Distributional Patterns of Aquatic Macrophytes in the San Marcos and Comal Rivers from 2000 to 2015

Final Report

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INTRODUCTION

Aquatic macrophytes contribute to the biodiversity of streams by 1) providing structure and cover for epiphytes, invertebrates, salamanders, and fish, 2) stabilizing substratum with roots and rhizomes, 3) trapping and resuspending nutrients, and 4) increasing habitat diversity by altering water velocity (Butcher 1933, Chambers et al. 1991, Holmes 1999, and Gurnell et al. 2006). Water velocity is highest at the upstream section but declines sharply inside the macrophyte bed (Sand-Jensen and Mebus 1996). Macrophyte beds can reduce water velocity by 10 to 46% compared to upstream areas without macrophytes (Wilcock et al. 1999). Changes in water velocity within macrophyte beds results in microhabitats (Champion and Tanner 2000). The increased habitat diversity from macrophyte structure and varying water velocity provides structure for specialized and rare higher forms of life (Suren 1991, Westwood et al. 2006).

Disturbance can be defined as event resulting in biomass reduction within a habitat (Grime 1979). Frequent and low-scale pulsing events, such as floods followed by lower or normal flows in streams, are frequent in most ecosystems and result in large-scale energy transfer (Odum et al. 1995). Aquatic macrophytes resistance and resilience to disturbance intensity is believed to be related to several factors. Species that are found in frequently disturbed streams have lower drag that reduced stem fragmentation, reduced uprooting and a deep tap root and rhizome system, sexual and asexual dispersal of propagules, and fast growth rates (Riis and Biggs 2001). Long linear leaves are more resistant to high water velocity compared to broad-shaped and palmate shaped leaves (Sand-Jensen and Mebus 1996). High resilience to disturbance has been attributed to effective dispersal and establishment of propagules (Barrat-Segretain et al. 1998) and re-sprouting from roots.

Macrophytes often form large monoculture patches that exhibit pulsating shifts in area coverage based on drought and flood regimes (Sand-Jansen and Madsen 1992). High discharge from flood events results in increased water velocity that moves larger sediment particles and creates greater sheer-stress on macrophytes. Streams that experience more than 13 floods per year at seven times the median flow lack aquatic macrophytes (Riis and Biggs 2003). Exposure to frequent flooding results in macrophyte communities that are dominated by deep rooted species and the exhibition of reproductive plasticity (Riis and Biggs 2001). Discharge can be highly variable on a daily and seasonal scale in streams and has been positively correlated with higher plant biomass for rooted plants, but inversely related to green algae and epiphyte biomass (Sand-Jensen et al. 1989). Some deeply rooted species exhibit rapid regrowth following cutting or floods (Nielsen et al. 1985, Barrat-Segretain and Amoros, 1996).

Water velocity can vary within a reach and changes in water velocity within a specific reach is related to macrophyte coverage and density (Gurnell et al. 2006). Water velocities of 0.3 to 0.4 m s^{-1} are often associated with greater macrophyte biomass and richness, with lower macrophyte biomass associated with water velocities < 0.3 m s^{-1} and loss of macrophytes > 1.0 m s^{-1} (Nilsson 1987, Chambers et al. 1991, Riis and Biggs 2003). Thus, within a large stand of macrophytes, large variations in water velocity can occur along with a mix of species. Some macrophytes tolerate high water velocities up to 3.5 m s^{-1}, but exhibit reduced coverage at lower velocities and increased accumulation of epiphytes on their leaves (Ham et al. 1982). Reduced discharge rates and lower water velocities can result in lower macrophyte coverage and increase in filamentous algae (Wilby et al. 1998). Moreover, difference in water velocity, substrate and soil moisture can vary across a channel and result in varying macrophyte species and coverage (Westwood et al. 2006).

Extended periods of drought result in large scale habitat loss resulting in aquatic habitat replaced by terrestrial habitat. Low discharge over prolonged periods due to droughts results in extended periods in which macrophytes experience exposure to desiccation. In streams and rivers, long-term droughts would likely have greater impacts to aquatic macrophytes compared to floods which are typically short-term. Decreased water velocity and lower water levels result decreased dissolved oxygen and higher water temperatures. During decreased flows, gravel substrate is filled in with silt thereby altering the substrate and nutrient composition (Green 2005, Westwood et al. 2006). Aquatic macrophytes exhibit varying degrees of resilience to drought with some exhibiting little change in composition and density, while other species disappear and other species become dominant when flows return to normal (Holmes 1999).

Spring-fed rivers in Central Texas typically display consistent hydrological and physiochemical conditions and often contain a high number of endemic species (Brune 1981, Longley 1981, USFWS 1996, Groeger et al 1997). The San Marcos and Comal Spring ecosystems contain a high number of endemic species that are dependent on constant water velocity and temperatures and both aquatic ecosystems are designated as critical habitat (USFWS 1996). Critical flows have been established to protect these species and their habitat (EARIP 2011). Multiple biotic and abiotic factors simultaneously affect the density of macrophyte over both time and space such as discharge, water velocity, nutrients, competition, turbidity and light levels. The major threat to both rivers is ground water extraction resulting in reduced spring flows (USFWS 1996).

The upper reaches of both rivers are highly urbanized and flows are artificially controlled by water control structures (USFWS 1996). The Comal River is restricted by three dams, and flow is managed between the Old and New Channel with a culvert to maintain discharge in the Old Channel < 65 cfs (BioWest 2016). In the San Marcos River, three dams are present in the first 2.5 km of the headwaters and 0.16 km has been channelized in Sewall Park.

The overall trend documented in studies on listed species in the Comal and San Marcos Rivers indicate that flow rates and surface water quantity are important in maintaining population densities and habitat (EARIP 2011). Flow rates improve gas exchange in aquatic species such as invertebrates, fish and salamanders, and increase diffusion of CO_2 in aquatic plants. Evaluation of vegetative cover spatially and temporally is important because vegetation provides cover for listed species, escape from predators, food sources, and nursery areas. Texas wild rice (*Zizania texana*) exhibited higher net productivity and well developed root systems in higher water velocities compared to Texas wild rice in slower water velocities (Power 2002). Gene flow across endemic and sympatric taxa in Comal Springs indicates local adaptations and genetic variants could be lost if the spring flows cease (Lucas et al. 2016). Two genetic analyses of Texas wild rice indicate high genetic diversity in the San Marcos River (Richards et al 2007, Wilson et al. 2015). It is likely that a reduction in flows and water depth would result in a reduction of species density and genetic diversity. Moreover, non-native macrophytes such as hydrilla (*Hydrilla verticillata*) and East Indian hygrophila (*Hygrophila polysperma*) are highly invasive aquatic species that can form monocultures and out compete native macrophytes (Langeland 1996, Doyle et al. 2003).

Long-term biomonitoring databases are important for adaptive management during restoration projects and provide feedback on successes and failures. This allows for adjustments to management practices which can be monitored and further refined as more results become available. The Edwards Aquifer biomonitoring database has been in existence since 2000 and likely represent one of the longer aquatic ecosystem monitoring programs in the United States and globally. The objectives of this study were to analyze temporal patterns and discharge, seasonal trends, species richness and diversity, and coverage of native and non-native species of aquatic macrophytes in the Long-Term Biological Goal sites within the aquatic ecosystems of the Comal and San Marcos Rivers.

METHODS

We analyzed data collected by Edwards Aquifer Authority (EAA) contractors from 2000 to 2015 to evaluate the effects of discharge on aquatic macrophytes in the Comal and San Marcos rivers. Data was organized in Excel spreadsheets and analyzed with Excel and SAS. In the Comal River, four Long-Term Biological Goal sites (LTBG) have been monitored since 2000 that include the Upper Spring Run (6,008 m^2), Landa Lake (26,786 m^2), Old Channel (4,093 m^2) and Lower New Channel (5,855 m^2). Three LTBG sites were established in the San Marcos River in 2002 that include Spring Lake Dam (4,369 m^2), City Park (5,716 m^2), and I-35 (6,368 m^2, expanded to 11,619 m^2 in 2014).

Each LTBG site was monitored twice per year by EAA contractors in the spring and fall with additional monitoring during low and high discharge periods. The area coverage (m^2) of all aquatic macrophytes was determined in the seven LTBG sites within the Comal and San Marcos rivers, by creating a polygon around each species using GPS (Bio-West 2016). Aquatic macrophytes were mapped with a Trimble Pro-XT GPS and a Trimble Tempest external antenna within sub meter accuracy. Mapping was done in a kayak by creating a perimeter around the patch. All macrophyte species within mixed stands were assigned a percentage cover that was multiplied by total area to determine area coverage of each species. Vegetation stands between 0.5 and 1.0 m in diameter were mapped with a single GPS point and stands less than 0.5 m in diameter were not mapped.

Daily and mean yearly discharge (cubic feet per second – cfs) was graphed from 2000 to 2015 to evaluate periods of low (droughts) and high (floods) flows. Daily discharge values for each river were taken from USGS gauges GS_0816900 in the Comal River and GS_08170500 in the San Marcos River. Discharge values included both spring flow and stormflow. Descriptive statistics were calculated for mean daily discharge from 2000 to 2015 for both rivers. Mean discharge from 2000 to 2015 was 311 cfs (SE = 3.8) in the Comal River and 187 cfs (SE = 1.1) in the San Marcos River. Based on descriptive statistics and hydrographs, low flows in the Comal River were set at ≤ 200 cfs and ≥ 400 cfs for high flows. Discharge for low flows in the San Marcos

River were set at ≤ 100 cfs and ≥ 400 cfs for high flows. For each low and high flow period documented during 2000 to 2015, the number of days, the mean discharge over each period, and the range of discharges over the period were tabulated for each river. Analysis of variance (ANOVA) was used to test for differences ($P < 0.05$) in mean annual discharge by year. If differences were detected a Tukey's HSD mean separation test was utilized to determine where significant differences occurred. For each period of low and high flow, the number of days, mean discharge, standard error and range were compiled.

Macrophyte Coverage and Discharge

Total macrophyte coverage (m^2) of native and non-native macrophytes in both rivers was compared to discharge (cfs) using scatter plots to examine overall trends. Temporal periods were segmented into five groups spaced three years apart that include 2003, 2006, 2009, 2012, and 2015. These dates were chosen to represent the second or third year after monitoring began in three year increments with 2015 representing the period in which planting of native and removal of non-natives macrophytes had occurred for three years.

For each of the LTBG sites, the total macrophyte coverage (m^2) in both rivers was compared to the discharge (cfs) value using linear regression analysis. Data for each LTBG site was evaluated from 2000-2015 in the Comal River and 2002-2015 in the San Marcos River. Trends were examined to determine if macrophyte area coverage increased or decreased with discharge.

Within each LTBG site, dominant macrophytes based on area coverage from 2013 to 2015 were evaluated with Spearman's correlation analysis based on mean monthly discharge. The years 2013 to 2015 represent the breakpoint when native plantings and non-native removal was initiated. Dominant macrophytes were all species that were documented during monitoring in at least four years from 2002 to 2015.

Seasonal Macrophyte Coverage

Differences in aquatic macrophyte coverage from 2002 to 2015 were evaluated for seasonal differences using a t-test ($P < 0.05$) and correlation. Spearman's correlation was used to examine trends in macrophyte coverage between spring and fall. Data in each LTBG site was combined for all monitoring periods each year during the spring (May) and fall (October). Seasonal differences were evaluated for total macrophyte, native, non-native, and dominant individual species coverage. Seasonal differences were evaluated to determine if significant differences occurred in the fall compared to spring following the impacts of recreation in the river.

Macrophyte Richness, Evenness, Diversity, Native and Non-Native Coverage

Species richness, evenness and Simpson's Index of Diversity were evaluated to examine trends in diversity. Native and non-native coverage were evaluated to examine trends total coverage from 2000 to 2015. Aquatic macrophyte species richness patterns were determined by counting the number of species documented in each survey for all LTBG sites. Species evenness patterns were determined using the methods of William (1964). Evenness patterns were calculated as E = 1 / DS, where D is Simpson's Index [Σ (n/N)^2] and S is species richness (Williams 1964). Simpson's Index of Diversity was calculated as 1 - D (Williams 1964). Data were combined for years 2001-2003, 2004-2006, 2007-2009, 2010-2012 and 2013-2015 to test for differences in diversity indices. Analysis of variance (ANOVA) was used to test for differences ($\alpha < 0.05$) among years for richness, evenness, Simpson's Index of Diversity, and total (native and non-native), native and non-native macrophyte coverage. If differences were detected. Tukey's HSD mean separation test was utilized to determine where significant differences occurred ($\alpha < 0.05$).

RESULTS

Discharge Patterns

Hydrographs of discharge exhibited a pulsating pattern from 2000 to 2015 in the Comal and San Marcos rivers with steep peaks in discharge followed by rapid recession (Figures 1 and 2). The rising and recession decreasing limbs of the hydrographs during high discharge events was much steeper and over shorter durations in the Comal River compared to the San Marcos River. The Comal River was more susceptible to intense high flow events than the San Marcos River. Based on the hydrographs, low discharge rates were set at 200 and 100 cfs in the Comal and San Marcos rivers, respectively, and high discharge rates were set at 400 cfs for both rivers. Both rivers showed relatively stable discharge trends from 2001-2005 with declining discharge trends from 2008-2014 (Figures 3 and 4).

In the Comal River, we documented 29 periods in which the mean discharge dropped below 200 cfs for more than 1 days (Table 1). The extent of low discharge was from 2 to 385 days, with mean discharge rates ranging from 130 to 199 cfs. The lowest mean discharge of 130 cfs had a duration of 73 days from June 18, 2013 to September 28, 2013. We documented 35 periods when the mean discharge remained above 400 cfs for more than one day (Table 2). The periods of high discharge continued for 2 to 238 days, with mean discharge rates ranging from 405 to 2459 cfs. The highest mean discharge of 2459 cfs persisted for 2 days from October 4-5, 2009.

In the San Marcos River, we documented 16 periods in which the mean discharge dropped below 100 cfs for more than one days (Table 3). The length of periods of low discharge were from 2 to 157 days, with mean discharge rates ranging from 90 to 99 cfs. The lowest mean discharge of 90 cfs continued for 157 days from April 18, 2009 to September 21, 2009. We documented six periods when the mean discharge remained above 400 cfs for more than one day (Table 4). High discharge periods continued for 3 to 55 days, with mean discharge rates ranging from 448 to 705 cfs. The highest mean discharge of 705 cfs had a duration of three days from October 31, 2013 to November 2, 2013.

We observed no relationship between total macrophyte coverage (m^2) and discharge (cfs) from 2000 to 2015 in the four Comal River LTBG sites based on regression analysis (Figures 5-8).

Based on these analyses, no R^2 value was greater 0.22 at any of the LTBG sites indicating that discharge and macrophytes coverage are not related. In the Lower New Channel and Old Channel, we observed a slight decline in macrophytes coverage with increasing discharge. In contrast, the Upper Spring Run showed a slight increase in macrophytes coverage with increasing discharge. However, no trend was observed in Landa Lake with macrophyte coverage reaming stable regardless of discharge.

In the three San Marcos River LTBG sites, we observed no relationship between total macrophyte coverage (m^2) and discharge (cfs) from 2002 to 2015 based on regression analysis (Figures 9-11). Based on regression analysis, no R^2 value was greater 0.08 at any of the LTBG sites indicating that discharge and macrophytes coverage were not related. A weak relationship was observed in Spring Lake Dam with a slight increase in macrophytes with increasing discharge. No trend was observed in City Park and I-35 with macrophyte coverage remaining stable regardless of discharge.

The same trends of no pattern in macrophyte coverage regardless of discharge was observed in both rivers when macrophyte coverage was combined for all LTBG sites (Figures 12 and 13). There was large variation in macrophyte coverage in the Comal River due to the large macrophyte coverage in Landa Lake compared to the other three LTBG sites, but no trend in macrophyte coverage was observed. Combining all macrophyte coverage in both rivers again indicated that discharge did not have an effect on macrophyte coverage but with a large separation in coverage for Landa Lake and the other six LTBG sites (Figure 14). When the macrophyte coverage was removed for Landa Lake, a comparison of the other six LTBG sites revealed no trends comparing coverage to discharge (Figure 15).

Macrophyte Coverage and Discharge

Comal River

Vallisneria spp. coverage remained relatively constant in Landa Lake (Figure 16), and no correlation ($r = -0.07$, $P = 0.84$) was found with discharge over this period (Table 5). *Sagittaria platyphylla* coverage remained stable in both Landa Lake (Figure 17a) and the Upper Spring Run (Figure 17b). No correlation was found between coverage and discharge for *S. platyphylla* in Landa Lake (Table 5, $r = 0.15$, $P = 0.68$), but a moderate correlation was found in the Upper Spring Run (Table 6, $r = 0.44$, $P = 0.18$).

Cabomba caroliniana coverage remained constant with some increases and decreases in Landa Lake (Figure 19a) and the Lower New Channel (Figure 19b). There was no correlation between discharge *C. caroliniana* in either Landa Lake (Table 5, $r = 0.19$, $P = 0.58$) or the Lower New Channel (Table 7, $r = 0.07$, $P = 0.84$). In the Upper Spring Run, *C. caroliniana* exhibited an increase followed by a sharp decrease in November 2015 (Figure 19c). This pattern may be related to the discharge increasing to 300 cfs. *Cabomba caroliniana* exhibited a moderate correlation with increased discharge (Table 6, $r = 0.48$, $P = 0.14$).

Area coverage of *Ludwigia repens* was highly variable in three of four LTBG sites (Figures 20 a-c). Moderate correlations were observed between *L. repens* coverage and discharge in Landa Lake (Table 5, r = 0.52, P = 0.06), the Old Channel (Table 8, r = 0.41, P = 0.21) and the Upper Spring Run (Table 6, r = 0.34, P = 0.31). The most stable population coverage of *L. repens* was in Landa Lake, but coverage decreased in Old Channel and Upper Spring Run when discharge reached 300 cfs during November 2015.

Bryophyte coverage declined in all four LTBG sites (Figures 21 a-d) and was evident in November 2015 when discharge increased to 300 cfs. Bryophyte coverage was weakly correlated with discharge in Landa Lake (Table 5, r = -0.12, P = 0.73), the Upper Spring Run (Table 6, r = 0.22, P = 0.52), the Lower New Channel (Table 7, r = -0.25, P = 0.46), and the Old Channel (Table 8, r = 0.12, P = 0.72).

Nuphar advena coverage was positively correlated with discharge in Landa Lake (Table 5, r = 0.73, P < 0.05) and exhibited a declining pattern. In the old channel, *N. advena* was moderately correlated with discharge (Table 8, r = -0.41, P = 0.21).

Hygrophila polysperma coverage declined in all LTBG sites (Figures 22 a-d) and exhibited a low to moderate correlation with discharge with an overall trend of decreasing area coverage. There was low correlation of *H. polysperma* coverage to discharge in Landa Lake (Table 5, r = 0.002, P = 0.96), the Upper Spring Run (Table 6, r = 0.22, P = 0.52) and the Lower New Channel (Table 7, r = -0.13, P = 0.70). In the Old Channel, *H. polysperma* coverage was moderately correlated with discharge (Table 8, r = -0.55, P = 0.09) and decreased in coverage in November 2015 when discharge increased to 300 cfs.

San Marcos River

Zizania texana coverage tended to increase with increasing discharge from April 2013 to November 2015 in Spring Lake Dam (Figure 23a) and City Park (Figure 23b), however, coverage at I-35 (Figure 23c) tended to be greatest with lower discharge. Small declines in *Z. texana* area coverage were observed at Spring Lake Dam and City Park. Moderate correlations were found for between *Z. texana* area coverage and discharge at Spring Lake Dam (Table 9, r = 0.52, P = 0.19) and City Park (Table 10, r = 0.76, P <0.05), and a weak correlation was detected at I-35 (Table 11, r = -0.16, P = 0.71).

Sagittaria platyphylla coverage was variable at all three LTBG sites (Figures 24 a-c). As discharge increased, *S. platyphylla* coverage tended to decrease at Spring Lake Dam (Table 9, r = -0.73, P < 0.05). In City Park, with the exception of one outlier, coverage remained stable, but likewise showed an inverse relationship to discharge (Table 10, r = -0.32, P = 0.43). At I-35, *S. platyphylla* coverage tended to increase from April 2013 to November 2015 and was moderately correlated with discharge (Table 11, r = 0.65, P = 0.08).

Potamogeton illinoensis coverage tended to decrease with increasing discharge (Figure 25 a-b). There were moderate negative correlations between *P. illinoensis* coverage and discharge at Spring Lake Dam (Table 9, r = -0.71, P <0.05) and City Park (Table 10, r = -0.63, P = 0.10). In addition, *P. illinoensis* coverage was 281 m^2 in April 2013 but was absent at Spring Lake Dam in November 2015.

There were no observable trends in *Ludwigia repens* coverage when plotted with discharge in the three LTBG sites (Figures 26 a-c), although coverage was highest with some of the higher discharge rates. *Ludwigia repens* coverage was moderately correlated with discharge at Spring Lake Dam (Table 9, r = 0.57, P = 0.14), but weakly correlated with discharge at City Park (Table 10, r = 0.14, P = 0.74) and I-35 (Table 11, r = 0.23, P = 0.14).

Hydrilla verticillata coverage decreased with increasing discharge at Spring Lake Dam (Figure 27a) and City Park (Figure 27b). At I-35, *H. verticillata* coverage remained constant, but there was a pulse of increased coverage during April 2015 with subsequent decreases from June-November 2015 (Figure 27c). There were negative correlations between *H. verticillata* and discharge at Spring Lake Dam (Table 9, r = -0.53, P = 0.17) and City Park (Table 10, r = -0.69, P = 0.06), but no relationship was observed at I-35 (Table 11, R = 0.04, P = 0.93).

Hygrophila polysperma coverage was variable based on discharge at the three LTBG sites (Figures 28 a-c). At Spring Lake Dam, *H. polysperma* coverage exhibited a pulsating pattern of increase and decrease and a moderate correlation with discharge (Table 9, r = -0.36, P = 0.38). Coverage of *H. polysperma* in City Park decreased over time and was negatively correlated with discharge (Table 10, r = -0.63, P = 0.09). There was no observed correlation (Table 11, r = -0.07, P = 0.87) was observed between *H. polysperma* coverage and discharge at I-35.

Seasonal Macrophyte Coverage (2000 to 2015)

Comal River

Total macrophyte coverage was different (P < 0.05) between spring and fall in the LTBG sites at Landa Lake and the Upper Spring Run (Table 12). Macrophyte coverage was higher in the spring and lower in the fall in Landa Lake and the Upper Spring Run. No difference (P > 0.05) was found between the spring and fall coverage in the Lower New Channel and Old Channel.

In Landa Lake, total native and non-native macrophyte coverage was different (P < 0.05) between spring and fall with lower coverage in the fall (Table 13). Differences in macrophyte species varied with some species exhibiting increased, decreased or no change between spring and fall. Bryophytes, *Nuphar advena*, and *Hygrophila polysperma* coverages were lower in the fall (P < 0.05) while *Cabomba caroliniana* was greater in the fall (P < 0.05). No differences (P > 0.05) were detected between spring and fall coverage for algae, *Ludwigia repens*, *Sagittaria platyphylla*, and *Vallisneria* spp. No correlations were found for algae and *L. repens* coverage between spring and fall (Table 13). Moderate correlations were detected between spring and fall coverage for bryophytes and *Nuphar advena.* Strong correlations between spring and fall coverage of *C. caroliniana*, *S. platyphylla*, *Vallisneria* spp. and *H. polysperma* were observed.

In contrast, no differences (P > 0.05) were detected for total native and non-native macrophyte coverage based on spring and fall surveys in the lower New Channel (Table 14). Only bryophyte showed a seasonal difference ($P < 0.05$), with more coverage in the spring and less in the fall. The coverage of all macrophytes (native and non-native) and individual species was moderately to highly correlated between the spring and fall, with the exception of *L. repens* (Table 14).

There were no observed differences ($P > 0.05$) for native, non-native and individual macrophyte species based on coverage between spring and fall in the Old Channel (Table 15). The coverage of all macrophytes (native and non-native) and individual species was moderately to highly correlated between the spring and fall, with the exception of algae and *N. advena* (Table 15).

Total and native macrophyte coverages were greater in the spring compared to the fall in the Upper Spring Run ($P < 0.05$), but there was no difference ($P > 0.05$) in total non-native coverage (Table 16). Only bryophytes showed a significant difference ($P < 0.05$) between spring and fall coverage, with higher coverage recorded in the spring. The coverage of all macrophytes (native and non-native) and most individual species were moderately correlated between the spring and fall (Table 16). However, algae exhibited a low correlation and while *C. caroliniana* and *S. platyphylla* high correlations between spring and fall.

San Marcos River

Total macrophyte coverage was different ($P < 0.05$) between spring and fall in both Spring Lake Dam and City Park (Table 12) with both sites having greater coverage in the spring. No difference ($P > 0.05$) was detected between seasons for total macrophyte coverage at I-35.

At Spring Lake Dam, the total macrophyte, native and non-native macrophyte coverage was different ($P < 0.05$) between spring and fall with lower coverage in the fall (Table 17). Differences in individual macrophyte species between seasons was variable. *Zizania texana* and *Hydrilla verticillata* coverage was lower ($P < 0.05$) in the fall compared to the spring. No differences ($P < 0.05$) were detected for *Potamogeton illinoensis*, *Sagittaria platyphylla* and *Hygrophila polysperma* between spring and fall monitoring periods. The coverage of all macrophytes (native and non-native) and individual species was moderately to highly correlated between the spring and fall (Table 17).

Total and non-native macrophyte coverage was different ($P < 0.05$) between spring and fall in City Park with lower coverage in the fall (Table 18). No differences ($P > 0.05$) were detected in native macrophyte coverage at City Park. *Potamogeton illinoensis* and *Hydrilla verticillata* had greater coverage ($P < 0.05$) in the spring compared to fall monitoring periods. No differences ($P > 0.05$) were detected for *Zizania texana*, *Sagittaria platyphylla*, and *Hygrophila polysperma* coverage during the spring and fall monitoring periods. The coverage of all macrophytes (native and non-native) and individual species were moderately to highly correlated between the spring and fall, with the exception of *H. polysperma* which exhibited a weak correlation (Table 18).

No seasonal differences ($P > 0.05$) were detected for native, non-native or any macrophyte species at I-35 (Table 19). *Zizania texana*, *Cabomba caroliniana*, *Sagittaria platyphylla*, *Hydrilla verticillata* and *Hygrophila polysperma* maintained similar area coverages during the spring and fall monitoring periods. The coverage of all macrophytes (native and non-native) and individual species at I-35 was moderately to highly correlated between the spring and fall, with the exception of *C. caroliniana* and *H. verticillata* which exhibited a weak correlation (Table 18).

Macrophyte Richness, Evenness, Diversity, Native and Non-Native Coverage

Comal River

From 2000 to 2015, discharge ranged from 76 to 445 cfs during macrophyte surveys and peaked at 13,400 cfs during July 2002 in the Comal River. Over the study time frame, no effects were observed on the diversity indices examined when data for all LTBG sites were combined. No trends were observed for species richness (Figure 29, $R^2 = 0.02$, $P = 0.06$), evenness (Figure 30, $R^2 = 0.006$, $P = 0.33$) and Simpson's Index of Diversity (Figure 31, $R^2 = 0.41$, $P = 0.41$) when compared to discharge.

Species richness was different ($P < 0.05$) among year groupings in Landa Lake but no trend was observed (Table 20). Mean species was lowest in the first (2001-2003) and last (2013-2015) temporal periods and greatest in the 2007-2009 and 2010-2012 periods. Evenness was different ($P < 0.05$) among year groupings with the highest values occurring in 2001-2003 and 2013-2015. No differences ($P > 0.05$) were detected for Simpson's Index of Diversity among year groupings with diversity values ranging from 0.43 to 0.50. There was no difference ($P > 0.05$) in total macrophyte and native macrophyte coverage among year groupings. In contrast, differences ($P < 0.05$) were detected in non-native species coverage among year groupings with the lowest area coverage recorded during 2013-2015 compared to the other four periods.

No differences ($P > 0.05$) were found among year groupings for species richness and evenness in the Lower New Channel (Table 21). Similar to the findings in Landa Lake, mean species richness was lowest in the first (2001-2003) and last (2013-2015) temporal periods and the highest value in the 2007-2009 period. Evenness ranged from 0.48 in 2001-2003 to 0.70 during 2010-2012. Differences ($P < 0.05$) among year groupings were detected for Simpson's Index of Diversity but a trend was not observed. Diversity values were highest during 2010-2012 (0.53) and lowest in 2001-2003 (0.13). There were differences ($P < 0.05$) in total macrophyte, native and non-native macrophyte coverage among the year groupings. Total macrophyte coverage was greatest during 2001-2003 (3265 m^2) and 2013-2015 (3194 m^2). Native macrophyte coverage during the 2013-2015 (2629 m^2) was greater ($P < 0.05$) than all other periods examined. Native coverage was 3 to 15 times greater during 2013-2015 compared to all periods from 2001 to 2012. Non-native coverage was significantly greater ($P < 0.05$) from 2001-2003 (3046 m^2) compared to the other temporal periods.

In the Old Channel, species richness was different ($P < 0.05$) among year groupings but no trend was observed (Table 22). Lowest richness values were observed in 2001-2003 and 2013-2015 with the highest richness values observed in 2004-2006 and 2007-2009. Evenness was also difference ($P < 0.05$) among year groupings with the highest evenness values observed in 2001-2003 and 2013-2015. In addition, differences ($P < 0.05$) among year groupings were detected for Simpson's Index of Diversity. Diversity values were highest during 2001-2003 and decreased over time; however, values increased again during 2013-2015. There were differences ($P < 0.05$) in total and non-native macrophyte coverage among the year groupings. Total macrophyte coverage was lowest in 2001-2003 and increased over time. Non-native coverage was also lowest in 2001-2003 and tended to increase over time. Native coverage was not different ($P > 0.05$) among the year groupings.

Species richness and evenness was different ($P < 0.05$) among the year groupings in the Upper Spring Run (Table 23). Mean species richness was greater ($P < 0.05$) during 2001-2003 and was lowest in the final sampling period during 2013-2015. Overall, evenness was lowest ($P < 0.05$) in the first sample period of 2001-2003 and tended to increase over time. No differences ($P > 0.05$) among year groupings were detected for Simpson's Index of Diversity. There were differences ($P < 0.05$) in total macrophyte, native and non-native macrophyte coverage among the year groupings. Total macrophyte coverage was greatest ($P < 0.05$) in 2007-2009 and decreased by nearly 50% over the next two periods during 2010-2015. Native macrophyte coverage was also greatest during 2007-2009 and lowest in both 2001-2003 and 2013-12015. Non-native coverage was significantly greater ($P < 0.05$) during 2001-2003 but coverage was approximately 13 times lower during the 2013-2015 sampling period.

San Marcos River

From 2002 to 2015, discharge ranged from 92 to 348 cfs during macrophyte surveys and peaked at 1280 cfs during November 2008 in the San Marcos River. Over the study time frame, no effects were observed on the diversity indices examined when data for all LTBG sites were combined. No trends were observed for species richness (Figure 32, $R^2 = 0.004$, $P = 0.50$,), evenness (Figure 33, $R^2 = 0.003$, $P = 0.57$) and Simpson's Index of Diversity (Figure 34, $R^2 = 0.003$, $P = 0.59$) when compared to discharge.

No significant difference ($P > 0.05$) was detected for species richness at Spring Lake Dam among year groupings (Table 24). Evenness patterns were different ($P < 0.05$) among year groupings, but no pattern was observed over the five periods. However, the lowest evenness values were observed in the first (2002-2003) and last temporal periods (2013-2015), and the highest value was seen during 2007-2009 and 2010-2012. No differences ($P > 0.05$) were detected for Simpson's Index of Diversity but the highest value was observed in 2010-2012 and the lowest in 2013-2015. There were differences ($P < 0.05$) in total and native macrophyte coverage for the five temporal periods examined, with decreases over time. Total macrophyte coverage was highest during 2002-2003 (1615 m^2) and lowest during 2010-2012 (1156 m^2). Native macrophyte coverage was highest during 2002-2003 (1058 m^2) compared to the other four temporal periods with the lowest coverage recorded during 2010-2012 (773 m^2). No differences ($P > 0.05$) were detected for non-native macrophyte coverage.

A significant difference ($P > 0.05$) was detected for species richness among year groupings at City Park with the highest mean richness value of 8.5 recorded during 2013-2015 (Table 25). Evenness patterns were different ($P < 0.05$) with the lowest value documented during 2013-2015. No differences ($P > 0.05$) were detected for Simpson's Index of Diversity among the year groupings. There were differences ($P < 0.05$) in total, native and non-native macrophyte coverage for the five temporal periods. From 2002-2015, all three measurements tended to decrease, with the highest coverages in 2002-2003.

Species richness, evenness, and Simpson's Index of Diversity were significant ($P < 0.05$) among the year groupings at I-35 (Table 26). Overall, richness tended to increase, whereas both evenness and Simpson's Index of Diversity decreased. Total macrophyte, native and non-native macrophyte coverages were likewise among year groupings and tended to increase over time.

DISCUSSION

The results of this analysis indicate that discharge did not have an overall effect on aquatic macrophyte coverage in the Comal and San Marcos rivers from 2000 to 2015. Confounding factors in this analysis include the planting of native and removal of non-native macrophytes which began in 2013. It appears, with a few exceptions, that the macrophyte species in both rivers are resilient to disturbances, and exhibit fast growth rates, high reproductive abilities and a perennial life cycles that allows quick recovery time following a disturbance.

This finding is not in accordance with other studies that have found that macrophyte abundance and diversity decreases in relation to increased flood pulses (Bilby 1977, Henry et al. 1994, Riis and Biggs 2003). Negative correlations with floods and reductions in biomass is thought to be due to scouring of the plants during the rising limb of the flood hydrograph (Wilby et al. 1998). This was true with *L. repens* in the Old Channel which decreased in coverage when discharge exceeded 70 cfs (BioWest 2016). On October 31, 2013, a period of heavy precipitation resulted in an intense flood and discharge that peaked at 1110 cfs in the upper reach of the San Marcos River, and Hardy et al. (2016) reported that less than 10% of planted *Zizania texana* was lost from scouring during the flood. The aquatic macrophytes in both rivers appear to be unaffected to increases in discharge. *Zizania texana* and *Sagittaria platyphylla* exhibit heterophylly becoming emergent with stiff leaves supported with lignin in lower water velocities and remaining submerged with flexible ribbon-like leaves in higher water velocities, which may explain the lack of effect during discharge variations. In addition, as noted by Santamaria (2002) aquatic plants often have a cosmopolitan distribution, occur in a wide variety of habitats, and are adapted to varying patterns of water velocity (Santamaria 2002), which may also be a factor in the lack of discharge effect on coverage.

However, both *Ludwigia repens* and *Potamogeton illinoensis* had decreased coverage with higher discharge in some LTBG sites in both rivers, which is in line with the findings of others (Bilby 1977, Henry et al. 1994, Riis and Biggs 2003). *Ludwigia repens* did not establish well in some of the LTBG sites in the Comal and San Marcos Rivers. *Ludwigia repens* is a broad-leaved macrophyte with flexible stems, multiple nodes and forms a dense canopy and is more likely to be scoured during high discharge events. In the Old Channel, it was found that discharge > 70 cfs resulted in the loss of Ludwigia repens (BioWest 2016). Moreover, shade from canopy trees along the bank in the Old Channel are thought to inhibit *L. repens* from establishing (BioWest 2016). In the San Marcos River, greater than 12,000 *L. repens* individuals were planted in a variety of flows and substrates in 2013 covering 550 m^2, but less 1% remained 2015 (BioWest 2016). In addition, competition and photosynthesis studies between *Ludwigia repens* and *Hygrophila polysperma* indicate that *L. repens* growth is favored in full sun while *H. polysperma* is a shade tolerant (Jeffrey Hutchinson, unpublished data). Since light is rapidly attenuated in water, *L. repens* may be unable to compete with *H. polysperma* or other non-native macrophytes. Species of *Potamogeton* have thin longitudinal leaves but have little strengthening tissue making them susceptible to sheer stress from high water velocities (Sculthorpe 1967) and may explain why decreases in coverage were seen. In other cases some *Potamogeton* spp. have declined significantly due to increases in floods and habitat loss (Mountford 1994, Riis and Sand-Jensen 2001). In addition, populations of *P. illinoensis* have shown the ability to recover following floods by re-sprouting from roots and rhizomes and turions in the sediment (Sculthorpe 1967).

The majority of previous studies on aquatic macrophytes have examined the effects of water velocity on coverage and biomass and found that macrophyte beds greatly reduce flow within the beds (reviewed in Lacoul and Freedman 2006). Water velocity increases with increasing discharge but is greatly reduced by large areas of aquatic macrophytes (Sand-Jensen et al. 1989). Several studies have reported discharges that were highly variable within large macrophyte beds (Madsen and Warncke 1983, Sand-Jensen and Mebus 1996, Wilcock et al. 1999). *Ranunculus* spp. was found to have greater biomass as discharge increased from 18 to 120 cfs (Ham et al. 1982). Sand-Jensen et al. (1989) found that macrophytes with linear, flexible leaves were more resistant to higher discharge and while broad-leave and rootless algae were more resistant to lower discharge in a river in which discharge ranged between 14 and 247 cfs. Macrophyte biomass and discharge were weakly correlated with high variability in biomass at < 2825 cfs, less variability between 2825 and 4238 cfs, and no macrophytes were present when discharge was > 4238 cfs (Chambers et al. 1991).

In this analysis, discharge exceeded 400 cfs multiple times in both rivers. The highest discharges recorded from 2000-2015 in the Comal and San Marcos Rivers were 13400 and 1280 cfs, respectively. The maximum discharges recorded in the Comal and San Marcos Rivers are higher than those reported by Ham et al. (1982) and Sand-Jensen et al. (1989), and intermediate with those reported by Chambers et al. (1991). From 2000 to 2015, discharge in the Comal River exceeded 400 cfs for 771days and the highest discharge of 13400 cfs was recorded in July 2002. From 2002 to 2015, discharge in the San Marcos River exceeded 400 cfs for 55 days in July to September 2017. Based on the data analyzed, most macrophytes appear to be resistant and resilient to flood discharge rates between > 1000 cfs in the Comal and San Marcos rivers.

It is likely that an extreme flood event in which discharge exceeds 4000 cfs would result in a large decline in aquatic macrophyte coverage from scouring as found by Chambers et al. (1991). Moreover, a series of multiple floods over a 6-12 month period in which discharge exceeds 500 cfs may potentially result in large declines in aquatic macrophytes as Riis and Biggs found in New Zealand (2001). As suggested by Riis and Biggs (2001), research is needed to determine the impacts of sequential disturbances on aquatic macrophytes and the time required for recolonization. We hypothesize that a series of multiple floods over a 6-18 month period in which discharge exceeds 1000 cfs would result in a large decline of aquatic macrophytes.

The results of planting native and removing non-native macrophytes based on the EARIP (2011) to date has been successful in the Comal and San Marcos rivers during 2013-2015. In the Comal River, increases in coverage were seen for *Ludwigia repens* in Landa Lake and decreases in *Hygrophila polysperma* were documented in Landa Lake, the Lower New Channel and Old Channel. The most stable pattern of macrophyte coverage documented was *Vallisneria* spp. at Landa Lake. Landa Lake is more characteristic of a lentic system while the other 6 LTBM sites are characteristics of lotic systems. In the San Marcos River, increases were documented for *Zizania texana* at Spring Lake Dam and City Park. In the San Marcos River, decreases of *Hydrilla verticillata* coverage was documented at Spring Lake Dam and City Park with decreases in *Hygrophila polysperma* also documented in City Park.

An extended drought was documented from April 2013 to March 2015, with 385 consecutive days from November 2, 2013 to November 21, 2014 in which discharge dropped below 200 cfs in the Comal River. During the same time period, only 6 days were documented in the San Marcos River in which discharge dropped below 100 cfs. In the San Marcos River, a period of low flow was documented from December 2008 to October 2009, with 157 consecutive days from April 18, 2009 to September 21, 2009 in which discharge dropped below 100 cfs. Extended droughts result in loss of hydrological connectivity, loss of habitat and desiccation of aquatic macrophytes and recovery can be variable among streams (Holmes 1999, Lake 2003). Decreased macrophyte coverage was not documented over this low flow period. Coverage of *Vallisneria* spp. in Landa Lake and *Sagittaria platyphylla* in Landa Lake the Upper Spring Run remained stable from 2013 to 2015. *Cabomba caroliniana* coverage also remained stable from 2013 to 2015 in Landa Lake and the Lower New Channel. *Ludwigia repens* exhibited lower coverage in Landa Lake and Old Channel from June 2013 to April 2015, but exhibited increases in coverage as discharge increased in May 2015.

Overall, general trends were not detected for seasonally for aquatic macrophyte coverage in either the Comal or San Marcos Rivers. However, there were several exceptions (Tables 13, 17 and 18). Differences in some macrophyte coverage in the spring and fall may have been confounded to some degree with the advent of planting of natives and the removal of non-native macrophytes from 2013 to 2015. Macrophyte coverage was variable and was correlated with discharge in some stream reaches. In both rivers, all macrophytes are perennial and re-sprout from roots and rhizomes following scouring and sheer stress caused by high discharge. Of the macrophytes evaluated, *Zizania texana* is most likely to be impacted during the summer recreation period due to submergence of flowers that may result in a reduction of viable seeds. Many of the root-less or unattached species of algae and bryophytes exhibited a pulsating pattern indicating their coverage decreases during periods of low discharge and increases during periods of high discharge. Perennial streams are heterogeneous due to dynamic hydrological regimes and species coverage fluctuates greatly (Minshall et al, 1985). While there were shifts in the coverage of some species, we observed no major shifts of large declines or increases in macrophyte coverage, except for some natives that were planted and non-natives that were removed.

Species richness, evenness and Simpson's Index of Diversity values exhibited minor variations in the LTBG sites from 2001-2015, but an overall trend was not obvious. In addition, and more importantly, a loss of native species was not observed in either the Comal or San Marcos River. In contrast, non-native macrophyte coverage tended to decrease in the Comal River at Landa Lake, Lower New Channel and Upper Spring Run, and in the San Marcos River at City Park. At the same time, increases in native plant coverage were seen in Landa Lake in the Comal River and at I-35 in the San Marcos River.

CONCLUSION

The results of this analysis indicate that: 1) discharge had minor impacts on aquatic macrophytes and the plants were not impacted by discharges up to 13400 cfs in the Comal River and 1280 cfs in the San Marcos River, 2) species assemblages were variable, 3) seasonal disturbance (spring vs. fall) effects were not universal, 4) planting of native macrophytes increased area coverage of *Zizania texana*, *Ludwigia repens*, and *Cabomba caroliniana*, and 5) removal of non-natives (*Hydrilla verticillata* and *Hygrophila polysperma*) resulted in reduced coverage.

The EARIP represents one of the few long-term aquatic macrophyte monitoring programs (2000-present) that exists globally and none are known from the United States. The Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service's *Zizania texana* monitoring program has occurred from 1989-present and may be the longest aquatic macrophyte monitoring program in the United States. Continuation of these monitoring programs is important to gain a better understanding of the impacts of droughts and floods on macrophytes and other listed species in the Comal and San Marcos Rivers. Moreover, the data can be used to asses which macrophytes are indicators of disturbance such as extreme droughts and floods.

RESEARCH AND MONITORING NEEDS

Installation of gauges that collect daily water velocity readings at each LTBG sites would provide more accurate description of how water velocity affects macrophytes. Ideally, installing several gauges at each site is needed as different habitats exist within each site.

Information is needed on water velocity which is related to discharge but can vary greatly among cross-sections of a stream gradient resulting in different species of macrophytes. Additional studies are needed to determine the specific habitats required by native macrophytes, especially *Ludwigia repens* and *Potamogeton illinoensis* which may be more suited to low velocity environments and out compete *Hygrophila polysperma* and *Hydrilla verticillata*. Other native species found in these rivers should be evaluated for planting such as *Bacopa monnieri*, *Heteranthera dubia*, *Hydrocotyle umbellata*, *Justicia americana*, *Marsilea macropoda*, *Myriophyllum heterophyllum*, and *Potamogeton illinoensis*. Studies are needed to determine if

Ludwigia repens can be planted and succeed in areas where *Hygrophila polysperma* has been removed.

In addition, research is needed to determine if larger areas of macrophytes provide protection to interior species and prevent the complete loss of the plants from scouring during flood events. For example, would an area of macrophytes 50 m^2 result in less loss from high discharge events compared to patches 10 or 25 m^2 in area. Knowledge of this information would assist planting efforts and could provide greater stability to macrophyte populations.

Continued removal and monitoring is needed for control of non-native macrophytes with a focus on *Hydrilla verticillata* and *Hygrophila polysperma*. *Hydrilla verticillata* can reproduce rapidly from fragments, resprouts from roots, and turions and tubers. Several million tubers / ha have been recorded in some sites infested with *Hydrilla verticillata* (Sutton and Portier 1985). Long-term monitoring will be needed for control of both these species. *Hygrophila polysperma* resprouts readily from apical tips and fragments.

Planting of native macrophytes should focus on two strategies. The first should be to continue planting efforts to extend the area coverage of existing zones of native macrophytes to ensure continued presence in the Comal and San Marcos rivers. Large patches and density of macrophytes reduce water velocity and trap sediment and nutrients. The reduced water velocity within the perimeter may provide protection to macrophytes from scouring and sheer stress during high discharge events. The second strategy should be high density planting of native macrophytes in areas where non-natives have been removed. *Zizania texana* is known to be competitive in areas where *Hydrilla verticillata* has been removed, but other native macrophytes should be evaluated, especially in areas with lower water velocities.

Restrictive barriers should be installed in areas where native vegetation is planted to allow the plants time to establish. Restrictive barriers have been installed to protect established *Zizania texana* in the San Marcos River have proven successful, but barriers have not been used in either river for new plantings. Protection is most important during the first 2 years to allow macrophytes to established anchoring by developing their root and rhizome systems.

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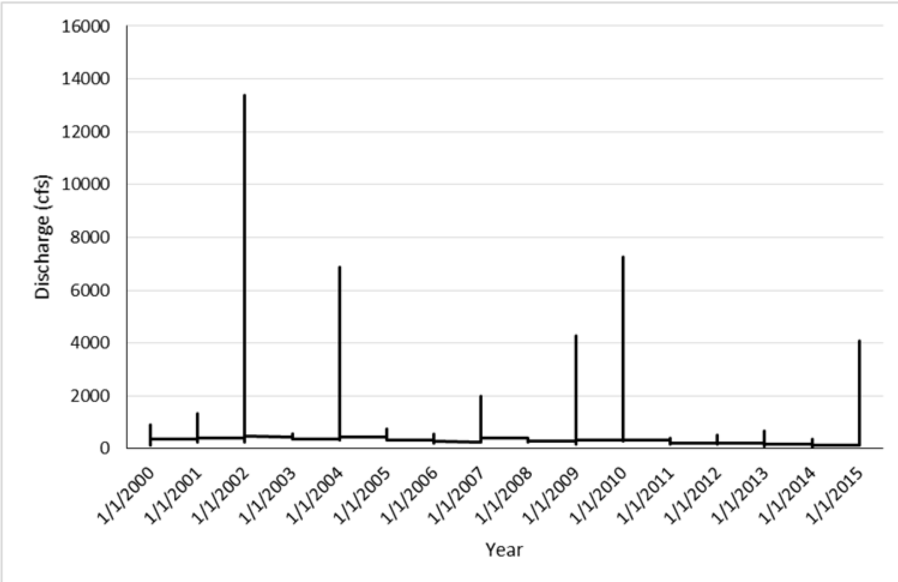


Figure 1. Hydrograph of daily discharge (cubic feet per second - cfs) in the Comal River from January 2000 to December 2015 with red line denoting low and high discharge.

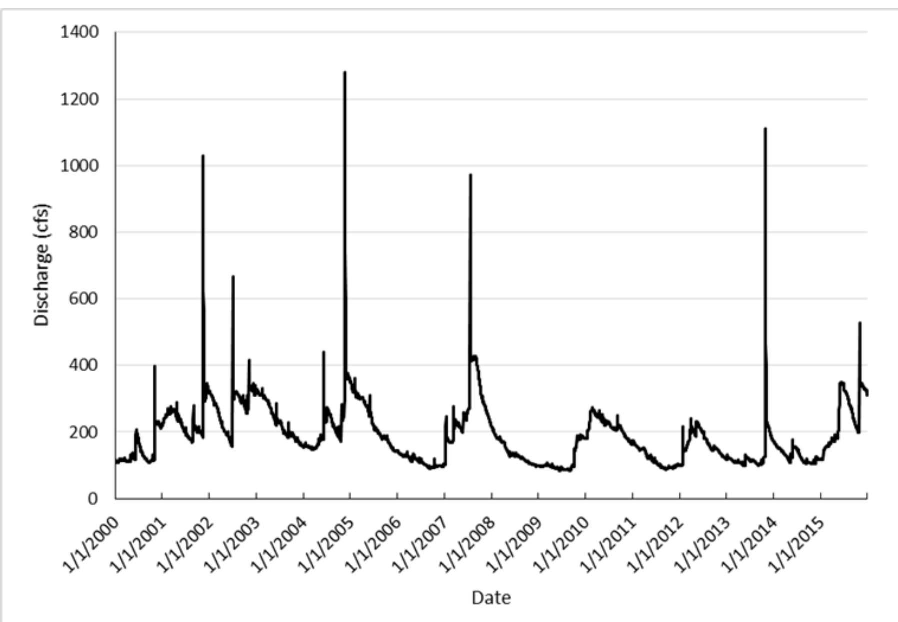


Figure 2. Hydrograph of daily discharge (cubic feet per second - cfs) in the San Marcos River from January 2000 to December 2015 with red line denoting low and high discharge.

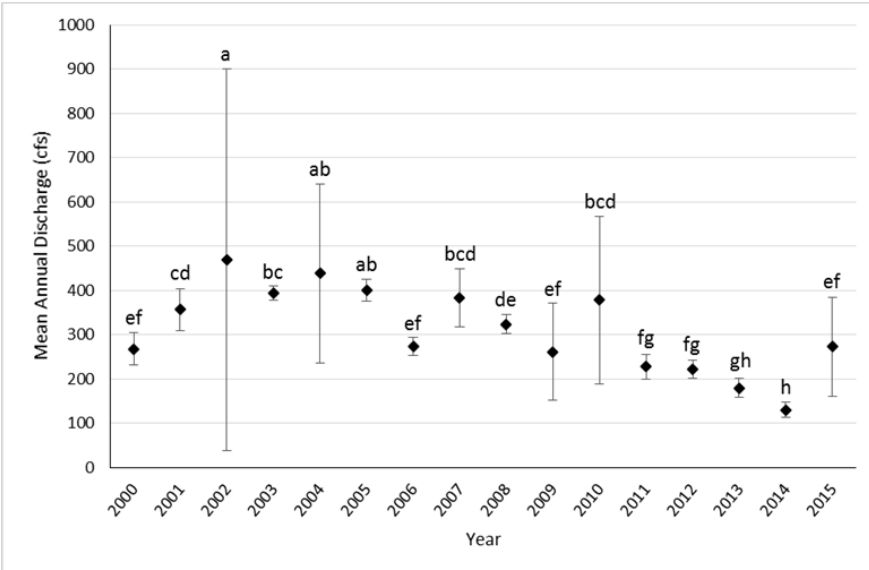


Figure 3. Mean annual discharge (cubic feet per second - cfs) in the Comal River from January 2000 to December 2015. Different letters among years represent significant differences at P < 0.05. Bars represent standard deviation.

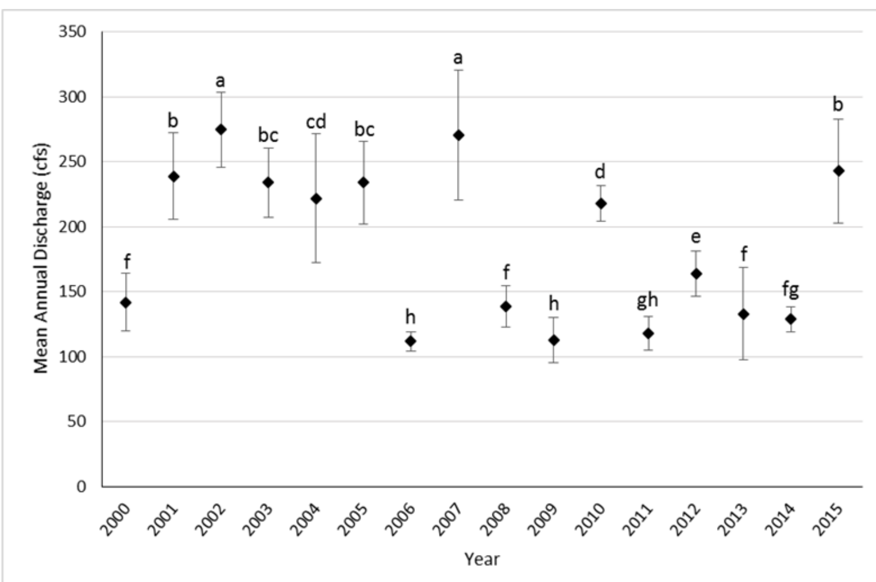


Figure 4. Mean annual discharge (cubic feet per second - cfs) in the San Marcos River from January 2000 to December 2015. Different letters among years represent significant differences at P < 0.05. Bars represent standard deviation.

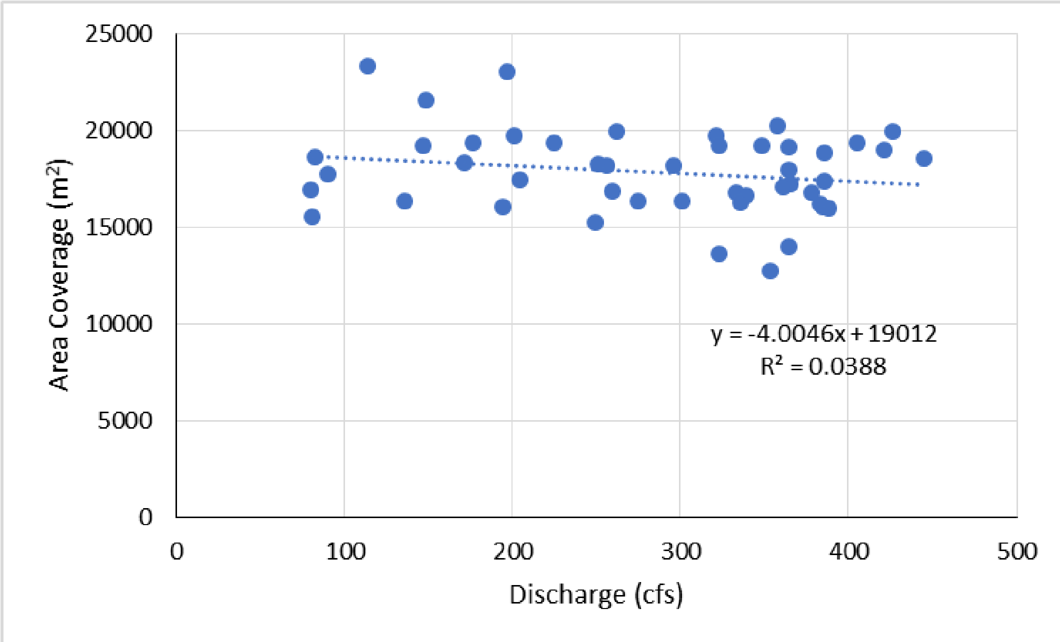


Figure 5. Regression of macrophyte area coverage (m^2) from 2000-2015 compared to discharge (cfs) in Landa Lake, Comal River.

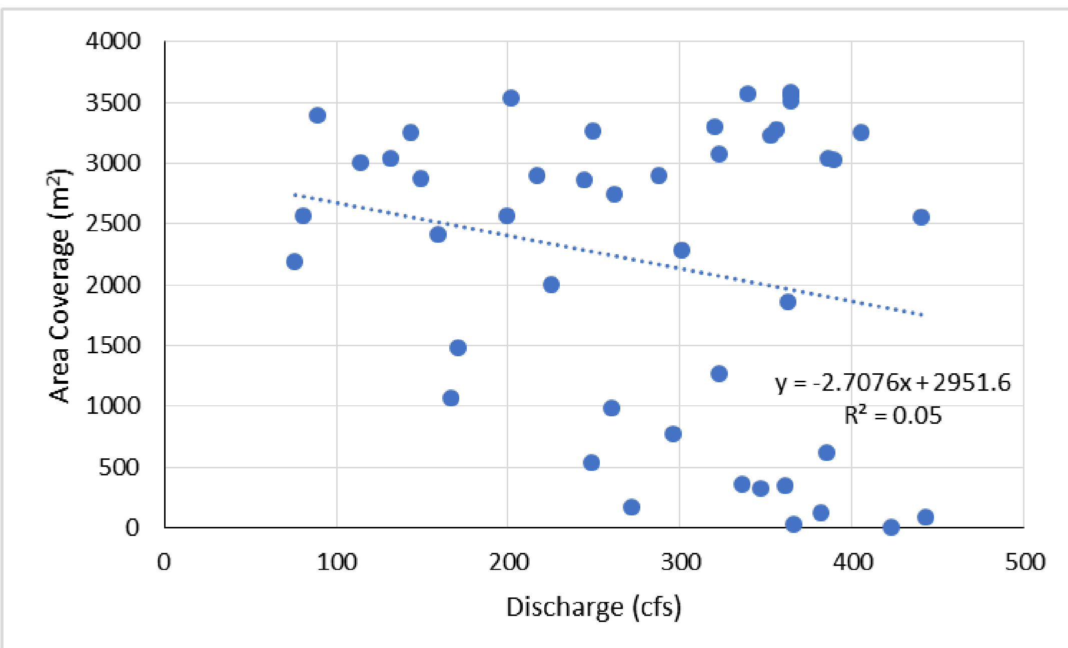


Figure 6. Regression of macrophyte area coverage (m^2) from 2000-2015 compared to discharge (cfs) in the Lower New Channel, Comal River.

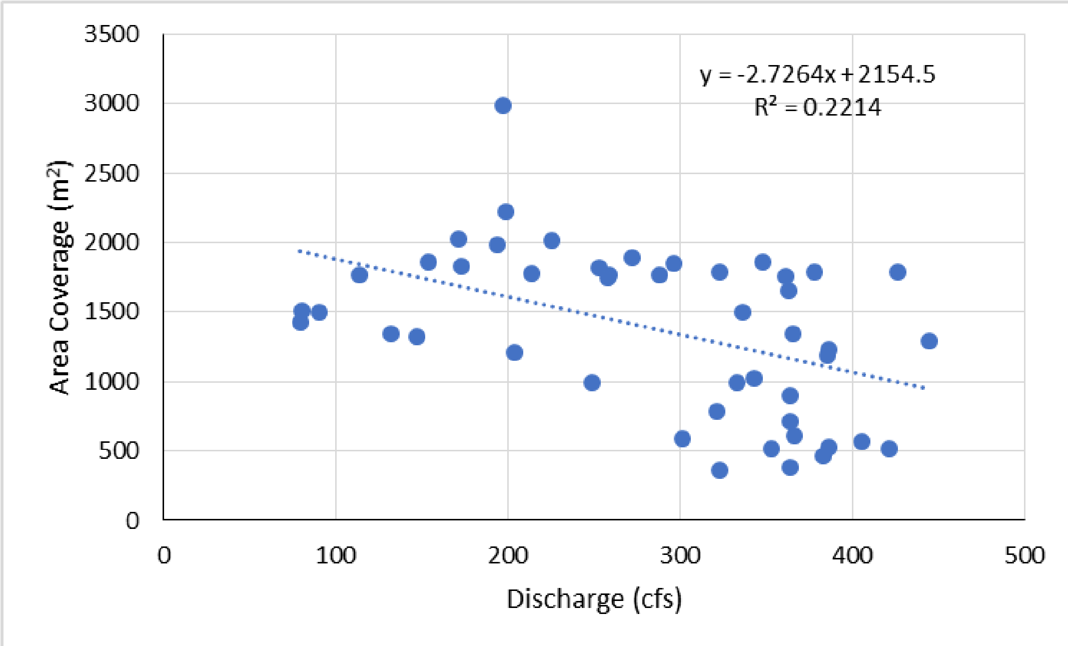


Figure 7. Regression of macrophyte area coverage (m^2) from 2000-2015 compared to discharge (cfs) in the Old Channel, Comal River.

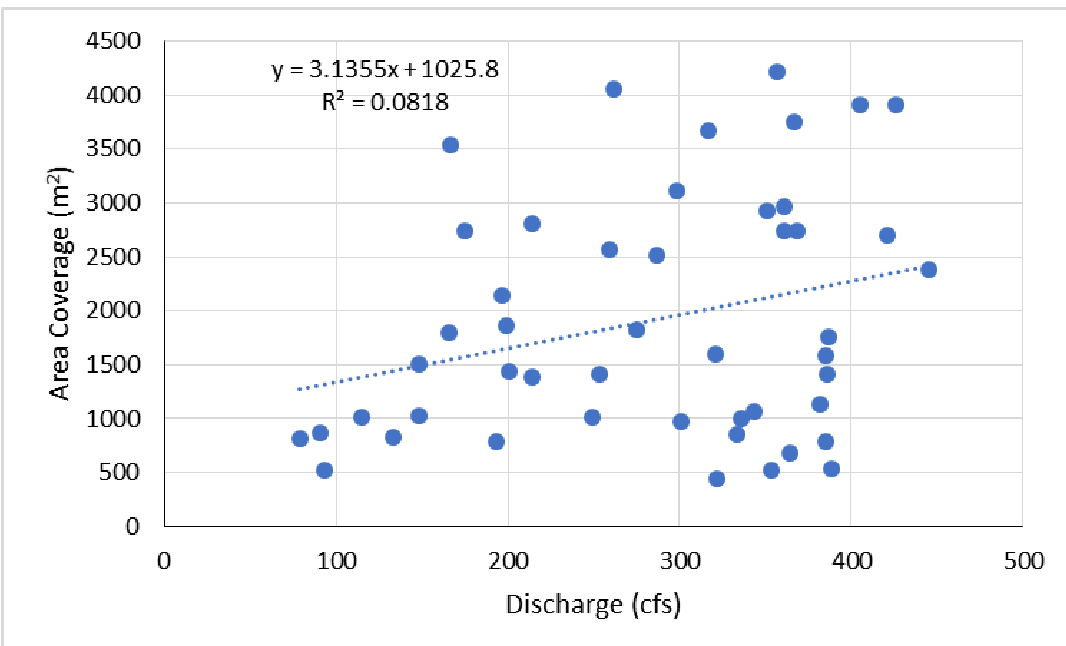


Figure 8. Regression of macrophyte area coverage (m^2) from 2000-2015 compared to discharge (cfs) in the Upper Spring Run, Comal River.

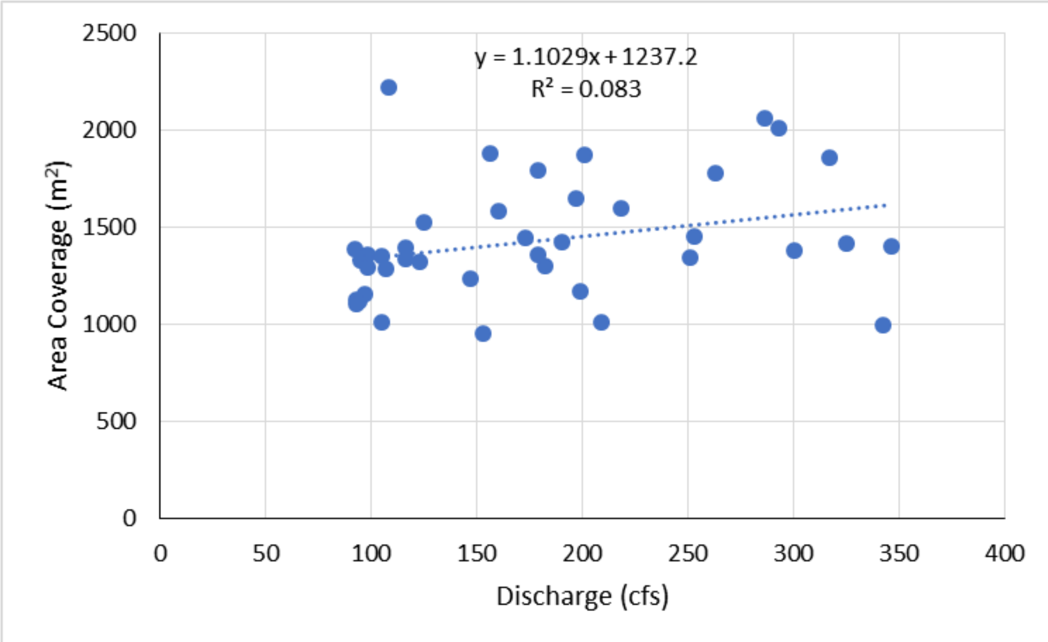


Figure 9. Regression of macrophyte area coverage (m^2) from 2002-2015 compared to discharge (cfs) in Spring Lake Dam, San Marcos River.

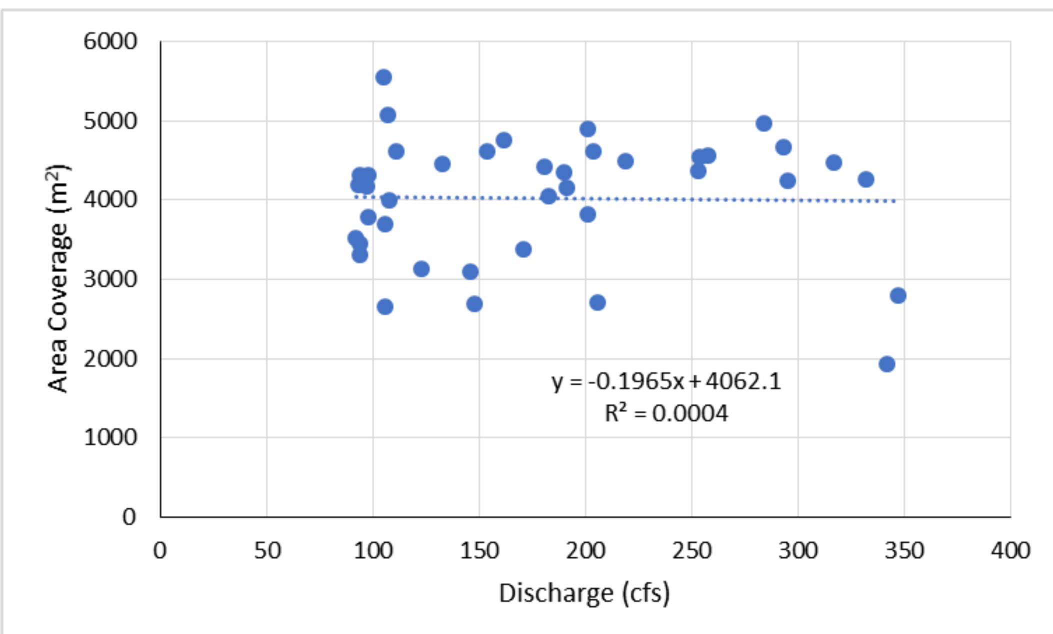


Figure 10. Regression of macrophyte area coverage (m^2) from 2002-2015 compared to discharge (cfs) in City Park, San Marcos River.

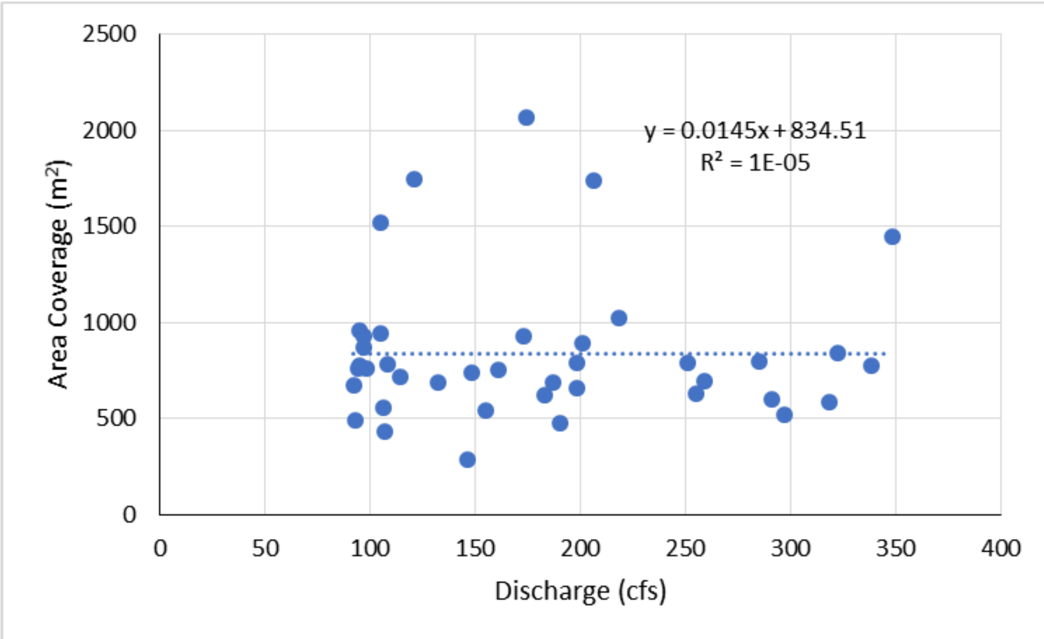


Figure 11. Regression of macrophyte area coverage (m^2) from 2002-2015 compared to discharge (cfs) at I-35, San Marcos River.

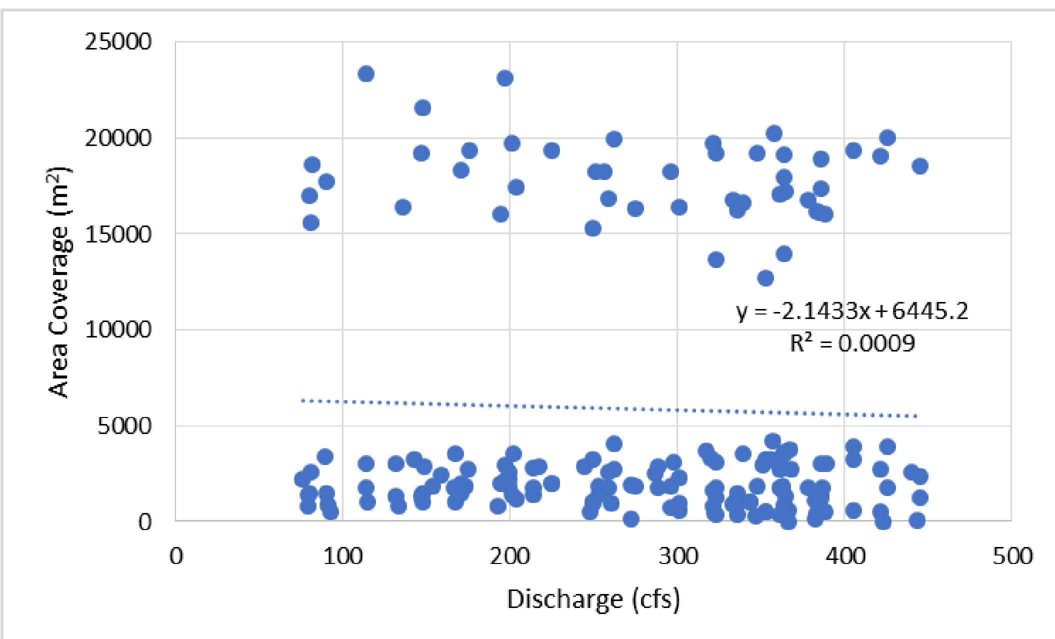


Figure 12. Combined area coverage (m^2) for all aquatic macrophytes in the four LTBG sites within the Comal River from 2000 to 2015.

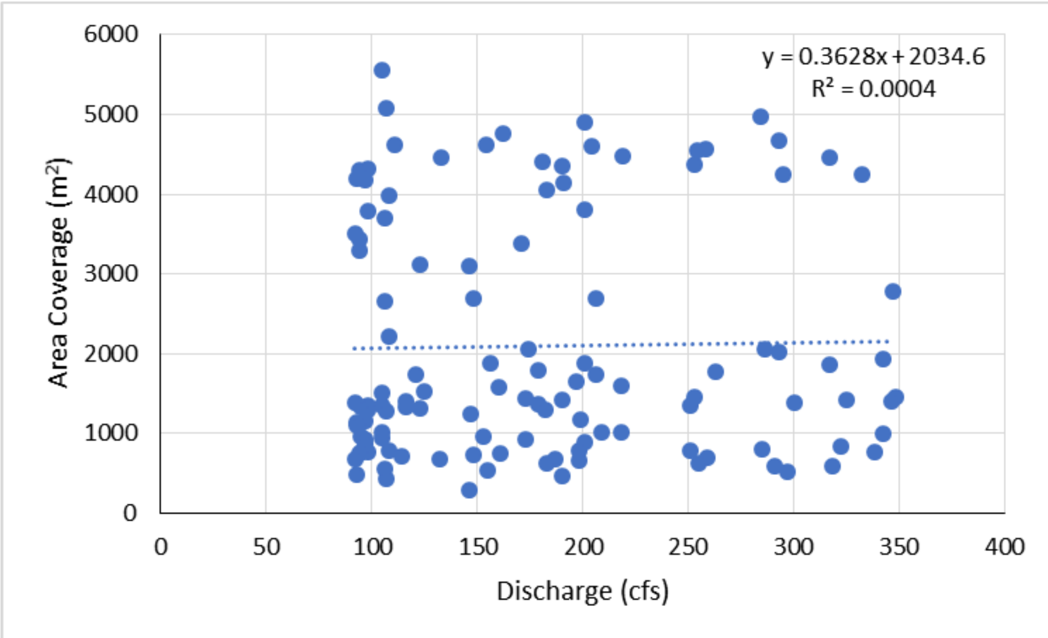


Figure 13. Combined area coverage (m^2) for all aquatic macrophytes in the three LTBG sites within the San Marcos River from 2002 to 2015.

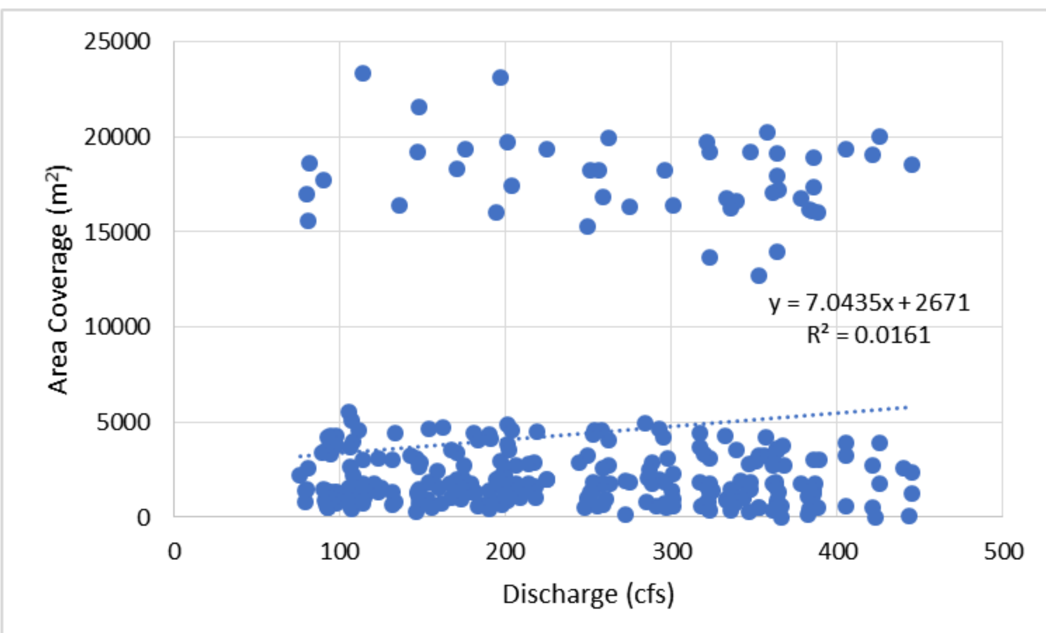


Figure 14. Combined area coverage (m^2) for all aquatic macrophytes in the three LTBG sites in the San Marcos River (2002 to 2015) and four LTBG sites within the Comal River (2000 to 2015).

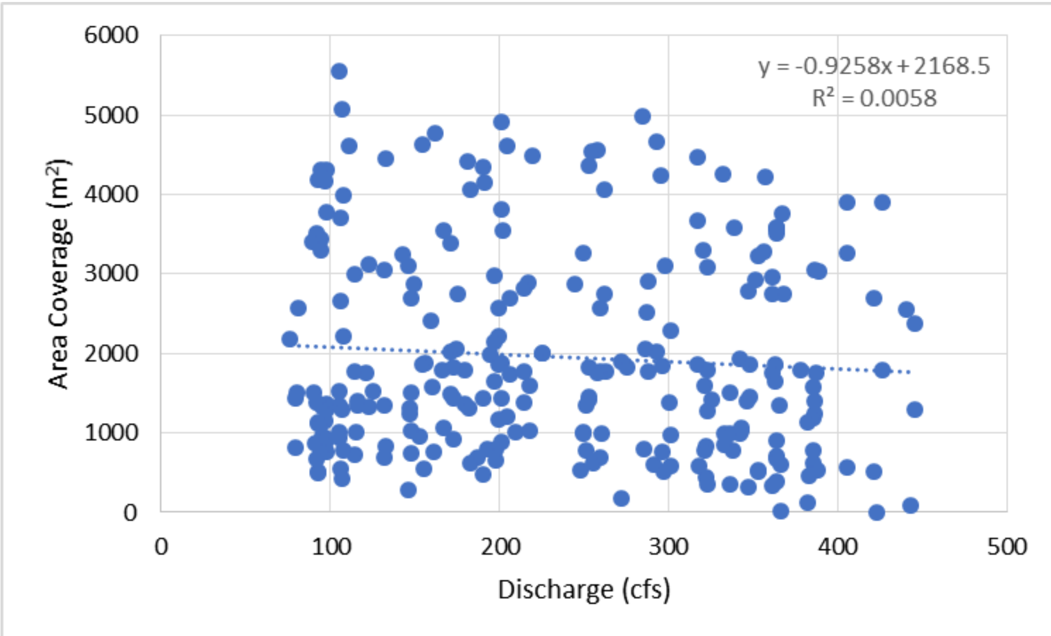


Figure 15. Combined area coverage (m^2) for all aquatic macrophytes in the three LTBG sites in the San Marcos River (2002 to 2015) and LTBG sites (not including Landa Lake) within the Comal River (2000 to 2015).

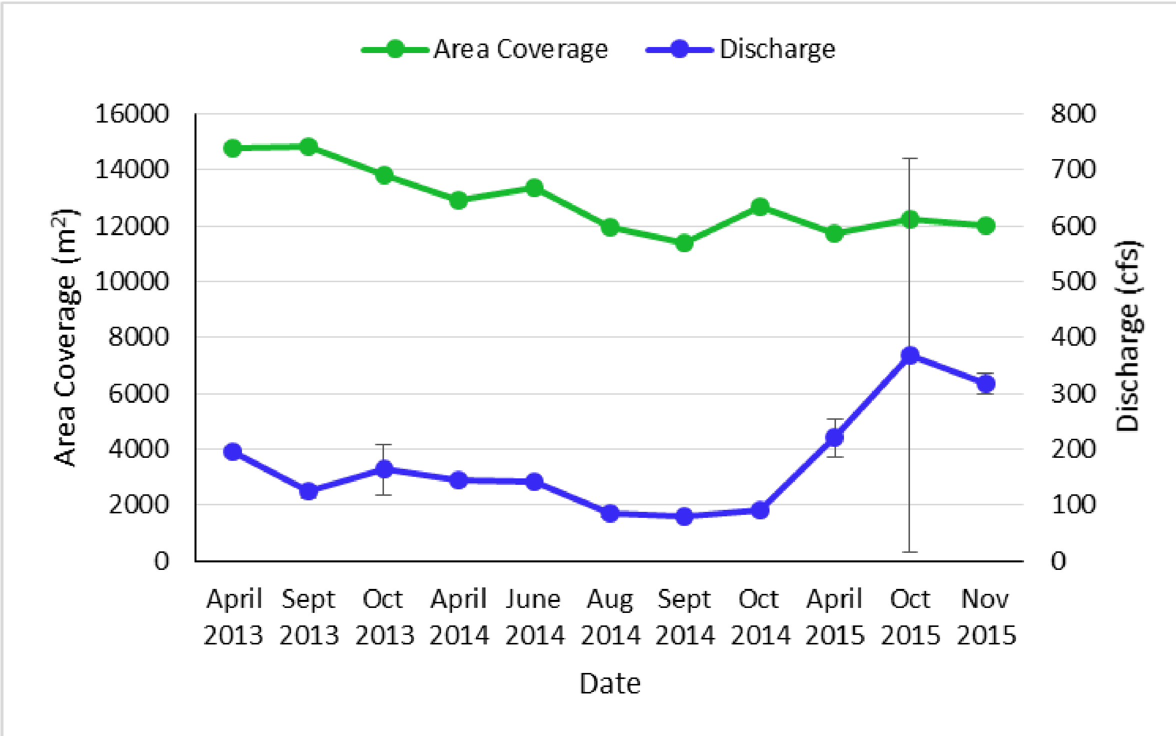
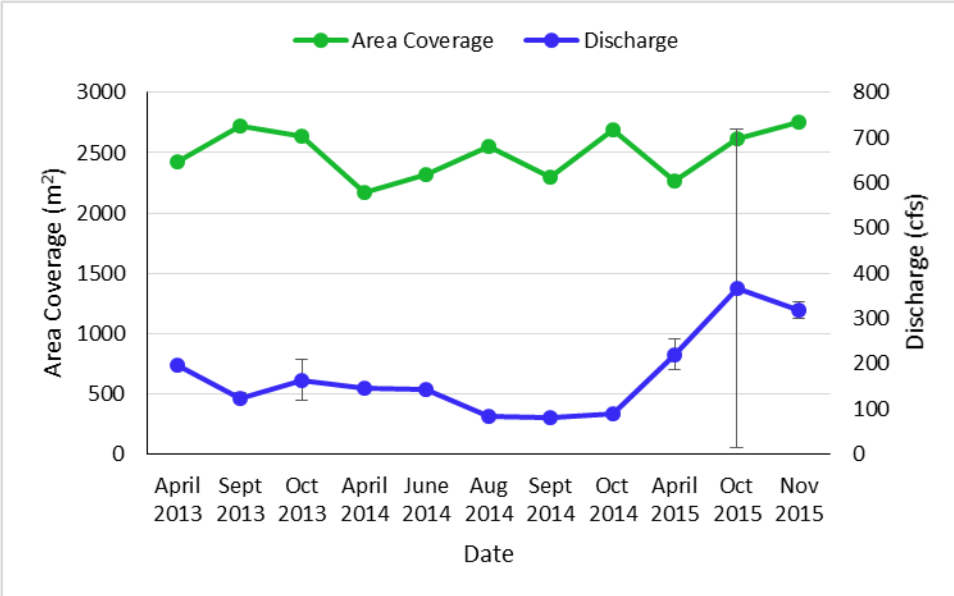
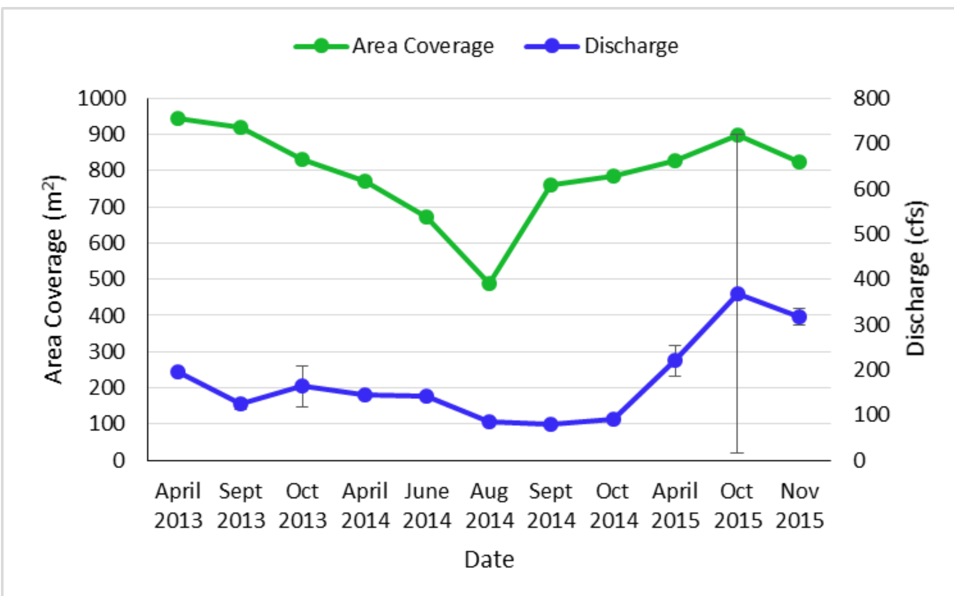


Figure 16. Area coverage (m^2) of eelgrass (*Vallisneria* spp.) and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in Landa Lake. Bars represent standard deviation for monthly discharge.



A



B

Figure 17. Area coverage (m^2) of delta arrowhead (*Sagittaria platyphylla*) and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in A) Landa Lake, and B) Upper Spring Run. Bars represent standard deviation for monthly discharge.

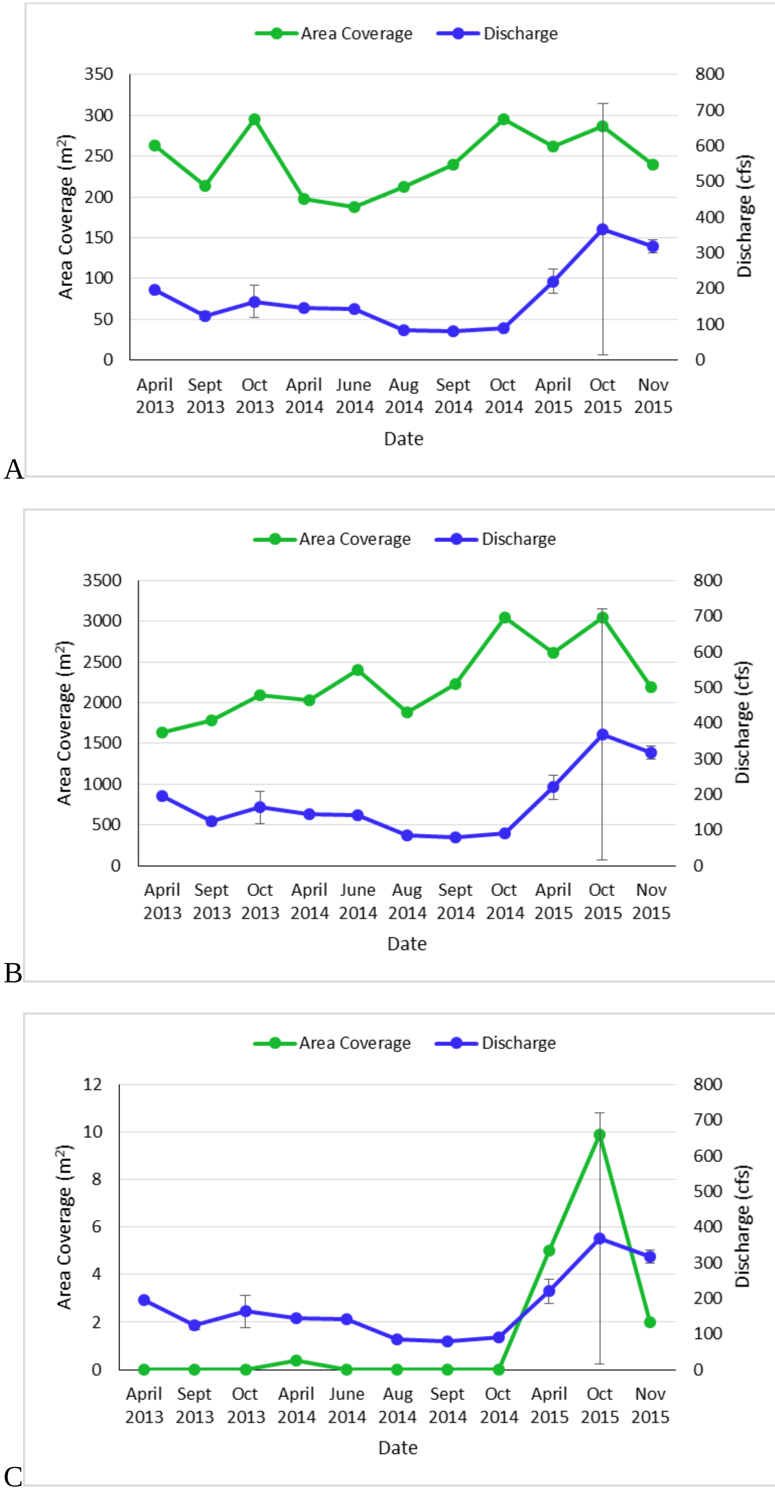


Figure 19. Area coverage (m^2) of fanwort (*Cabomba caroliniana*) and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in A) Landa Lake, B) Lower New Channel, and C) Upper Spring Run. Bars represent standard deviation for monthly discharge.

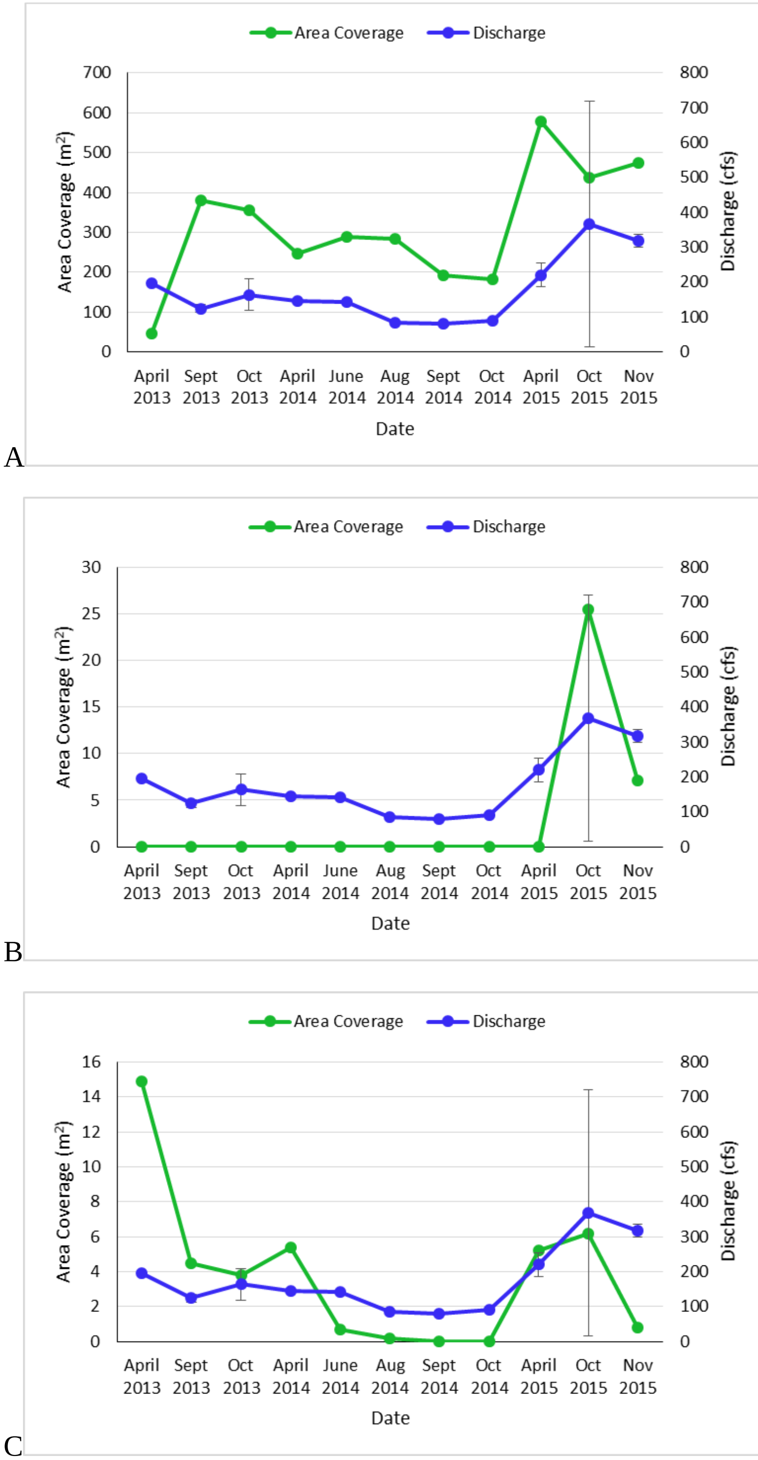
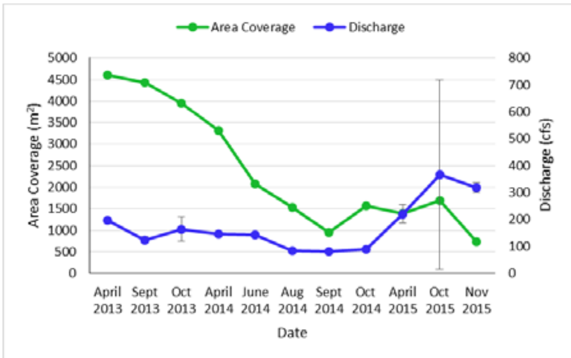
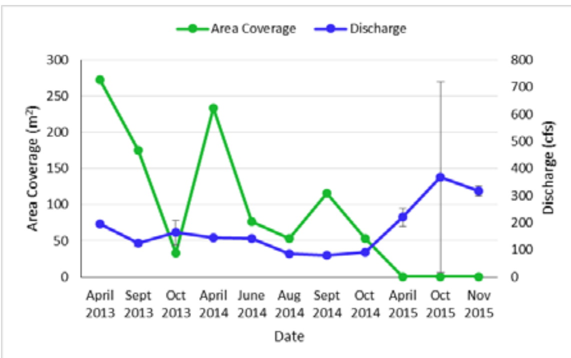


Figure 20. Area coverage (m^2) of creeping primrose willow (*Ludwigia repens*) and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in A) Landa Lake, B) Old Channel, and C) Upper Spring Run. Bars represent standard deviation for monthly discharge.



A



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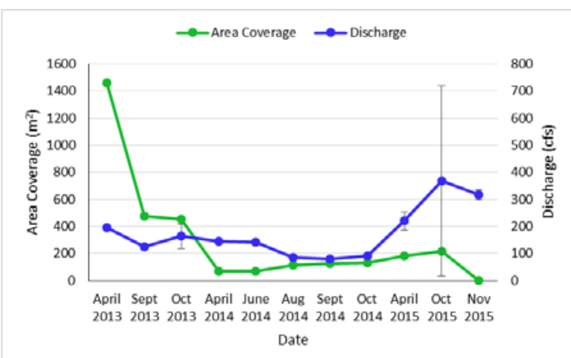

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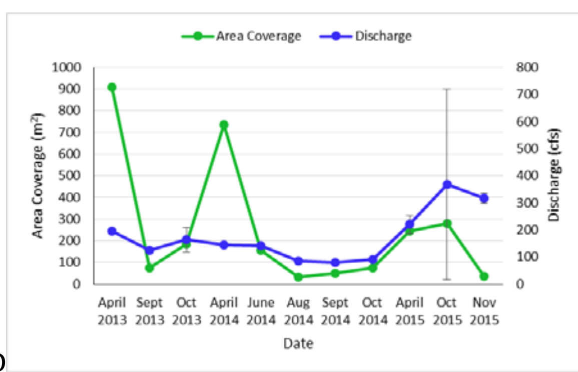
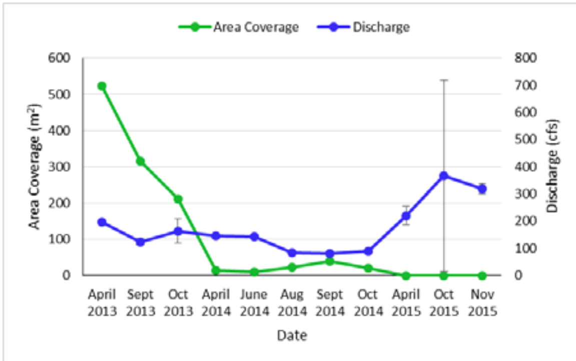
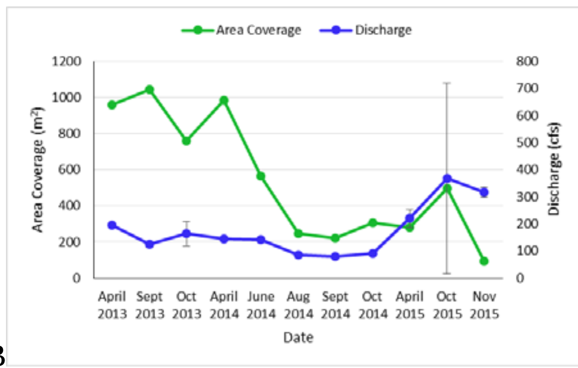


D

Figure 21. Area coverage (m^2) of bryophytes and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in A) Landa Lake, B) Lower New Channel, C) Old Channel, and D) Upper Spring Run. Bars represent standard deviation for monthly discharge.



A



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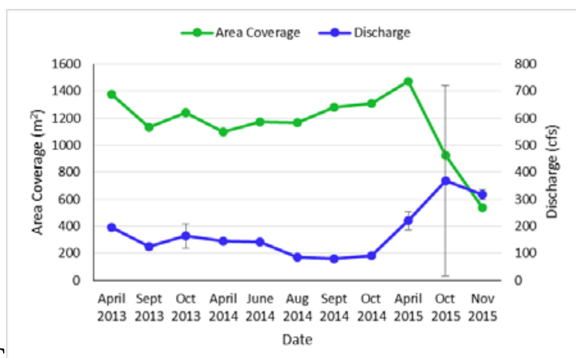

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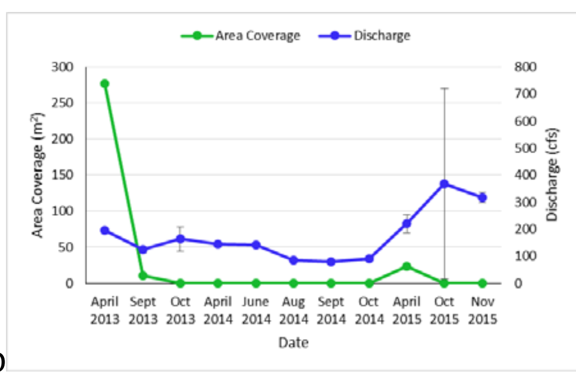
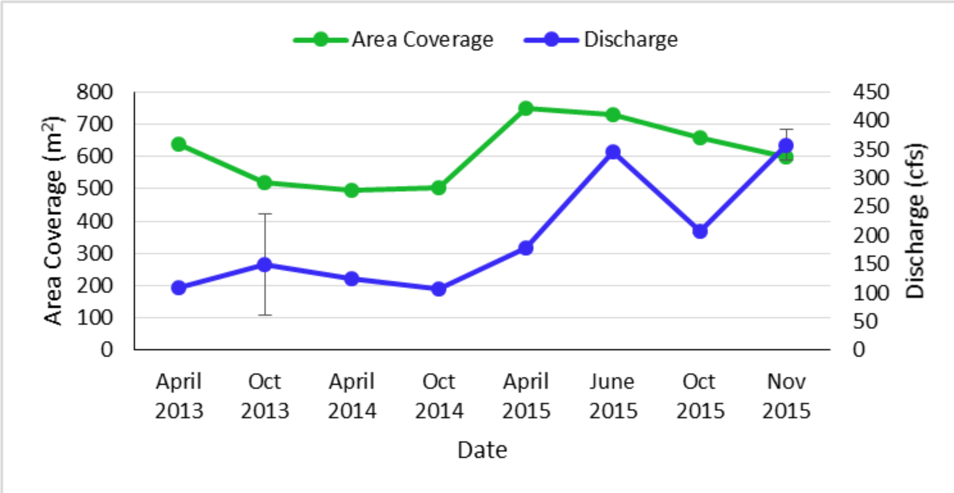
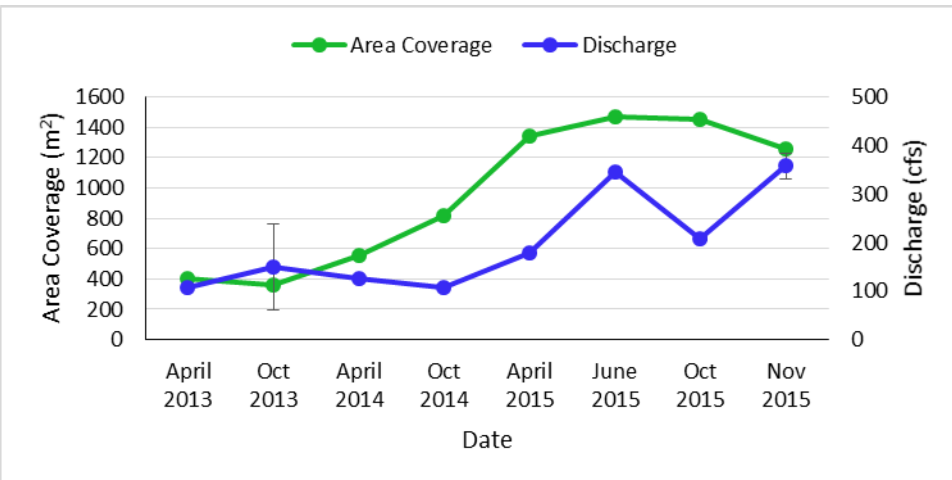


D

Figure 22. Area coverage (m^2) of East India hygrophila (*Hygrophila polysperma*) and mean monthly discharge (cfs) in the Comal River, USGS gauge 8169000 during sampling from April 2013 through November 2015 in A) Landa Lake, B) Lower New Channel, C) Old Channel, and D) Upper Spring Run. Bars represent standard deviation for monthly discharge.



A



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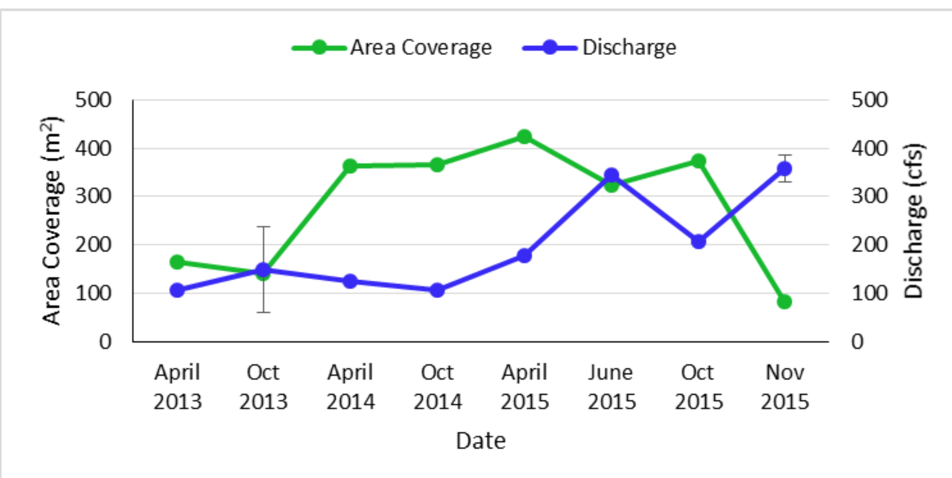


C

Figure 23. Area coverage (m^2) of Texas wild rice (*Zizania texana*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam, B) City Park, and C) I-35. Bars represent standard deviation for monthly discharge.

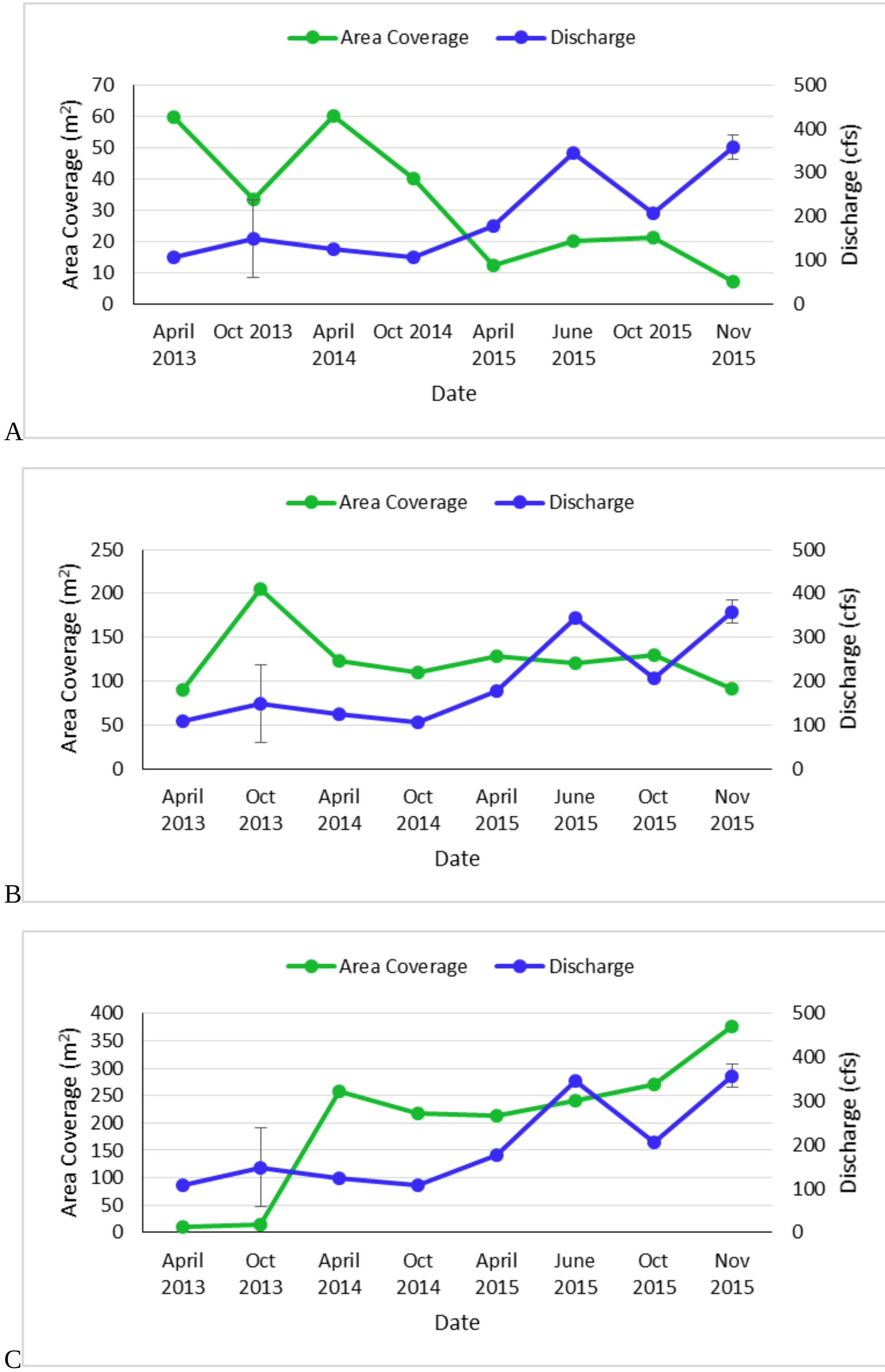
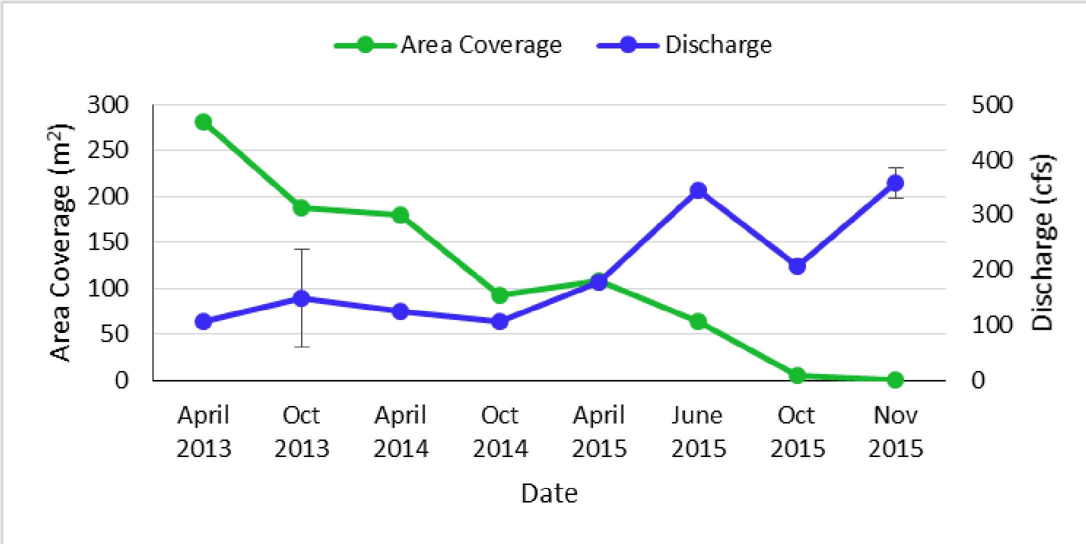
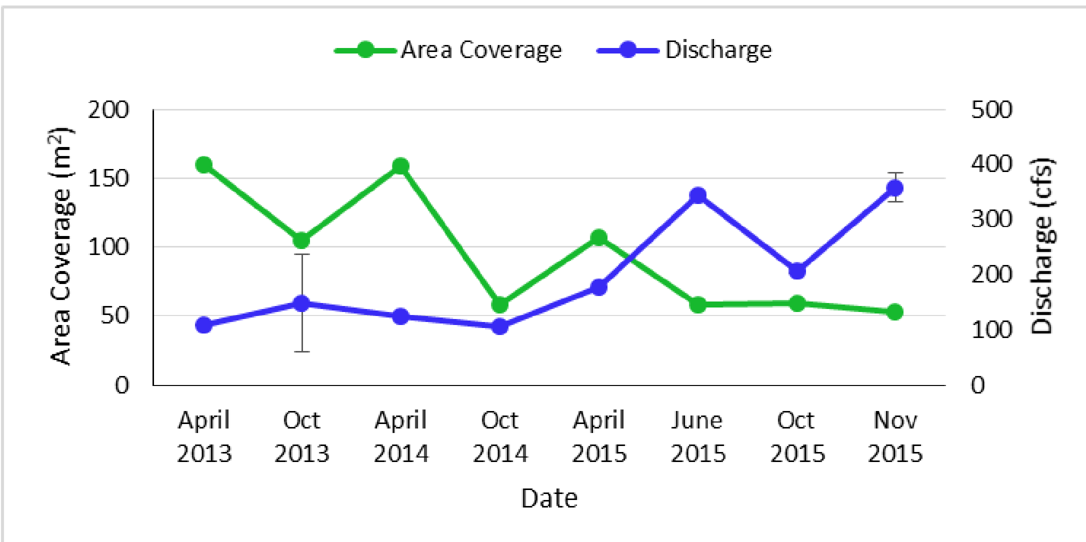


Figure 24. Area coverage (m^2) of delta arrowhead (*Sagittaria platyphylla*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam, B) City Park, and C) I-35. Bars represent standard deviation for monthly discharge.



A



B

Figure 25. Area coverage (m^2) of Illinois pondweed (*Potamogeton illinoensis*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam and B) City Park. Bars represent standard deviation for monthly discharge.

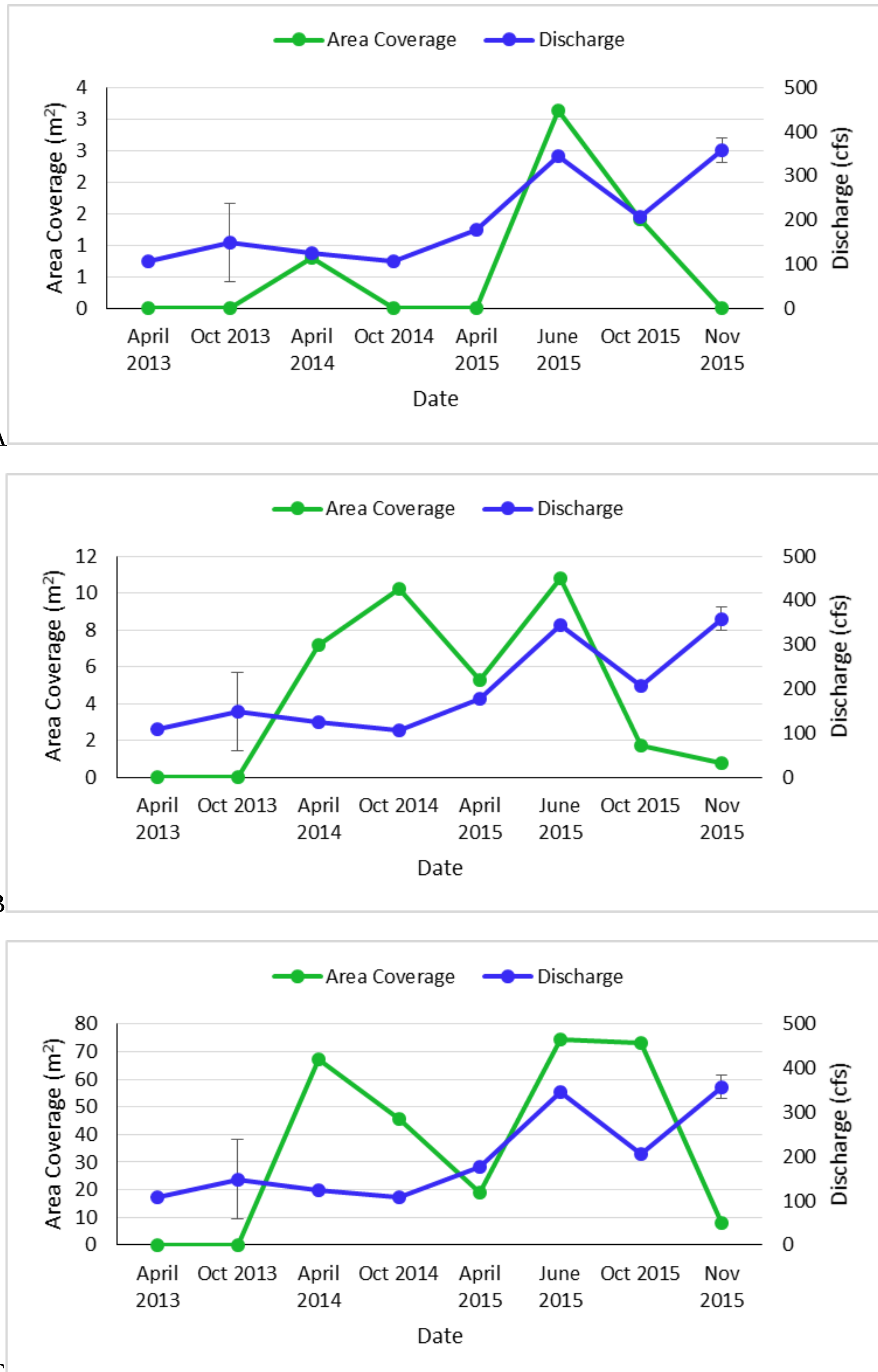


Figure 26. Area coverage (m^2) of creeping primrose willow (*Ludwigia repens*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam, B) City Park, and C) I-35. Bars represent standard deviation for monthly discharge.

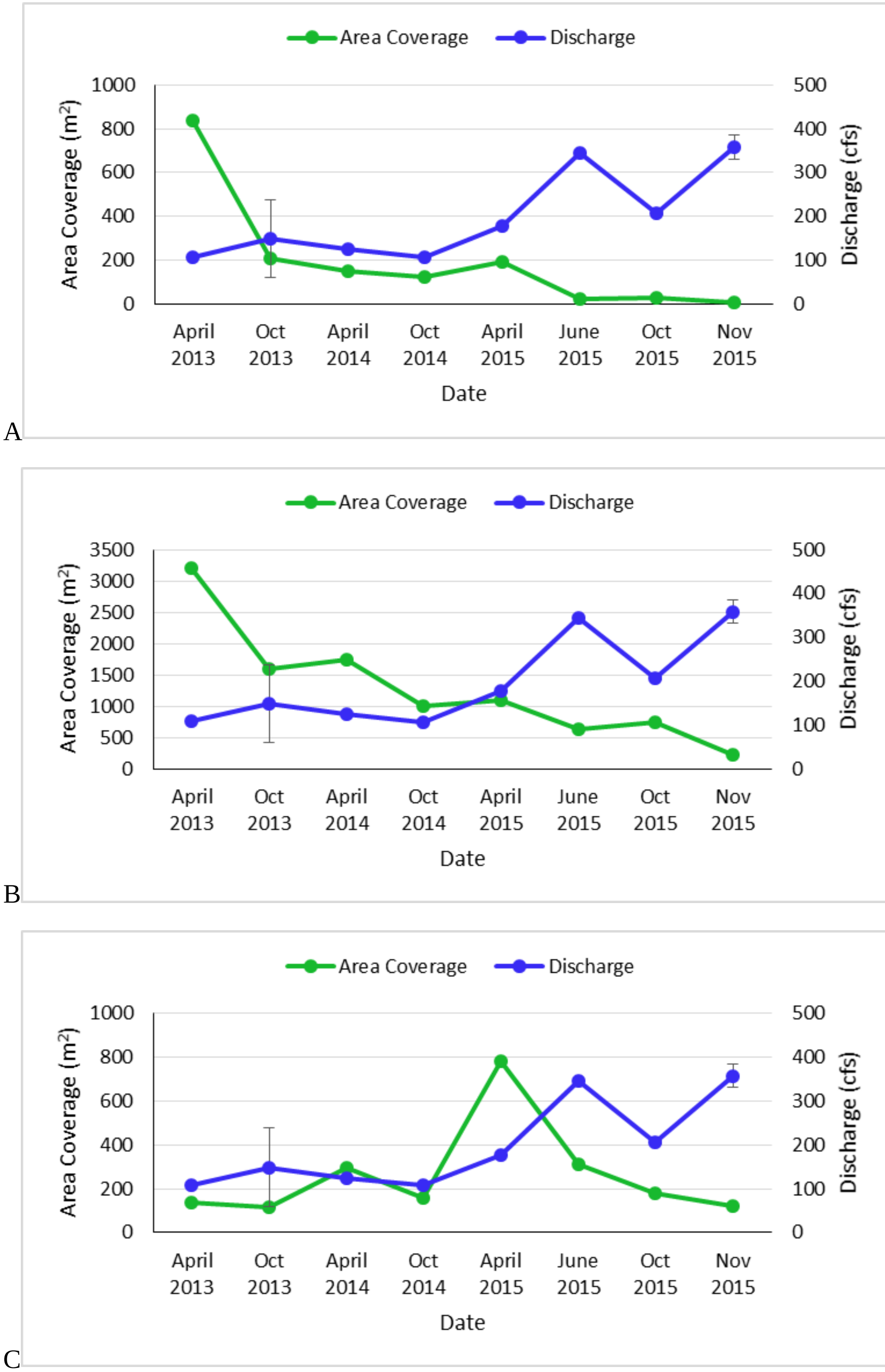
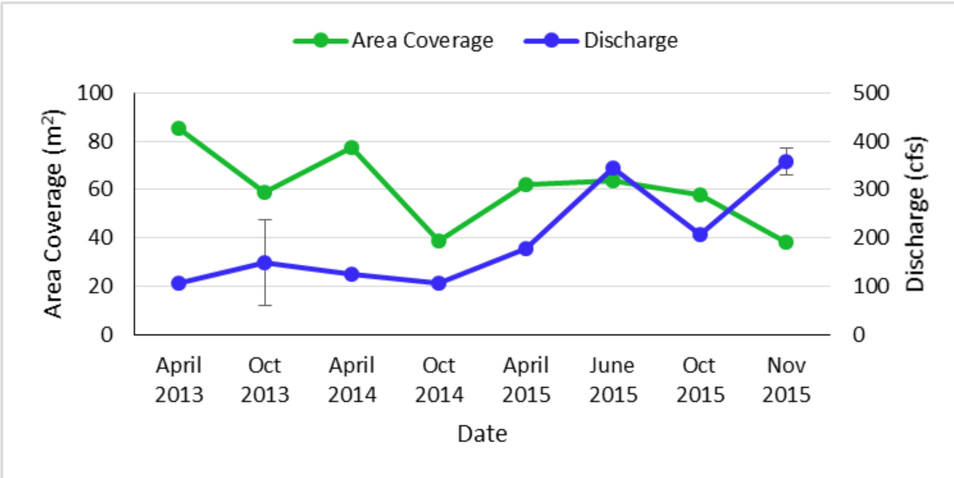
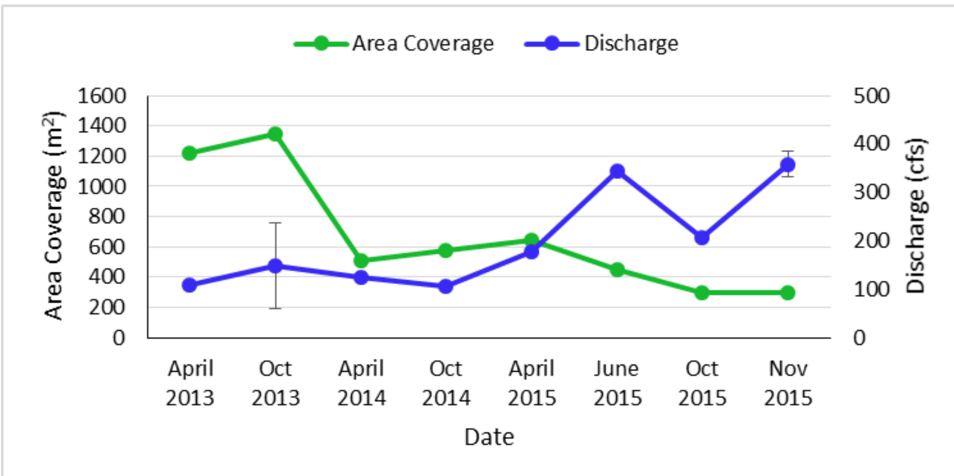


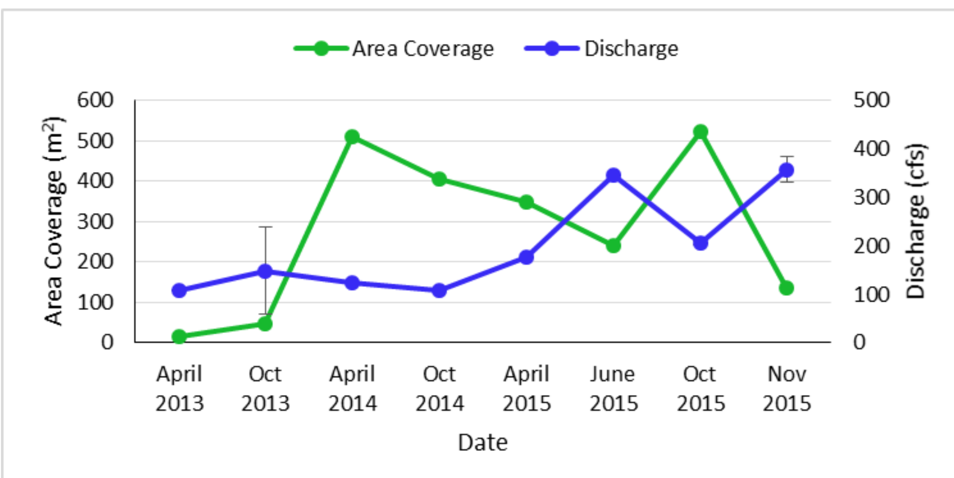
Figure 27. Area coverage (m^2) of hydrilla (*Hydrilla verticillata*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam, B) City Park, and C) I-35. Bars represent standard deviation for monthly discharge.



A



B



C

Figure 28. Area coverage (m^2) of East India hygrophila (*Hygrophila polysperma*) and mean monthly discharge (cfs) in the San Marcos River, USGS gauge 8170500 during sampling from April 2013 through November 2015 in A) Spring Lake Dam, B) City Park, and C) I-35. Bars represent standard deviation for monthly discharge.

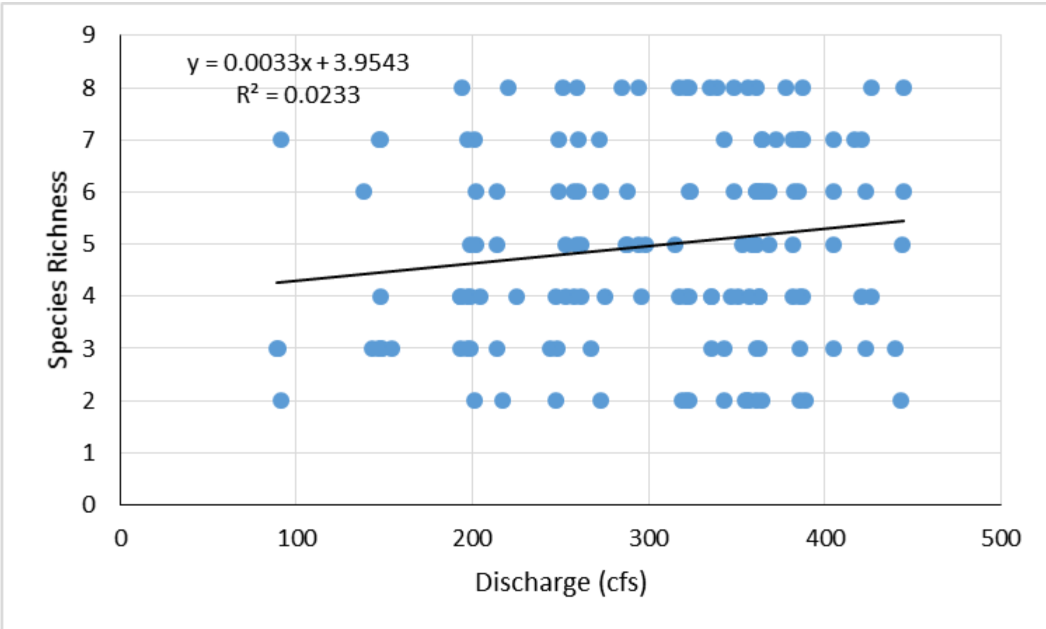


Figure 29. Species richness compared to discharge (cfs) from 2000 to 2015 for all LTBG sites combined in the Comal River.

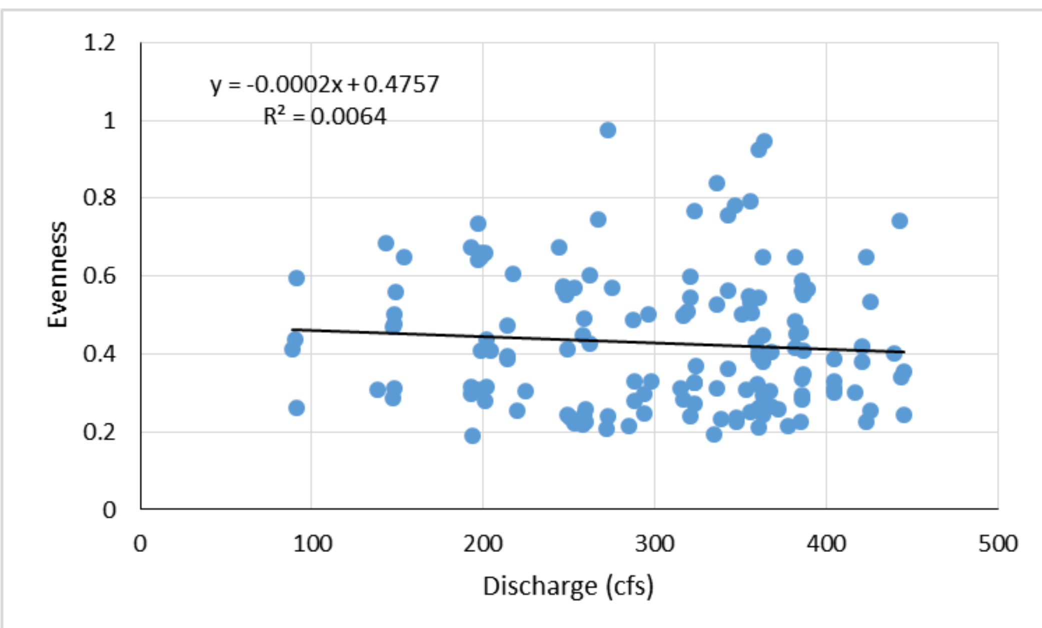


Figure 30. Species evenness compared to discharge (cfs) from 2000 to 2015 for all LTBG sites combined in the Comal River.

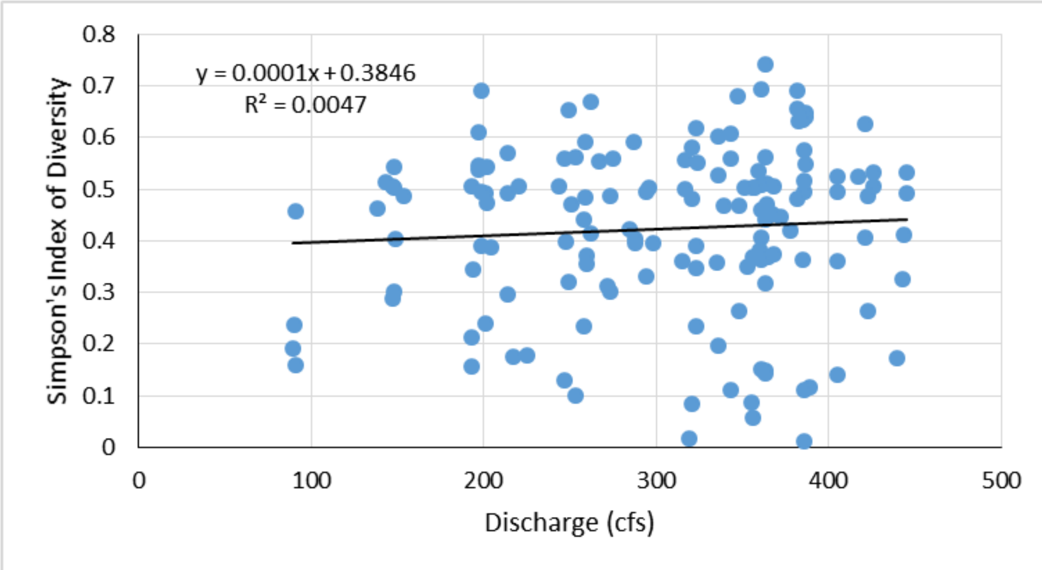


Figure 31. Simpson's Index of Diversity compared to discharge (cfs) from 2000 to 2015 for all LTBG sites combined in the Comal River.

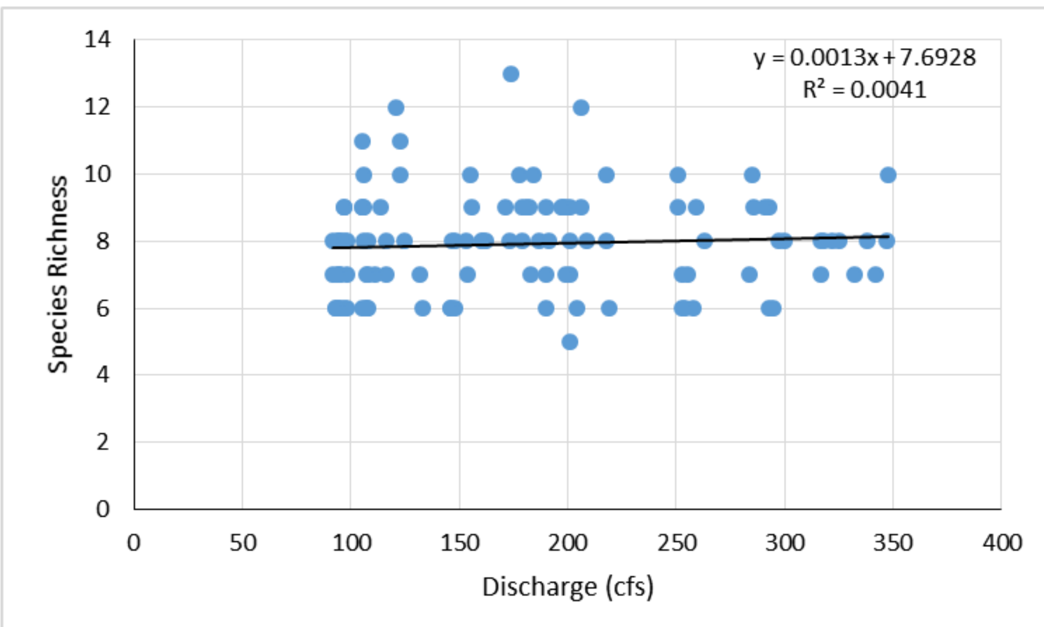


Figure 32. Species richness compared to discharge (cfs) from 2002 to 2015 for all LTBG sites combined in the San Marcos River.

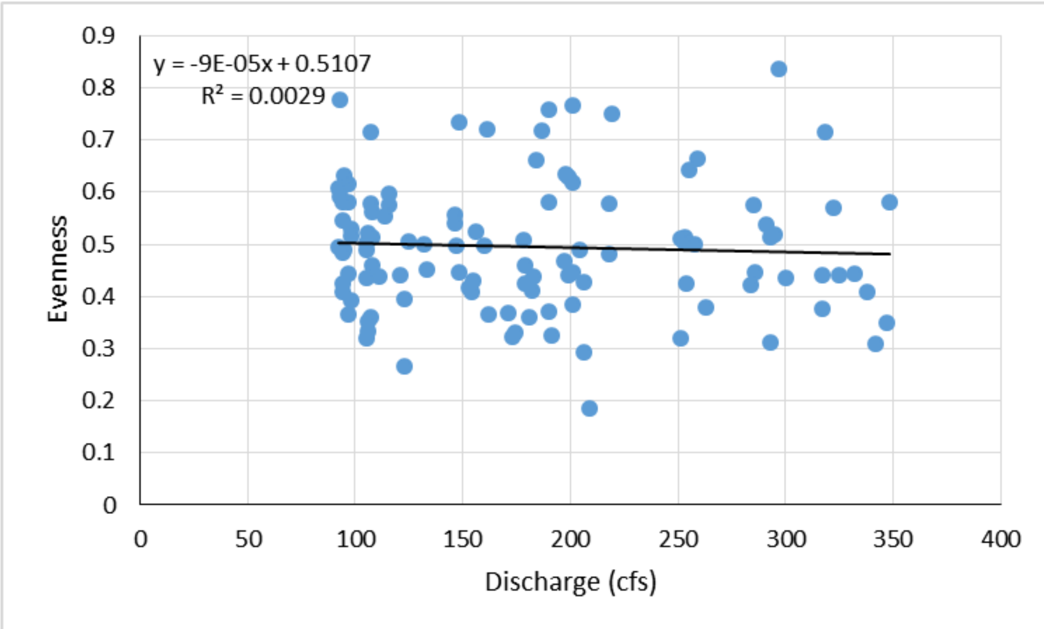


Figure 33. Species evenness compared to discharge (cfs) from 2000 to 2015 for all LTBG sites combined in the San Marcos River.

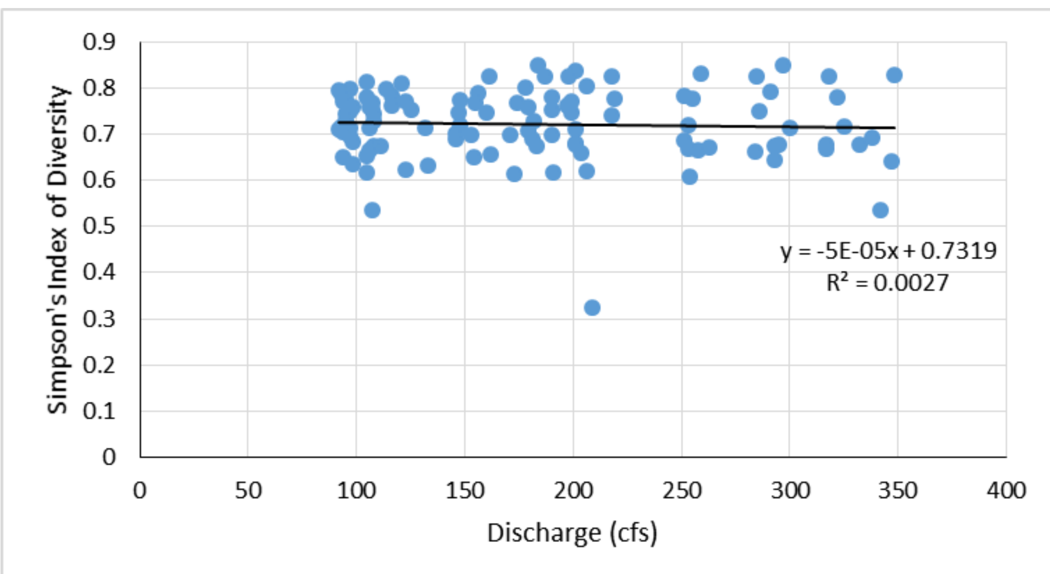


Figure 34. Simpson's Index of Diversity compared to discharge (cfs) from 2000 to 2015 for all LTBG sites combined in the San Marcos River.

Table 1. Temporal periods in the Comal River in which discharge (cfs) rates dropped below 200 cfs for greater than 1 day.

Dates	Number of Days	Mean Discharge (cfs)	SE	Discharge Range
7/25/00 to 10/6/00	74	176	1.8	138 - 199
6/19/09 to 9/9/09	83	170	0.8	158 - 199
6/6/11 to 10/14/11	125	176	0.7	159 - 198
10/10/11 to 10/14/11	4	197	0.6	195 -199
10/26/11 to 11/14/11	20	195	0.4	192 - 198
11/16/11 to 11/19/11	4	198	0.5	197 - 199
11/21/11 to 11/25/11	5	198	0.4	197 - 199
6/26/12 to 7/8/12	13	193	0.5	190 - 197
7/24/12 to 9/15/12	54	174	1.6	155 - 199
9/18/12 to 9/28/12	11	178	1.0	174 - 187
10/31/12 to 11/3/12	4	199	0.3	198 - 199
11/20/12 to 11/21/12	2	199	0.0	199
3/26/13 to 4/2/13	8	195	0.9	192 - 198
4/4/13 to 4/5/13	2	198	1.0	197 - 199
4/9/13 to 5/4/13	26	195	0.5	190 - 199
5/6/13 to 5/9/13	4	195	1.7	191 - 199
5/11/13 to 5/24/13	14	192	1.4	183 - 197
6/21/13 to 7/15/13	25	182	2.0	165 - 198
7/18/13 to 9/28/13	73	130	2.0	111 - 172
9/30/13 to 10/30/13	31	148	1.2	138 - 162
11/2/13 to 11/21/14	385	134	1.7	62 - 182
11/24/13 to 1/21/14	59	138	0.7	131 - 156
1/24/15 to 3/8/15	44	184	1.0	170 - 195
3/12/15 to 3/14/15	3	197	0.7	196 - 198
3/16/15 to 3/19/15	4	195	0.3	194 - 195
3/30/15 to 4/12/15	14	192	0.8	187 - 197
4/20/15 to 4/22/15	3	198	1.0	196 - 199
9/29/15 to 10/3/15	5	198	0.5	196 - 199
10/5/15 to 10/7/15	3	196	0.6	195 - 197

Table 2. Temporal periods in the Comal River in which discharge (cfs) rates increased above 400 for greater than 1 day.

Dates	Number of Days	Mean Discharge (cfs)	SE	Discharge Range
1/10/01 to 1/11/01	25	500	79	421 - 579
8/30/001 to 8/31/01	2	645	229	416 - 873
9/22/01 to 9/23/01	2	412	12	400 - 424
11/15/01 to 11/17/01	3	1009	297	418 - 1350
11/28/01 to 11/29/01	2	429	14	415 - 443
12/2/01 to 12/6/01	5	430	15	402 - 480
12/8/01 to1/7/02	31	427	7	402 - 574
6/30/02 to 7/3/02	4	828	118	588 - 1150
7/5/02 to 7/10/02	6	5010	2173	460 - 13400
9/7/02 to 9/12/02	6	424	8	403 - 455
9/19/02 to 9/20/02	2	444	42	402 - 485
10/9/02 to 10/10/02	2	407	5	402 - 411
10/22/02 to 4/27/03	188	450	6	400 - 1250
6/14/03 to 6/15/03	2	414	1	413 - 414
7/16/03 to 7/17/03	2	417	9	408 - 425
9/21/03 to 9/22/03	2	405	0	405
10/11/03 to 10/13/03	3	458	30	401 - 503
4/11/04 to 4/12/04	2	422	11	411 - 433
6/9/04 to 6/19/04	11	770	252	406 - 3150
6/27/04 to 7/2/04	6	629	82	400 - 913
7/25/04 to 7/26/04	2	525	16	509 - 541
10/2/04 to 10/3/04	2	668	101	567 - 769
10/13/04 to 10/15/04	2	423	12	411 - 435
10/23/04 to 6/17/05	238	505	29	401 - 6860
7/3/07 to 7/4/07	2	568	92	476 - 659
7/6/07 to 7/08/07	3	420	12	405 - 444
7/18/07 to 1/18/08	185	452	11	402 - 1980
10/4/09 to 10/05/09	2	2459	1831	628 - 4290
2/3/10 to 2/5/10	3	502	30	446 - 546
2/11/10 to 2/12/10	2	447	20	427 - 466
5/25/10 to 5/26/10	2	466	64	402 - 530
6/8/10 to 6/16/10	9	1340	744	407 - 7280
9/7/10 to 9/10/10	4	922	400	417 - 2110
6/17/15 to 6/22/15	6	564	87	414 - 934
10/30/15 to 11/1/15	3	1854	1120	453 - 4070

Table 3. Temporal periods in the San Marcos River in which discharge (cfs) rates dropped below 100 cfs for greater than 1 day.

Dates	Number of Days	Mean Discharge (cfs)	SE	Discharge Range
8/20/06 to 9/4/06	16	95	0.4	93 - 99
9/6/06 to 10/17/06	42	94	0.2	90 - 97
10/20/06 to 11/17/06	29	98	0.2	96 - 99
11/27/06 to 12/5/06	9	98	0.2	98 - 99
12/12/08 to 12/22/08	11	98	0.2	97 - 99
12/24/08 to 2/9/09	48	98	0.1	96 - 99
2/24/09 to 3/8/09	13	99	0.1	98 - 99
3/28/09 to 4/16/09	20	97	0.2	96 - 99
4/18/09 to 9/21/09	157	90	0.3	83 - 99
9/23/09 to 10/02/09	10	97	0.5	95 - 99
8/11/11 to 11/14/11	96	92	0.2	88 - 98
11/16/11 to 11/25/11	10	94	0.2	93 - 95
11/27/11 to 12/3/11	7	96	0.6	94 - 99
12/5/11 to 12/14/11	10	99	0.2	98 - 99
5/13/13 to 5/14/13	2	99	0.5	98 - 99
5/20/13 to 5/23/13	4	99	0.0	99

Table 4. Temporal periods in the San Marcos River in which discharge (cfs) rates increased above 400 for greater than 1 day.

Dates	Number of Days	Mean Discharge (cfs)	SE	Discharge Range
11/15/01 to 11/19/01	5	641	100	487 - 1030
7/2/02 to 7/4/02	3	540	73	416 - 668
11/17/04/ to 11/25/04	7	688	110	410 - 1280
7/20/07 to 9/12/07	55	448	13	401 - 971
10/31/13 to 11/2/13	3	705	204	464 - 1110
11/3/15 to 11/5/15	3	507	14	480 - 528

Table 5. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the Landa Lake Long-Term Biological Goal site (Comal River) from 2013 to 2015 (n = 11 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Bryophytes	-0.12	0.73	Decreasing
Cabomba caroliniana	0.19	0.58	Stable
Ludwigia repens	0.52	0.06	Increasing
Nuphar advena	-0.73	<0.05	Decreasing
Sagittaria platyphylla	0.14	0.68	Stable
Vallisneria spp.	-0.07	0.84	Stable (slight decrease)
Hygrophila polysperma[b]	<0.05	0.96	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 6. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the Upper Spring Run Long-Term Biological Goal site (Comal River) from 2013 to 2015 (n = 11 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Bryophytes	0.22	0.52	Decreasing
Cabomba caroliniana	0.48	0.14	Increasing
Ludwigia repens	0.34	0.31	Decreasing
Sagittaria platyphylla	0.44	0.18	Stable
Hygrophila polysperma[b]	0.22	0.52	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 7. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the Lower New Channel Long-Term Biological Goal site (Comal River) from 2013 to 2015 (n = 11 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Bryophytes	-0.25	0.46	Decreasing
Cabomba caroliniana	0.07	0.84	Increasing
Hygrophila polysperma[b]	-0.13	0.70	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 8. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the Old Channel Long-Term Biological Goal site (Comal River) from 2013 to 2015 (n = 11 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Bryophytes	0.12	0.72	Decreasing
Ludwigia repens	0.41	0.21	Unknown
Nuphar advena	-0.41	0.21	Decreasing
Hygrophila polysperma[b]	-0.54	0.09	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 9. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the Spring Lake Dam Long-Term Biological Goal site (San Marcos River) from 2013 to 2015 (n = 8 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Hydrocotyle umbellata	-0.10	0.81	Decreasing
Ludwigia repens	0.57	0.14	Increasing
Zizania texana	0.52	0.19	Increasing
Potamogeton illinoensis	-0.71	<0.05	Decreasing
Sagittaria platyphylla	-0.73	<0.05	Decreasing
Hydrilla verticillata[b]	-0.53	0.17	Decreasing
Hygrophila polysperma[b]	-0.36	0.38	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 10. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the City Park Long-Term Biological Goal site (San Marcos River) from 2013 to 2015 (n = 8 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Ludwigia repens	0.14	0.74	Increasing (slight)
Zizania texana	0.76	<0.05	Increasing
Potamogeton illinoensis	-0.62	0.10	Decreasing
Sagittaria platyphylla	-0.32	0.43	Decreasing
Hydrilla verticillata[b]	-0.69	0.06	Decreasing
Hygrophila polysperma[b]	-0.63	0.09	Decreasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 11. Statistical comparison of aquatic macrophyte coverage (m^2) and discharge (cfs) in the I-35 Long-Term Biological Goal site (San Marcos River) from 2013 to 2015 (n = 8 monitoring periods).

	Aquatic Macrophyte Coverage vs Discharge (2013 to 2015)		
Species	r-value[a]	P-value	Trends in Coverage
Ludwigia repens	0.23	0.14	Increasing
Zizania texana	-0.16	0.71	Increasing
Cabomba caroliniana	-0.06	0.89	Increasing
Sagittaria platyphylla	0.65	0.08	Increasing
Hydrilla verticillata[b]	0.04	0.93	Increasing
Hygrophila polysperma[b]	-0.07	0.87	Increasing

[a] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between aquatic macrophyte coverage and discharge.
[b] - Indicates non-native species.

Table 12. Spring and fall aquatic macrophyte coverage (m^2) in the Long-Term Biological Goal sites in the Comal (2000-2015) and San Marcos (2002-2015) rivers.

		Total Macrophyte Coverage (m^2)		
River	LTBG Site	Spring	Fall	P-value[1]
Comal	Landa Lake	18,975[a] (524)	17,831[b] (456)	< 0.05
	Lower New Channel	2,120 (336)	1,865 (361)	0.21
	Old Channel	1,546 (166)	1,525 (120)	0.43
	Upper Spring Run	2,569[a] (285)	1,924[b] (241)	< 0.05
San Marcos	Spring Lake Dam	1,425[a] (78)	1,119[b] (63)	< 0.05
	City Park	4,403[a] (149)	3,698[b] (182)	< 0.05
	I-35	869 (125)	810 (104)	0.14

[1] - Difference letters in rows between spring and fall macrophyte coverage indicate significant differences (P < 0.05) between sites based on a t-test.

Table 13. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the Landa Lake Long-Term Biological Goal site (Comal River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	18975 (524)	17833 (456)	< 0.05	0.64	<0.05	Stable
Native	18308 (562)	17359 (473)	< 0.05	0.67	<0.05	Stable
Non-native	667 (70)	474 (54)	< 0.05	0.87	<0.05	Declining
Bryophytes	2860 (320)	1890 (375)	< 0.05	0.53	<0.05	Pulsating
Algae	193 (55)	180 (88)	0.45	0.19	0.52	Pulsating
Cabomba caroliniana	251 (37)	311 (30)	< 0.05	0.89	<0.05	Pulsating
Ludwigia repens	84 (21)	83 (26)	0.49	0.35	0.22	Increasing (2013-15)
Nuphar advena	461 (14)	416 (18)	< 0.05	0.59	<0.05	Stable
Sagittaria platyphylla	1418 (137)	1427 (172)	0.44	0.95	<0.05	Increasing
Vallisneria spp.	13040 (240)	13047 (149)	0.48	0.85	<0.05	Stable
Hygrophila polysperma[c]	667 (70)	474 (54)	< 0.05	0.87	<0.05	Declining

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 14. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the Lower New Channel Long-Term Biological Goal site (Comal River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	2120 (343)	1933 (36)	0.45	0.48	0.08	Pulsating
Native	697 (235)	841 (278)	0.32	0.93	<0.05	Stable (increase 2013)
Non-native	1423 (327)	1092 (292)	0.13	0.67	<0.05	Declining
Bryophytes	103 (39)	14 (8)	< 0.05	0.77	<0.05	Pulsating
Algae	5 (5)	9 (8)	0.15	0.99	<0.05	Pulsating
Cabomba caroliniana	584 (229)	807 (280)	0.12	0.94	<0.05	Increasing
Ludwigia repens	4 (2)	2 (1)	0.17	0.20	0.49	Pulsating
Hygrophila polysperma[c]	1432 (327)	1092 (292)	0.13	0.67	<0.05	Declining

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 15. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the Old Channel Long-Term Biological Goal site (Comal River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	1546 (166)	1525 (121)	0.85	0.72	<0.05	Decline 2012-15
Native	336 (95)	293 (39)	0.30	0.54	0.06	Stable, pulses
Non-native	1210 (131)	1232 (120)	0.37	0.88	<0.05	Declining, pulses
Bryophytes	131 (96)	85 (35)	0.26	0.82	<0.05	Pulsating
Algae	28 (18)	41 (31)	0.32	-0.04	0.89	Pulsating, spikes
Ludwigia repens	58 (22)	62 (20)	0.39	0.72	<0.05	Declining
Nuphar advena	123 (8)	105 (12)	0.12	-0.14	0.63	Pulsating
Hygrophila polysperma[c]	1092 (166)	1093 (155)	0.49	0.94	<0.05	Declining
Ceratopteis thalictroides[c]	118 (41)	139 (42)	0.19	0.85	<0.05	Declining

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 16. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the Upper Spring Run Long-Term Biological Goal site (Comal River) from 2002 to 2015 (n = 14 monitoring periods).

Species	Macrophyte Coverage (m^2) Spring	Fall	T-test P-value[a]	Correlation r-value[b]	P-value	Trends in Coverage
All Macrophytes	2570 (285)	1923 (242)	< 0.05	0.56	<0.05	No pattern, pulsating
Native	2180 (258)	1612 (198)	< 0.05	0.59	<0.05	No pattern, pulsating
Non-native	390 (78)	311 (79)	0.12	0.66	<0.05	Declining
Bryophytes	1500 (242)	905 (216)	< 0.05	0.60	<0.05	Pulsating
Algae	60 (52)	68 (44)	0.46	-0.10	0.73	Pulsating
Cabomba caroliniana	5 (2)	6 (2)	0.16	0.95	<0.05	No pattern
Ludwigia repens	13 (3)	12 (4)	0.40	0.51	0.06	Declining, pulses
Sagittaria platyphylla	582 (60)	605 (55)	0.18	0.92	<0.05	Increasing
Hygrophila polysperma[c]	386 (76)	307 (77)	0.11	0.65	<0.05	Declining, pulses

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 17. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the Spring Lake Dam Long-Term Biological Goal site (San Marcos River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	1426 (78)	1120 (63)	< 0.05	0.69	<0.05	Stable with pulses
Native	974 (30)	829 (38)	< 0.05	0.55	<0.05	Stable with pulses
Non-native	452 (56)	291 (34)	< 0.05	0.51	0.06	Declining
Zizania texana	388 (43)	321 (41)	< 0.05	0.88	<0.05	Increasing
Potamogeton illinoensis	401 (43)	370 (55)	0.09	0.93	<0.05	Declining
Sagittaria platyphylla	29 (6)	26 (3)	0.21	0.84	<0.05	Declining with pulses
Hydrilla verticillata[c]	367 (48)	223 (28)	<0.05	0.40	0.16	Declining with pulses
Hygrophila polysperma[c]	69 (11)	60 (6)	0.21	0.35	0.22	Stable with pulses

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 18. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the City Park Long-Term Biological Goal site (San Marcos River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	4399 (149)	3695 (182)	< 0.05	0.76	<0.05	Declining
Native	1397 (137)	1268 (95)	0.07	0.82	<0.05	Increasing (2013-15)
Non-native	3002 (180)	2427 (151)	< 0.05	0.62	<0.05	Declining (2013-15)
Zizania texana	349 (85)	345 (99)	0.45	0.97	<0.05	Increasing
Potamogeton illinoensis	867 (155)	753 (149)	< 0.05	0.95	<0.05	Declining
Sagittaria platyphylla	109 (11)	129 (16)	0.09	0.55	<0.05	Pulsating
Hydrilla verticillata[c]	2060 (156)	1534 (101)	< 0.05	0.18	0.53	Declining
Hygrophila polysperma[c]	938 (62)	871 (65)	0.12	0.64	<0.05	Declining

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 19. Statistical comparison of spring and fall aquatic macrophyte coverage (means and standard error) in the I-35 Long-Term Biological Goal site (San Marcos River) from 2002 to 2015 (n = 14 monitoring periods).

	Macrophyte Coverage (m^2)		T-test	Correlation		
Species	Spring	Fall	P-value[a]	r-value[b]	P-value	Trends in Coverage
All Macrophytes	870 (125)	811 (105)	0.28	0.91	<0.05	Increasing
Native	497 (51)	490 (60)	0.42	0.84	<0.05	Stable
Non-native	373 (82)	321 (49)	0.16	0.82	<0.05	Stable
Zizania texana	168 (26)	165 (23)	0.35	0.97	<0.05	Increasing
Cabomba caroliniana	136 (13)	168 (19)	0.08	0.01	0.97	Pulsating
Sagittaria platyphylla	76 (19)	69 (21)	0.15	0.95	<0.05	Increasing
Hydrilla verticillata[c]	236 (48)	176 (27)	0.14	0.07	0.81	Pulsating
Hygrophila polysperma[c]	125 (37)	142 (38)	0.19	0.87	<0.05	Pulsating

[a] - P-values < 0.05 indicate significant differences between spring and fall macrophyte coverage based on a t-test.

[b] - Correlation values (r) range from -1 to +1, with -1 indicating a strong negative correlation and +1 indicating a strong positive correlation between spring and fall macrophyte coverage.

[c] - Indicates non-native species.

Table 20. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2001 to 2015 at the Landa Lake Long-Term Biological Goal site in the Comal River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2001-2003	11	6.8 (0.3)^{b}	0.28 (0.01)^{a}	0.46 (0.02)	17282 (712)	16476 (750)	807 (92)^{a}
2004-2006	7	7.6 (0.2)^{ab}	0.23 (0.01)^{b}	0.43 (0.02)	17265 (321)	16561 (296)	704 (47)^{ab}
2007-2009	6	7.8 (0.2)^{a}	0.24 (0.01)^{b}	0.45 (0.03)	18992 (613)	18431 (593)	561 (24)^{ab}
2010-2012	6	7.8 (0.2)^{a}	0.23 (0.01)^{b}	0.44 (0.03)	18154 (662)	17683 (636)	471 (34)^{b}
2013-2015	6	6.7 (0.2)^{b}	0.30 (0.01)^{a}	0.50 (0.02)	19251 (1064)	19122 (987)	128 (86)^{c}
P-value		0.002	< 0.001	0.45	0.19	0.06	< 0.001

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 21. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2001 to 2015 at the Lower New Channel Long-Term Biological Goal site in the Comal River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2001-2003	10	2.5 (0.2)	0.48 (0.03)	0.13 (0.01)^{c}	3265 (103)^{a}	219 (17)^{bc}	3046 (100)^{a}
2004-2006	8	3.0 (0.3)	0.55 (0.07)	0.30 (0.07)^{bc}	1224 (493)^{b}	169 (55)^{c}	1055 (484)^{b}
2007-2009	6	3.7 (0.4)	0.53 (0.10)	0.41 (0.04)^{ab}	1494 (507)^{b}	382 (142)^{bc}	1112 (371)^{b}
2010-2012	7	3.1 (0.1)	0.70 (0.04)	0.53 (0.03)^{a}	1450 (404)^{b}	794 (257)^{b}	656 (162)^{b}
2013-2015	5	2.6 (0.2)	0.58 (0.05)	0.31 (0.07)^{bc}	3194 (133)^{a}	2629 (197)^{a}	565 (136)^{b}
P-value		0.06	0.10	< 0.001	< 0.001	< 0.001	< 0.001

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 22. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2001 to 2015 at the Old Channel Long-Term Biological Goal site in the Comal River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2001-2003	11	4.0 (0.4)[b]	0.59 (0.06)[a]	0.52 (0.03)[a]	742 (81)[b]	312 (69)	430 (32)[c]
2004-2006	7	5.4 (0.2)[a]	0.42 (0.06)[ab]	0.51 (0.07)[a]	1570 (106)[a]	375 (60)	1194 (119)[b]
2007-2009	6	5.8 (0.2)[a]	0.25 (0.02)[b]	0.32 (0.03)[b]	1774 (32)[a]	227 (20)	1547 (38)[a]
2010-2012	6	4.5 (0.3)[ab]	0.30 (0.03)[b]	0.21 (0.04)[b]	1900 (98)[a]	222 (62)	1677 (73)[a]
2013-2015	6	3.2 (0.2)[b]	0.53 (0.05)[a]	0.37 (0.05)[ab]	1775 (263)[a]	539 (223)	1236 (82)[b]
P-value		< 0.001	0.002	< 0.001	0.001	0.26	< 0.001

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 23. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2001 to 2015 at the Upper Spring Run Long-Term Biological Goal site in the Comal River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2001-2003	11	6.6 (0.3)[a]	0.36 (0.02)[c]	0.56 (0.03)	1932 (357)[ab]	1266 (327)[b]	657 (77)[a]
2004-2006	7	5.7 (0.3)[ab]	0.39 (0.03)[bc]	0.53 (0.04)	2355 (278)[ab]	2001 (273)[ab]	354 (46)[bc]
2007-2009	6	4.3 (0.2)[bc]	0.53 (0.02)[a]	0.56 (0.03)	3366 (396)[a]	2861 (309)[a]	505 (94)[ab]
2010-2012	6	4.3 (0.2)[bc]	0.49 (0.05)[ab]	0.50 (0.06)	1799 (370)[b]	1678 (334)[ab]	122 (42)[cd]
2013-2015	6	4.0 (0.6)[c]	0.51 (0.04)[ab]	0.45 (0.07)	1392 (183)[b]	1342 (147)[b]	50 (46)[d]
P-value		< 0.001	< 0.001	0.42	0.01	0.009	< 0.001

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 24. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2002 to 2015 at the Spring Lake Dam Long-Term Biological Goal site in the San Marcos River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2002-2003	7	8.7 (0.2)	0.40 (0.02)[b]	0.71 (0.02)	1615 (44)[a]	1058 (22)[a]	557 (47)
2004-2006	7	8.7 (0.3)	0.44 (0.03)[ab]	0.73 (0.02)	1241 (88)[ab]	831 (34)[b]	383 (60)
2007-2009	6	7.7 (0.2)	0.51 (0.03)[a]	0.74 (0.01)	1188 (92)[ab]	828 (46)[b]	359 (53)
2010-2012	6	7.8 (0.3)	0.51 (0.02)[a]	0.75 (0.01)	1156 (64)[b]	773 (40)[b]	383 (33)
2013-2015	6	8.5 (0.6)	0.38 (0.06)[b]	0.64 (0.06)	1264 (189)[ab]	867 (55)[b]	397 (140)
P-value		0.08	0.04	0.17	0.02	< 0.001	0.32

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 25. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2002 to 2015 at the City Park Long-Term Biological Goal site in the San Marcos River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2002-2003	7	6.9 (0.4)[b]	0.45 (0.02)[a]	0.67 (0.01)	4694 (85)[a]	1696 (39)[a]	2954 (65)[a]
2004-2006	9	6.7 (0.3)[b]	0.48 (0.03)[a]	0.68 (0.01)	4470 (150)[ab]	1583 (40)[a]	2887 (143)[ab]
2007-2009	9	6.8 (0.3)[b]	0.49 (0.04)[a]	0.69 (0.02)	4004 (209)[bc]	1409 (152)[ab]	2595 (141)[ab]
2010-2012	7	6.6 (0.4)[b]	0.47 (0.04)[a]	0.67 (0.02)	3841 (213)[c]	921 (36)[c]	2919 (222)[ab]
2013-2015	8	8.5 (0.5)[a]	0.33 (0.01)[b]	0.63 (0.02)	3172 (329)[d]	1212 (152)[bc]	1960 (442)[b]
P-value		0.006	0.002	0.09	< 0.001	0.001	0.03

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.

Table 26. Species richness, evenness, Simpson's Index of Diversity, and macrophyte coverage (m^2) over 5 periods from 2002 to 2015 at the I-35 Long-Term Biological Goal site in the San Marcos River.

		Diversity Indices[a]			Macrophyte Coverage (m^2)[a]		
Dates	N =	Richness	Evenness	Simpsons Index of Diversity	Total	Native	Non-native
2002-2003	7	8.7 (0.3)[ab]	0.66 (0.03)[a]	0.82 (0.01)[a]	720 (42)[b]	504 (30)[b]	216 (21)[b]
2004-2006	9	9.1 (0.3)[ab]	0.55 (0.04)[ab]	0.79 (0.01)[ab]	772 (60)[b]	464 (30)[b]	308 (43)[ab]
2007-2009	9	7.6 (0.4)[bc]	0.60 (0.03)[ab]	0.77 (0.01)[ab]	812 (30)[b]	444 (32)[b]	368 (19)[ab]
2010-2012	7	6.7 (0.3)[c]	0.64 (0.04)[ab]	0.76 (0.02)[ab]	557 (55)[b]	332 (17)[b]	225 (40)[b]
2013-2015	8	10.0 (0.9)[a]	0.49 (0.04)[b]	0.78 (0.02)[ab]	1285 (217)[a]	713 (98)[a]	572 (132)[a]
P-value		< 0.001	0.02	0.03	< 0.001	< 0.001	0.004

[a] - Different letters in column indicate differences ($P < 0.05$) based on analysis of variance and Tukey's means separation test.