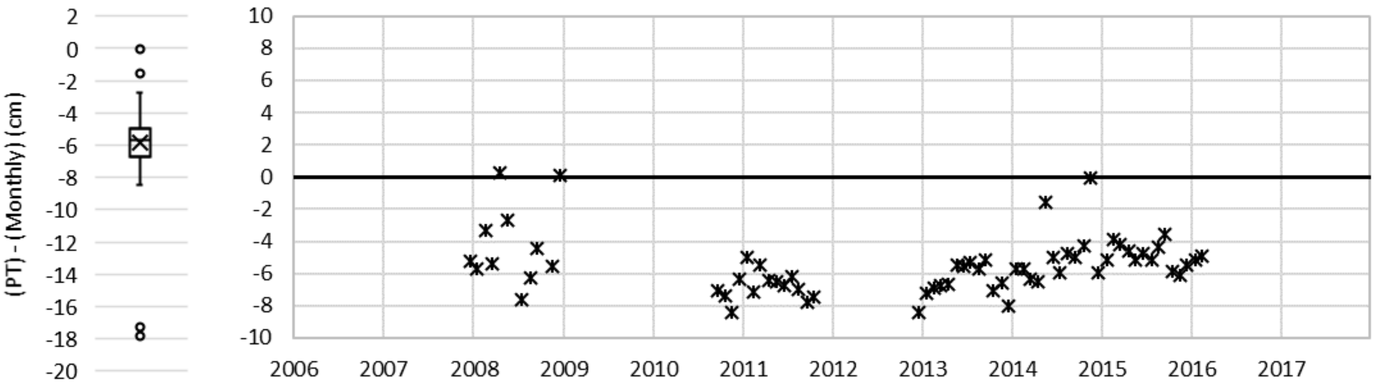
Diversion North (DIVN)

μ = -1.31 cm   std = 3.05 cm   NED = 0.33 cm $P_{<|5|cm}$ = 0.90



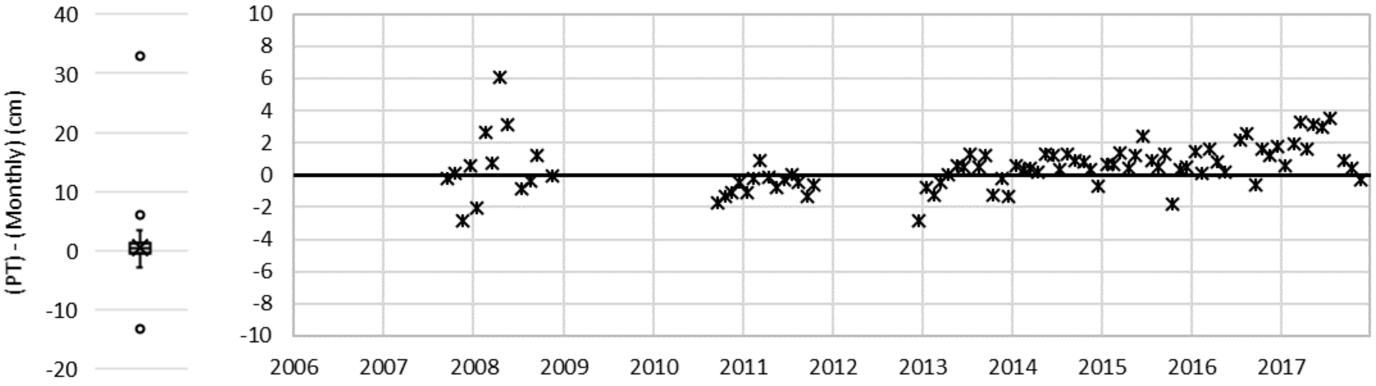
Diversion South (DIVS)

μ = -5.85 cm std = 2.74 cm NED = 0.79 cm $P_{<|5|cm}$ = 0.26



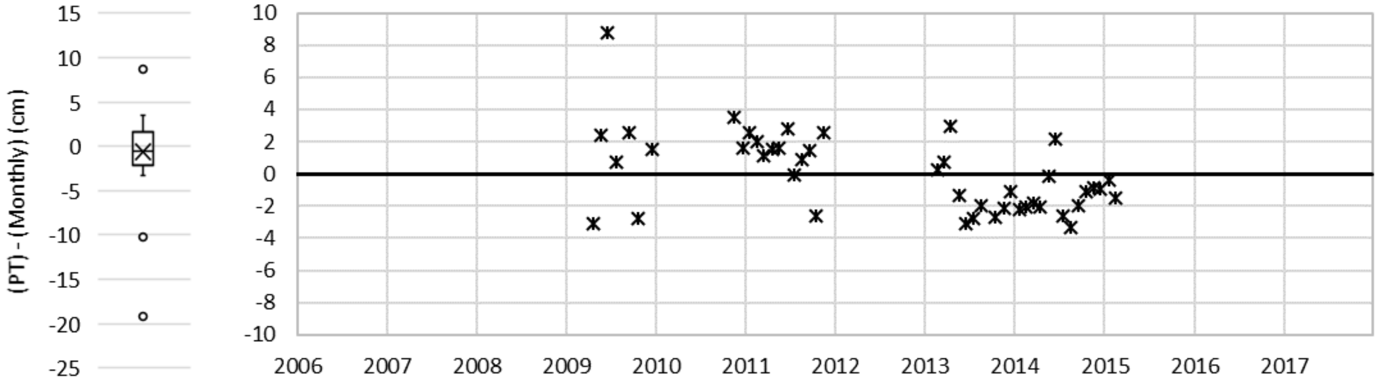
Diversion Center (DIVC)

μ = 0.56 cm std = 4.26 cm NED = 0.46 cm $P_{<|5|cm}$ = 0.95



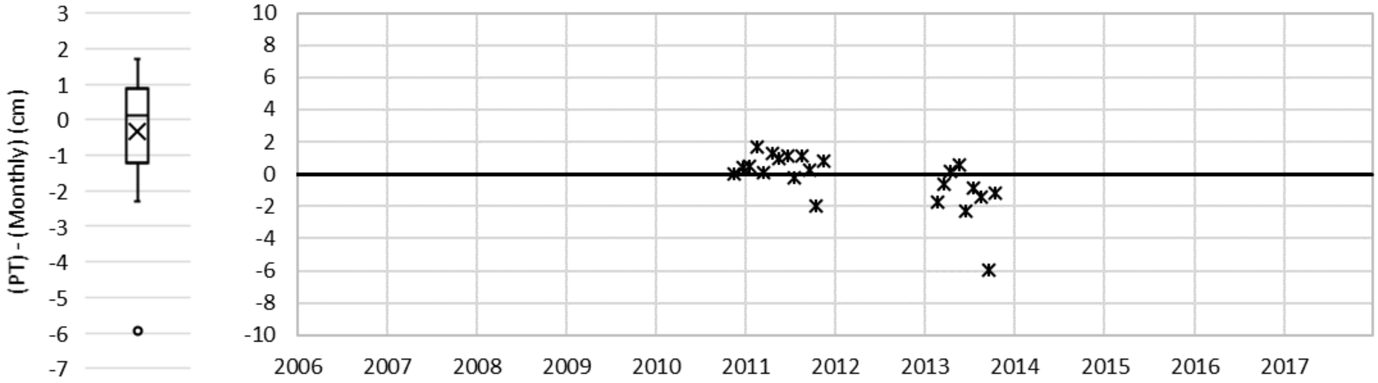
Belen East (BELE)

μ = -0.66 cm std = 3.98 cm NED = 0.59 cm $P_{<|5|cm}$ = 0.93



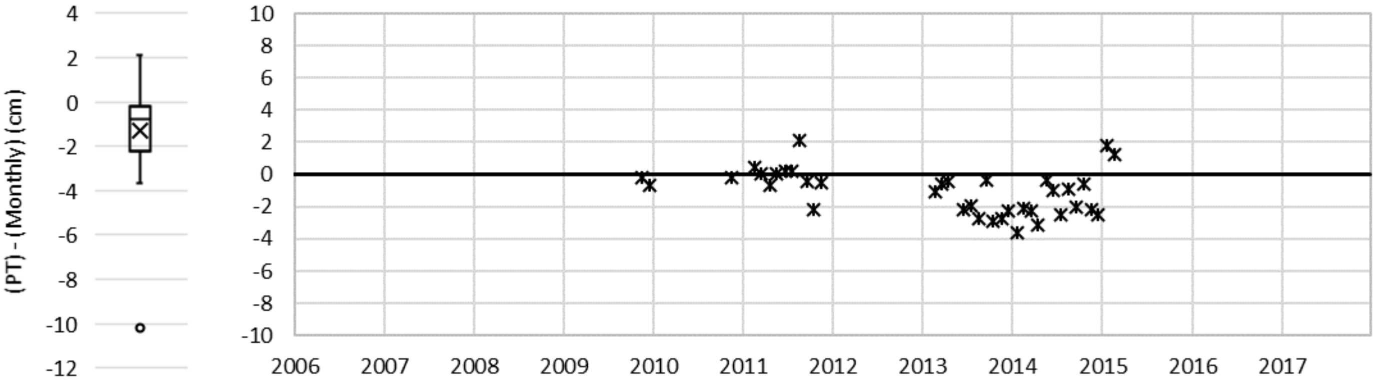
Belen Center (BELC)

μ = -0.32 cm std = 3.98 cm NED = 0.36 cm $P_{<|5|cm}$ = 0.91



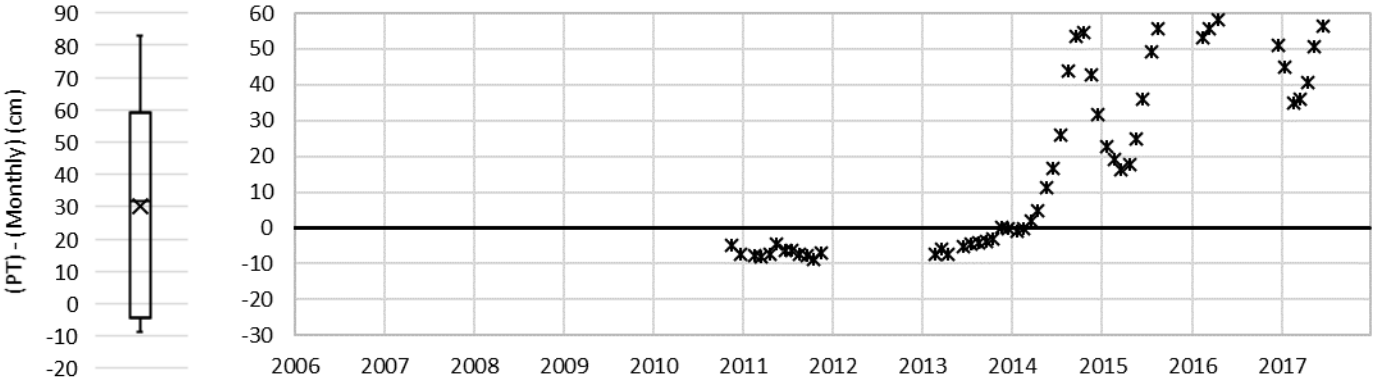
Valencia Forest East (VFOE)

μ = -1.29 cm std = 2.02 cm NED = 0.39 cm $P_{<|5|cm}$ = 0.97



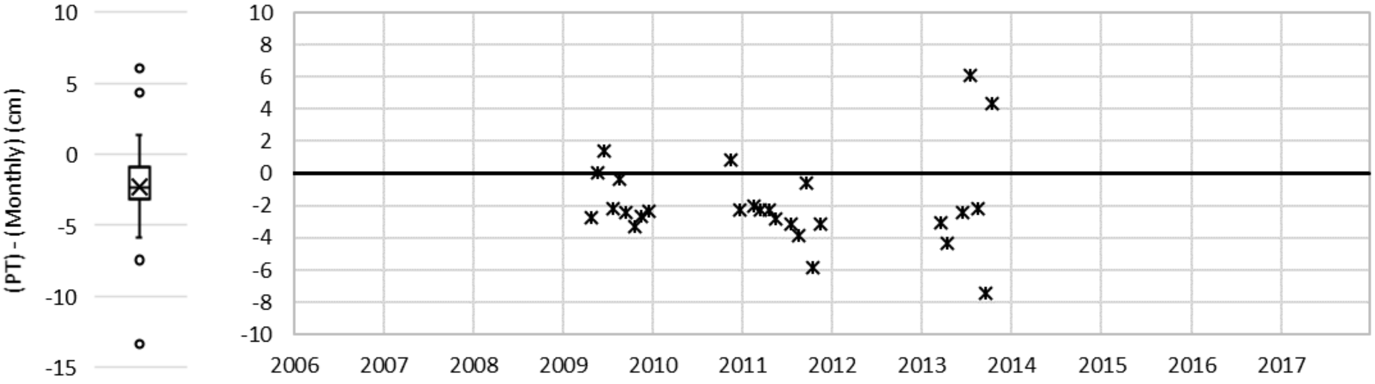
Valencia Forest Center (VFOC)

μ = 30.15 cm std = 31.42 cm NED = 5.22 cm $P_{<|5|cm}$ = 0.17



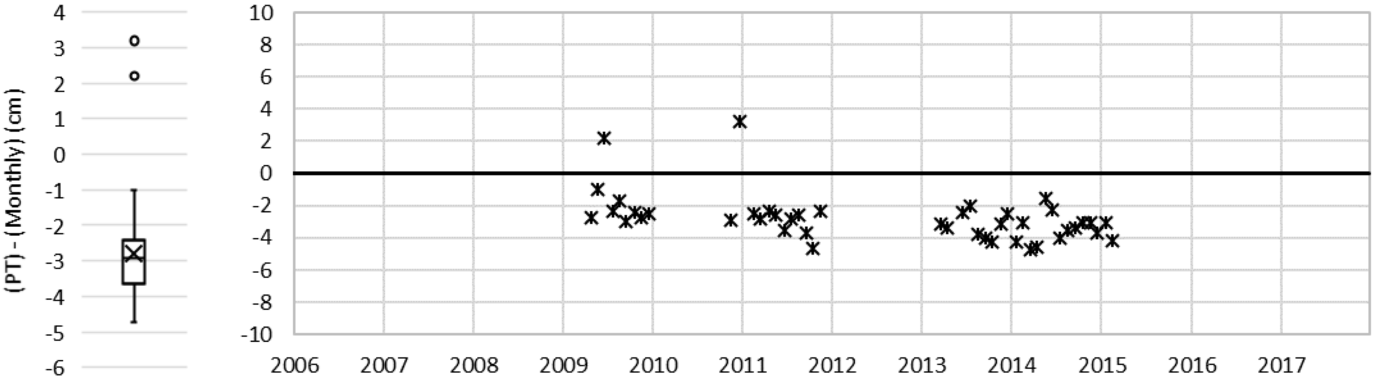
Crawford East (CRAE)

$\mu = -2.29$ cm std = 3.45 NED = 0.77 cm $P_{<|5|cm} = 0.86$



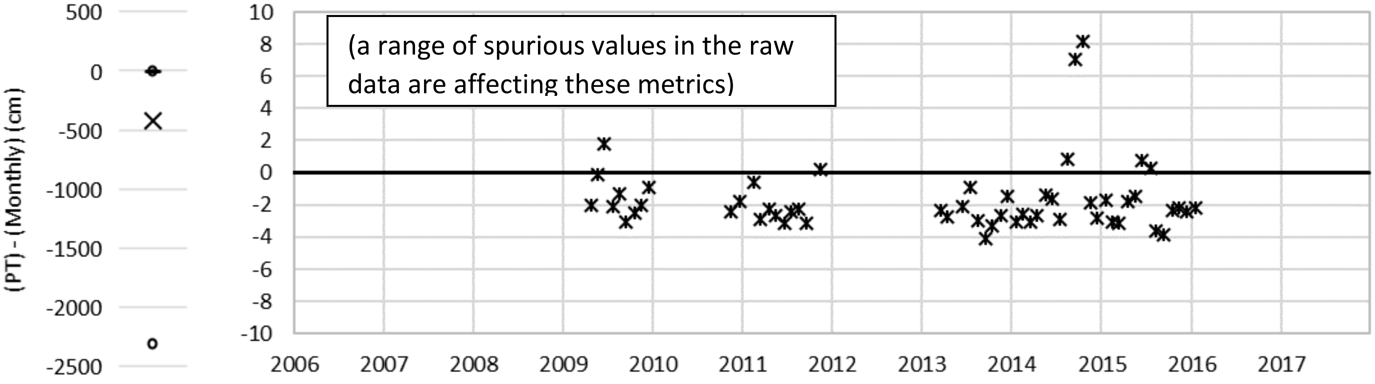
Crawford West (CRAW)

$\mu = -2.79$ cm std = 1.48 cm NED = 0.48 cm $P_{<|5|cm} = 1.00$



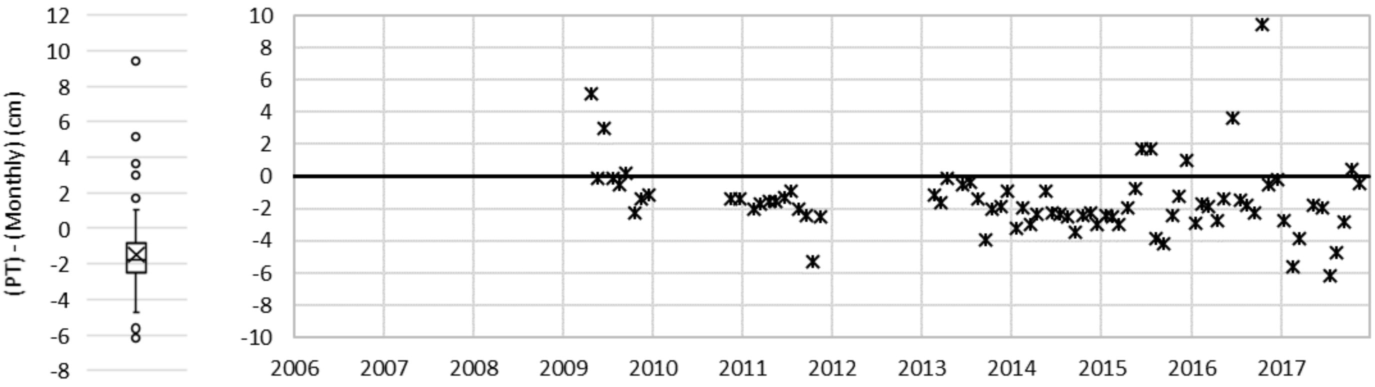
Crawford North (CRAN)

$\mu = -420.96$ cm std = 896.24 cm NED = 121.12 cm $P_{<|5|cm} = 0.79$


(a range of spurious values in the raw data are affecting these metrics)

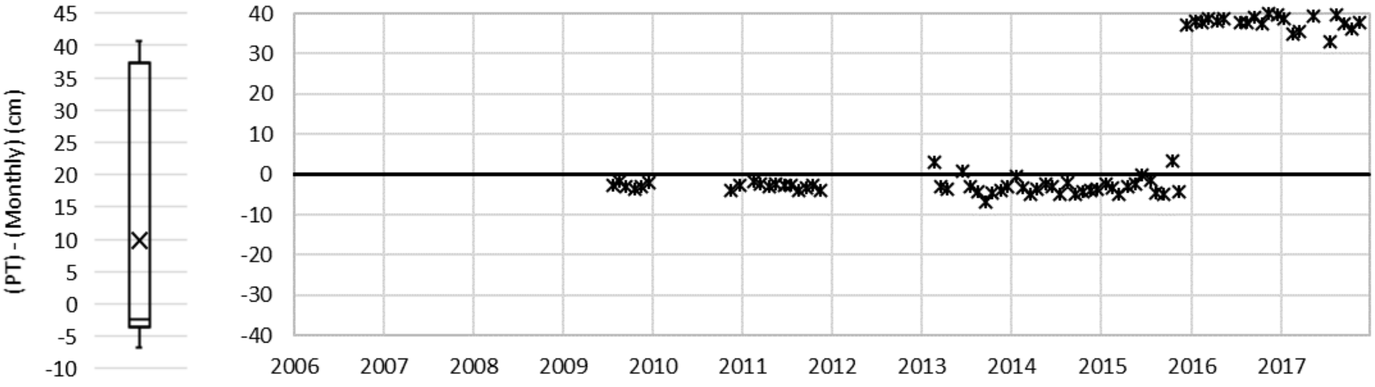
Crawford South (CRAS)

μ = -1.50 cm std = 2.23 cm NED = 0.31 cm $P_{<|5|cm}$ = 0.94



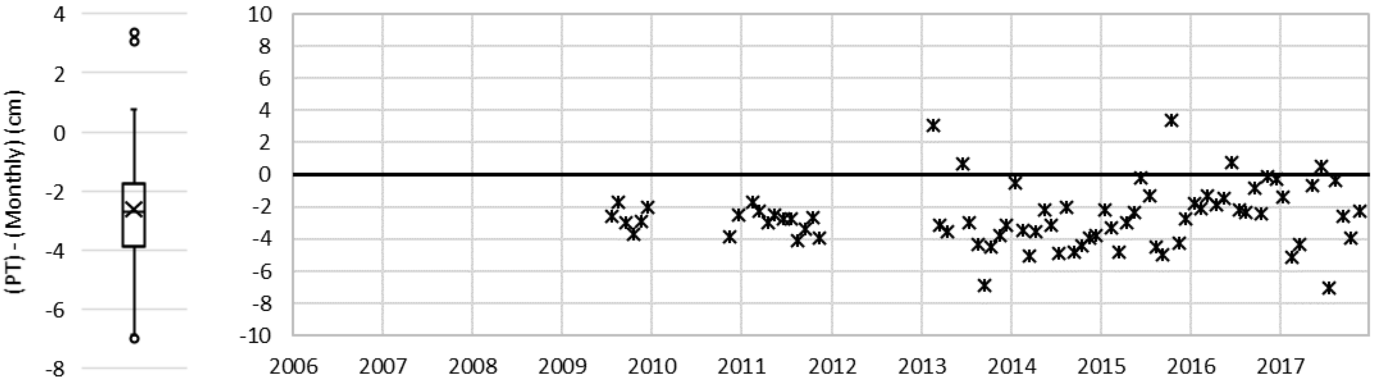
Crawford Center (CRAC)

μ = 9.81 cm std = 19.15 NED = 2.49 cm $P_{<|5|cm}$ = 0.66



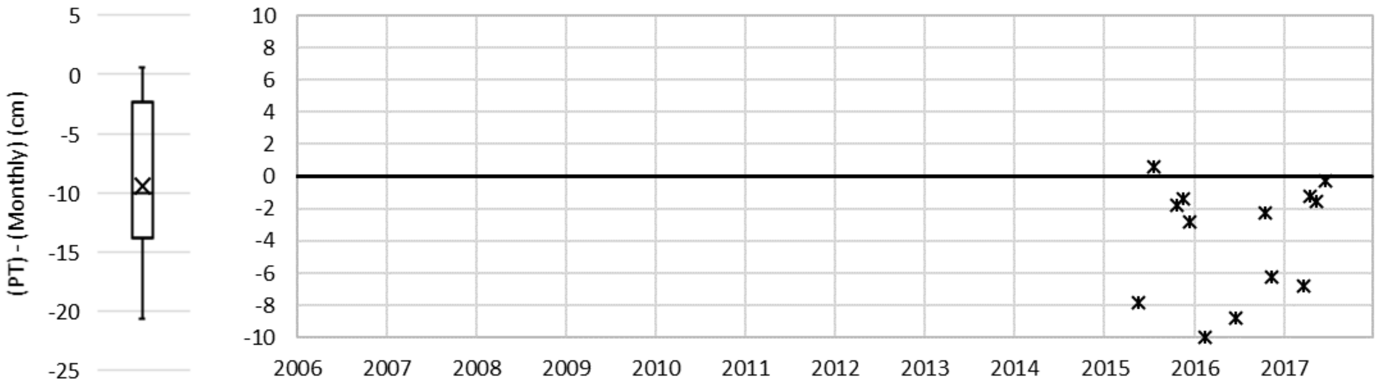
Crawford Center (CRAC) (PT data >2016 corrected by 40cm)

μ = 0.95 cm std = 1.85 NED = 0.37 cm $P_{<|5|cm}$ = 0.95



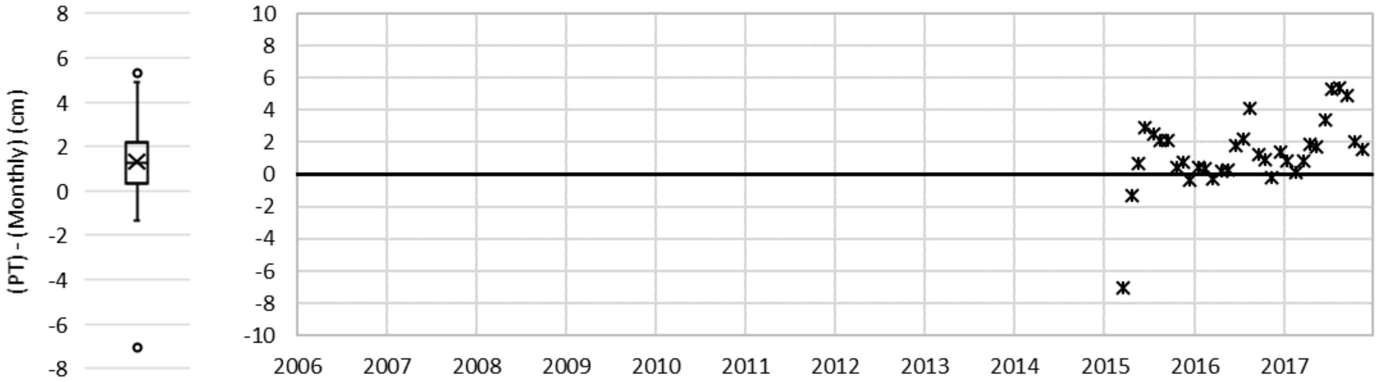
State Land Office East (SLOE)

μ = -9.43 cm std = 6.51 cm NED = 2.19 cm $P_{<|5|cm} = 0.30$



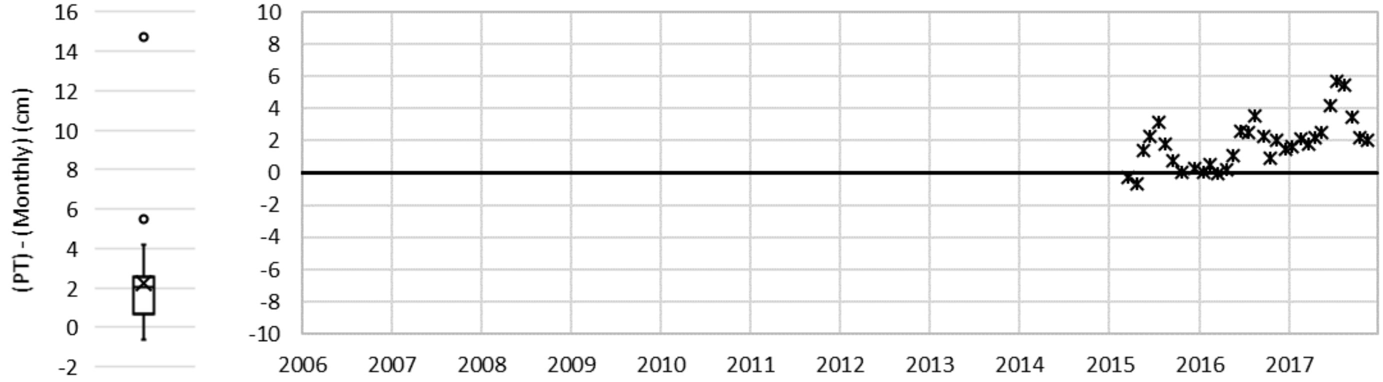
State Land Office West (SLOW)

μ = 1.31 cm std = 2.22 cm NED = 0.44 cm $P_{<|5|cm} = 0.91$



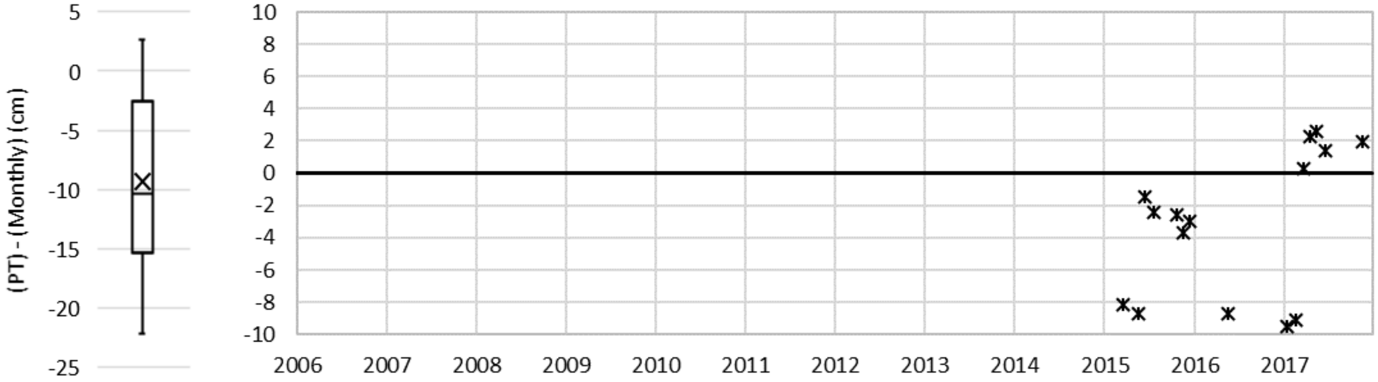
State Land Office North (SLON)

μ = 2.25 cm std = 2.71 NED = 0.61 cm $P_{<|5|cm} = 0.91$



State Land Office South (SLOS)

μ = 0.32 cm std = 7.17 cm NED = 2.10 cm $P_{<|5|cm}$ = 0.32



State Land Office Center (SLOC)

μ = 0.84 cm std = 1.59 cm NED = 0.31 cm $P_{<|5|cm}$ = 1.00