Texas Coastal Nutrient Input Repository - Task 3 Report

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# Introduction

A substantial proportion of coastal estuaries in the United States face excessive nutrient loading and exhibit symptoms of eutrophication (Bricker et al. 2008). Eutrophication leads to depletion of dissolved oxygen, degradation of habitat (Darby and Turner 2008) and increased risks of harmful algal blooms (Heisler et al. 2008).

There have been limited attempts at assessments of estuarine eutrophication along the Texas coastline. Notably, Bugica et al. (2020) provided evidence of regional eutrophication hot spots attributed to increases in coastal population, urbanization, and alterations of freshwater inflows along the Texas coast and is an important starting point for targeted regional studies. Bugica et al. (2020) assessed three sites in the Lavaca Bay and identified small but significant increases in Total Phosphorus (TP) and Orthophosphate (PO4-3) at two sites, Total Kjeldahl Nitrogen (TKN) at two sites, and chlorophyll-*a* at one site. Importantly, decreases in dissolved oxygen were not detected in the study. While there are indications that potential drivers of eutrophication are increasing in Lavaca Bay, the immediate symptoms of degraded dissolved oxygen are not evident. Significant decreases in pH at all sites assessed by Bugica et al. (2020) in Lavaca Bay also point to long-term decreases in freshwater inflow and a resulting increase in salinity. Long-term declines in the abundance of sensitive benthic fauna in Lavaca Bay have been linked to increases in salinity and reductions in freshwater inflows (Beseres Pollack et al. 2011; Palmer and Montagna 2015; Montagna et al. 2020).

The potential for negative impacts induced by eutrophication is a especially concerning given the significant declines already observed in benthic fauna abundance, biomass, and diversity within Lavaca Bay (Beseres Pollack et al. 2011). Underscoring this concern is the need for data that is adequate for evaluating changes over time in watershed nutrient loading. There is also a need to understand the effects of land management decisions on nutrient loading, relative to environmental drivers such as precipitation and discharge, and how it may contribute to or improve conditions related to eutrophication in Lavaca Bay. This work (1) quantifies Nitrate-Nitrogen (NO3-N) and TP loadings in the Lavaca Bay watershed and (2) assesses the relationship of eutrophication indicators in Lavaca Bay to changes in watershed discharge and loads.

# Methods

## Study Area and Data

Lavaca Bay is a secondary bay in the Matagorda Bay system located centrally along the Texas Gulf coast, roughly halfway between the cities of Houston and Corpus Christi (Figure ). Lavaca Bay is 190 km2 with the majority of freshwater inflow provided by the Lavaca-Navidad river system. The Garcitas-Arenosa, Placedo Creek, and Cox Bay watersheds provide additional freshwater inflows. The watershed land area for Lavaca Bay is 8,149 km2. The Lavaca-Navidad river watershed is 5,966 km2, or approximately 73% of the watershed area. Discharge from the Navidad River is regulated by Lake Texana which has been in operation since 1980. Lake Texana provides 170,000 acre-feet of water storage and discharges into the tidal section of the Navidad River which ultimately joins the tidal section of the Lavaca River 15 km upstream of the confluence with the Bay.

### Hydrology

Daily discharges for gaged locations within the watershed were obtained from the United States Geologic Survey (USGS) National Water Information System (NWIS) using the “dataRetrieval” R package (De Cicco et al. 2022). Gaged daily discharges from Lake Texana (USGS-0816425) and modeled daily discharges for the outlet of the Lavaca-Navidad watershed were obtained from the Texas Water Development Board (TWDB) (April 21, 2022 email to the author from R. Neupane, TWDB). Modeled discharges were developed by the TWDB for ungaged coastal basins using the Texas Rainfall-Runoff (TxRR) model described in Schoenbaechler et al. (2011). From 2000 through 2020, mean daily discharge from the Lavaca-Navidad watershed system was 700 (MGD) based on a combination of modeled runoff and gaged discharge. Approximately 61% of the mean daily discharge comes from Lake Texana (USGS-0816425, Figure ), 30% is from the Lavaca River at Edna (USGS-08164000) and the rest is ungaged runoff below those two gaged locations.

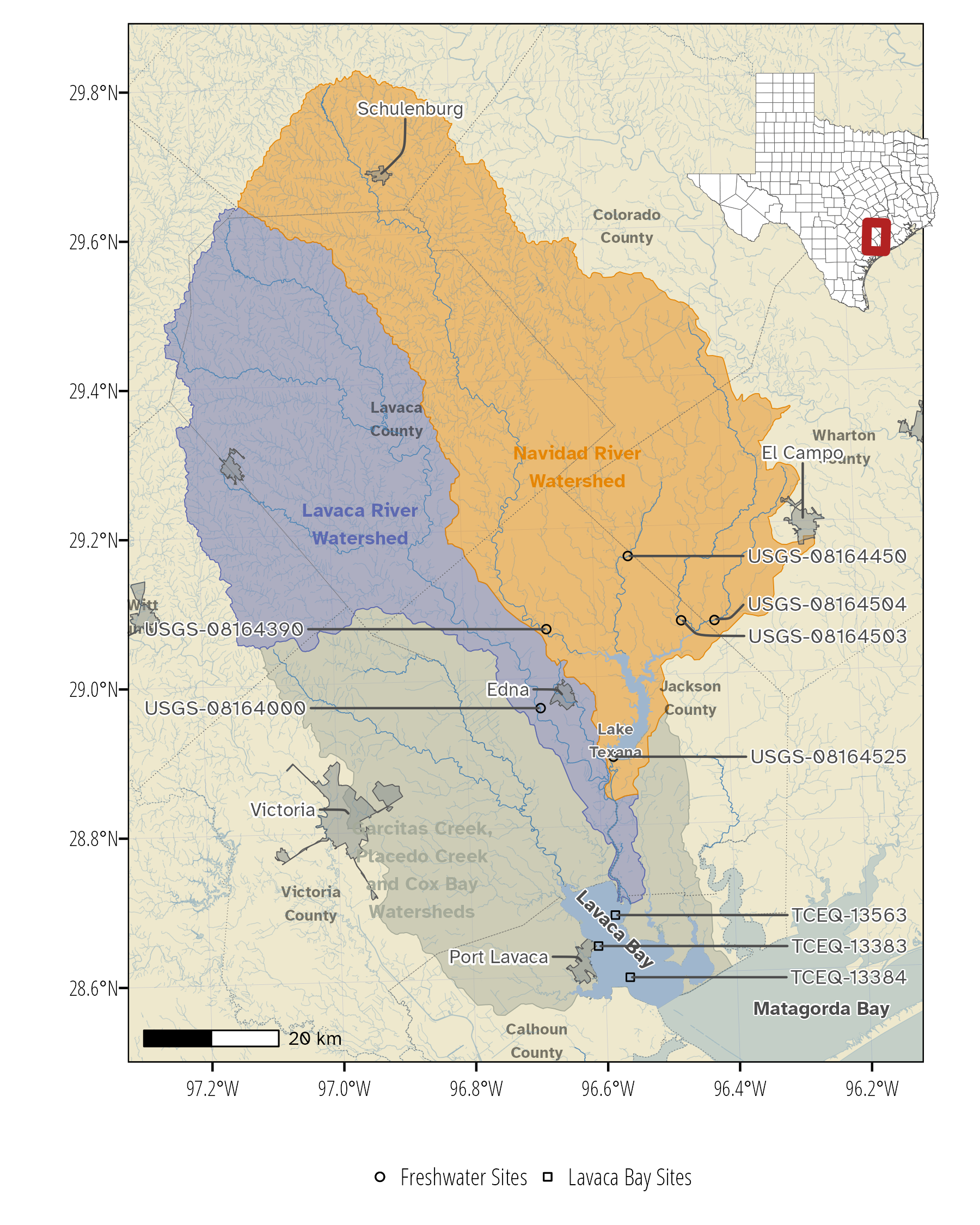


Figure . Study area map.

Table . Summary statistics for mean daily discharge, NO3-N, and TP at the freshwater sites where daily nutrient loads were estimated.

| **Site** | **Description** |  | **Mean Daily Discharge** | |  | **NO3-N** | |  | **TP** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Mean (SD)** | **N** |  | **Mean (SD)** | **N** |  | **Mean (SD)** | **N** |
| USGS-08164000 | Lavaca River near Edna |  | 332.78 (1667.47) | 7,671 |  | 0.18 (0.24) | 74 |  | 0.21 (0.09) | 80 |
| USGS-08164390 | Navidad River at Strane Pk. |  | 222.83 (926.18) | 7,671 |  | 0.17 (0.15) | 59 |  | 0.21 (0.09) | 77 |
| USGS-08164450 | Sandy Creek near Ganado |  | 176.63 (730.01) | 7,671 |  | 0.17 (0.17) | 56 |  | 0.21 (0.20) | 75 |
| USGS-08164503 | West Mustang Creek near Ganado |  | 144.65 (617.38) | 7,671 |  | 0.45 (0.57) | 63 |  | 0.32 (0.23) | 81 |
| USGS-08164504 | East Mustang Creek near Lousie |  | 39.58 (202.06) | 7,671 |  | 1.15 (2.52) | 61 |  | 0.40 (0.31) | 79 |
| USGS-08164525 | Lake Texana |  | 666.14 (2957.79) | 7,671 |  | 0.29 (0.26) | 62 |  | 0.20 (0.08) | 81 |

## Nutrient Load Estimation

Regression based approaches are commonly used to estimate constituent concentration and fluxes based on continuously measured streamflow and sparsely measured constituent concentrations.  
Most regression-based approaches estimate daily concentration based on modeled relationships between concentration and discharge, season, and time (Cohn et al. 1992; Hirsch et al. 2010). These approaches have recently been extended to include antecedent discharge variables that significantly improve model performance (Zhang and Ball 2017). We developed site-specific Generalized Additive Models (GAMs) relating NO3-N and TP to discharge and temporal covariates. GAMs are a semiparametric version of generalized linear models where the linear predictor is represented as the sum of multiple unknown smooth functions and parametric linear predictors. Recent work has shown GAMs can be specified in a functionally similar manner to popular linear regression based approaches such as LOADEST (Cohn et al. 1992) or WRTDS (Hirsch et al. 2010) and produce reliable estimates of nutrient and sediment loading (Wang et al. 2011; Kroon et al. 2012; Kuhnert et al. 2012; Robson and Dourdet 2015; Hagemann et al. 2016; McDowell et al. 2021; Biagi et al. 2022). Although the underlying parameter estimation procedure of GAMs is substantially different than WRTDS, both the functional form and results are demonstrated to be similar (Beck and Murphy 2017). Importantly, in comparison to linear regression based approaches, GAMs allow (1) simple incorporation of additional model terms into the regression equation, (2) specification of the exponential distribution family of the response, and (3) specification of a link function relating the expected value of the response to the linear predictor. We fit GAMs using the *mgcv* package in R which makes available multiple types of smooth functions with automatic smoothness estimation (Wood 2011). To model watershed NO3-N and TP loads, we fit a GAM relating constituent concentration to flow and time:

where μ is the conditional expected NO3-N or TP concentration, *g()* is the log-link, *α* is the intercept, *fn()* are smoothing functions. *y* is the response variable (constituent concentration) modeled as Gamma distributed with mean *μ* and scale *λ*. *ddate* is the date converted to decimal notation, *yday* is numeric day of year (1-366), and *log1p(Q)* is the natural log of mean daily streamflow plus 1.

Moving average (*ma*) is an exponentially smoothed moving average that attempts to incorporate the influence of prior streamflow events on current concentration. Wang et al. (2011), Kuhnert et al. (2012) and Zhang and Ball (2017) refer to this as averaged or smoothed discounted flow and demonstrated improvements in nutrient loading models by including the term. Kuhnert et al. (2012) expresses MA as

where *δ* is the discount factor (here, set equal to 0.95), *κi* is the cumulative flow (*Q*) up to the *i*th day.

Flow anomaly (*fa*) is a unitless term that represents how wet or dry the current time period is from a previous time period (Vecchia et al. 2009; Zhang and Ball 2017). Long-term flow anomaly (*ltfa*) is the streamflow over the previous year relative to the entire period and calculated as described by Zhang and Ball (2017):

and the short-term flow anomaly (*stfa*) calculated as the current day flow compared to the preceding 1-month streamflow:

where *x* are the averages of log-transformed streamflow over the the antecedent period (*1-year*, *1-month*, etc.) for time *t*.  
We used *ltfa* in NO3-N models and *stfa* in TP models based on results from Zhang and Ball (2017) demonstrating major improvements in NOx regression models that incorporated *ltfa* and moderate improvements in TP regression models that incorporated *stfa*.

Daily loads were calculated from the discrete daily concentration and the corresponding mean daily streamflow value. The model structure was slight altered for the Palmetto Bend dam site where daily loads are not a function of natural stream flow processes, but of dam operation procedures and nutrient concentration at the discharge point of the lake. At this location, nutrient concentrations were modeled as a function of total inflow for gaged tributaries. The *ma* and *fa* terms were also calculated based on total gaged inflow. Daily loads at the dam were calculated from the discrete daily concentration at the discharge point of the lake and corresponding reported daily discharge from the dam.

Thin-plate regression splines with used for *ddate*, *log1p(Q)*, *fa*, and *ma*. A cyclic cubic regression spline was used for *yday* to ensure the ends of the spline match (day 1 and day 366 are expect to match). First order penalties were applied to the smooths of flow-based variables which penalize departures from a flat function to help constrain extrapolations for high flow measurements. Basis dimensions smooths were adjusted after using the *gam.check* function to ensure models were not oversmoothed. Model residuals were inspected for distributional assumptions using the *gratia* package (Simpson 2022).

Left-censored data were not uncommon in this dataset. Several methods are available to account for censored data. We transformed left-censored nutrient concentrations to one-half the detection limit. Although this simple approach can introduce bias (Hornung and Reed 1990), we deemed it acceptable based on the fact that high concentrations and loadings are associated with high-flow events and low-flow/low-concentration events will account for a small proportion of total loadings (McDowell et al. 2021). Initial exploration using the *cenGAM* R package (Fang 2017), which provides the Tobit I family for censored Gaussian data fit using *mgcv*, as well as censored Gamma models fit with the *brms* R package (Bürkner 2017), resulted in models that substantially overestimated nutrient concentrations relative to *mgcv* models fit with the Gamma family. Similar results have been observed in other water quality studies (Bergbusch et al. 2021).

Split-sample tests are often used to fit and validate models against some presumed independent data. Given the relatively small sample sizes and in an effort to retain model robustness, nutrient load models were fit to the entire dataset (Shen et al. 2022). The modeling approach was assessed using repeated 5-fold cross validation (Burman 1989) and summarized Nash-Sutcliffe Efficiency (NSE), R2, and percent bias (PBIAS) performance metrics across folds for each model. These metrics were compared to values suggested by (Moriasi et al. 2015) as an assessment of model performance to independent data.

## Linking Watershed Loads to Estuary Water Quality

We explored relationships between watershed nutrient loads and nutrient concentrations at three monitoring sites in Lavaca Bay. We fit three different GAM models at each site for each parameter of interest.

where *f1(ddate)* is decimal date smoothed with a thin-plate regression spline, *f2(yday)* is the numeric day of year smoothed with a cyclic cubic regression spline and *f3(ddate, yday)* is a tensor product smooth of the two variables. *f4(Q)* is total daily watershed discharge and *f5(Load)* is total NO3-N or TP watershed load obtained from Equation (1). By comparing the model fits between the three GAMs, we evaluated if variance in Lavaca Bay nutrient concentrations are well explained by only temporal parameters (Equation (5)) or if the freshwater flow (Equation (6)) and nutrient loading (Equation (7)) can be used to explain additional variation. The relatively large impact of flow variability on nutrient loading creates a challenge for disentangling the impacts of flow and load (Murphy et al. 2022). Instead of using raw freshwater flow and nutrient loading values, these values were replaced by seasonally adjusted flow and flow-adjusted nutrient loads as described by Murphy et al. (2022). In short, a seasonal GAM was fit to daily flow values and the model residuals were used in *f4(Q)* and a GAM for nutrient loads was fit to daily streamflows with the model residuals used in *f5(Load)*.

# Tables

This is an example of an unformatted table and how we cross-reference that table ([Table](#tab:mtcars) ).

Table . this is the builtin mtcars data.

| mpg | cyl | disp | hp | drat | wt | qsec | vs | am | gear | carb |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 21.0 | 6 | 160.0 | 110 | 3.90 | 2.620 | 16.46 | 0 | 1 | 4 | 4 |
| 21.0 | 6 | 160.0 | 110 | 3.90 | 2.875 | 17.02 | 0 | 1 | 4 | 4 |
| 22.8 | 4 | 108.0 | 93 | 3.85 | 2.320 | 18.61 | 1 | 1 | 4 | 1 |
| 21.4 | 6 | 258.0 | 110 | 3.08 | 3.215 | 19.44 | 1 | 0 | 3 | 1 |
| 18.7 | 8 | 360.0 | 175 | 3.15 | 3.440 | 17.02 | 0 | 0 | 3 | 2 |
| 18.1 | 6 | 225.0 | 105 | 2.76 | 3.460 | 20.22 | 1 | 0 | 3 | 1 |
| 14.3 | 8 | 360.0 | 245 | 3.21 | 3.570 | 15.84 | 0 | 0 | 3 | 4 |
| 24.4 | 4 | 146.7 | 62 | 3.69 | 3.190 | 20.00 | 1 | 0 | 4 | 2 |
| 22.8 | 4 | 140.8 | 95 | 3.92 | 3.150 | 22.90 | 1 | 0 | 4 | 2 |
| 19.2 | 6 | 167.6 | 123 | 3.92 | 3.440 | 18.30 | 1 | 0 | 4 | 4 |

The [flextable](https://davidgohel.github.io/flextable/) package provides additional formatting flexibility when exporting to Word (Table ).

Table . flextable formatted table.

| mpg | cyl | disp | hp | drat | wt | qsec | vs | am | gear | carb |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 21.0 | 6 | 160.0 | 110 | 3.90 | 2.620 | 16.46 | 0 | 1 | 4 | 4 |
| 21.0 | 6 | 160.0 | 110 | 3.90 | 2.875 | 17.02 | 0 | 1 | 4 | 4 |
| 22.8 | 4 | 108.0 | 93 | 3.85 | 2.320 | 18.61 | 1 | 1 | 4 | 1 |
| 21.4 | 6 | 258.0 | 110 | 3.08 | 3.215 | 19.44 | 1 | 0 | 3 | 1 |
| 18.7 | 8 | 360.0 | 175 | 3.15 | 3.440 | 17.02 | 0 | 0 | 3 | 2 |
| 18.1 | 6 | 225.0 | 105 | 2.76 | 3.460 | 20.22 | 1 | 0 | 3 | 1 |
| 14.3 | 8 | 360.0 | 245 | 3.21 | 3.570 | 15.84 | 0 | 0 | 3 | 4 |
| 24.4 | 4 | 146.7 | 62 | 3.69 | 3.190 | 20.00 | 1 | 0 | 4 | 2 |
| 22.8 | 4 | 140.8 | 95 | 3.92 | 3.150 | 22.90 | 1 | 0 | 4 | 2 |
| 19.2 | 6 | 167.6 | 123 | 3.92 | 3.440 | 18.30 | 1 | 0 | 4 | 4 |

# Figures

We can embed and cross-reference plots (Figure ).

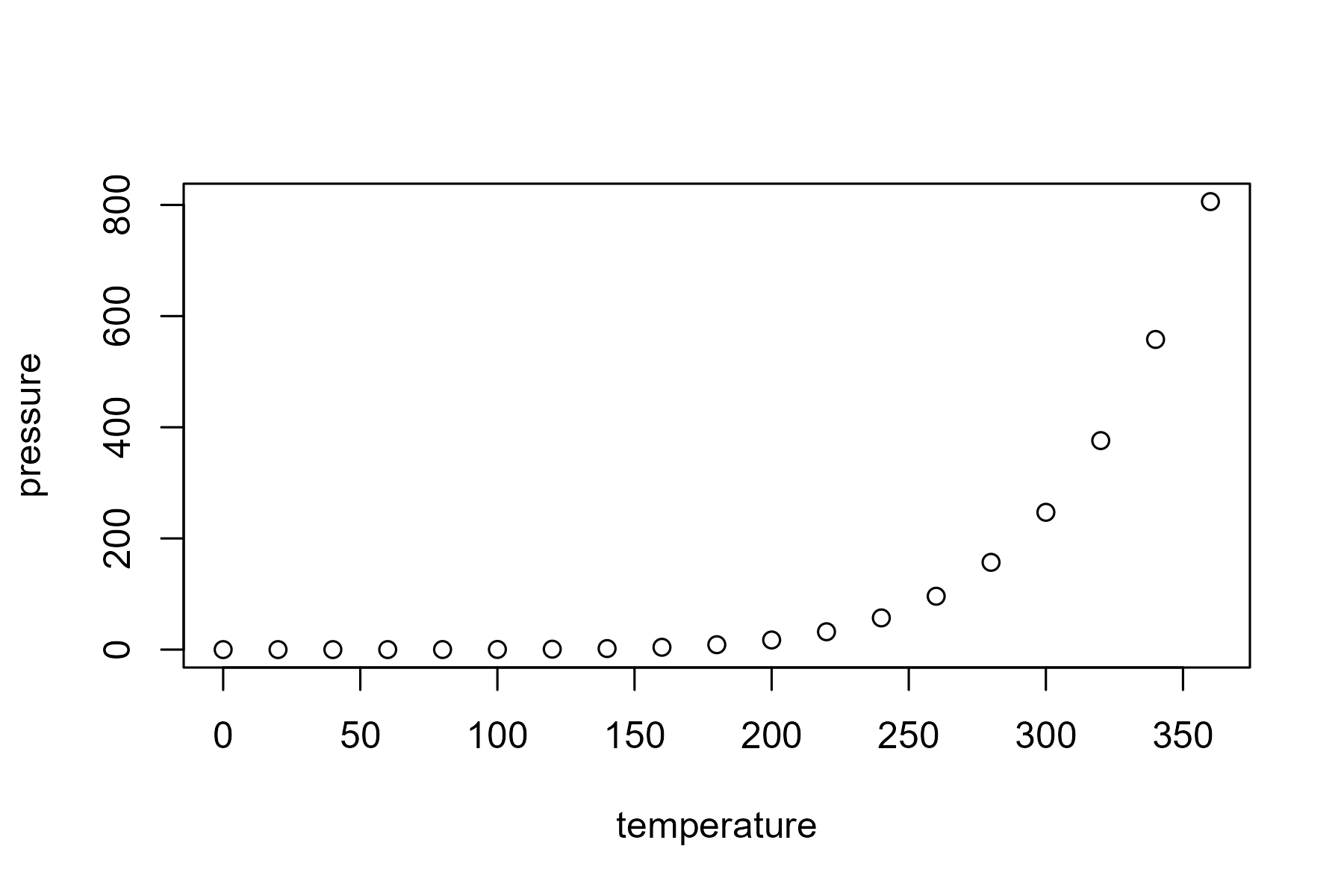


Figure . pressure dataset

# Landscape Section

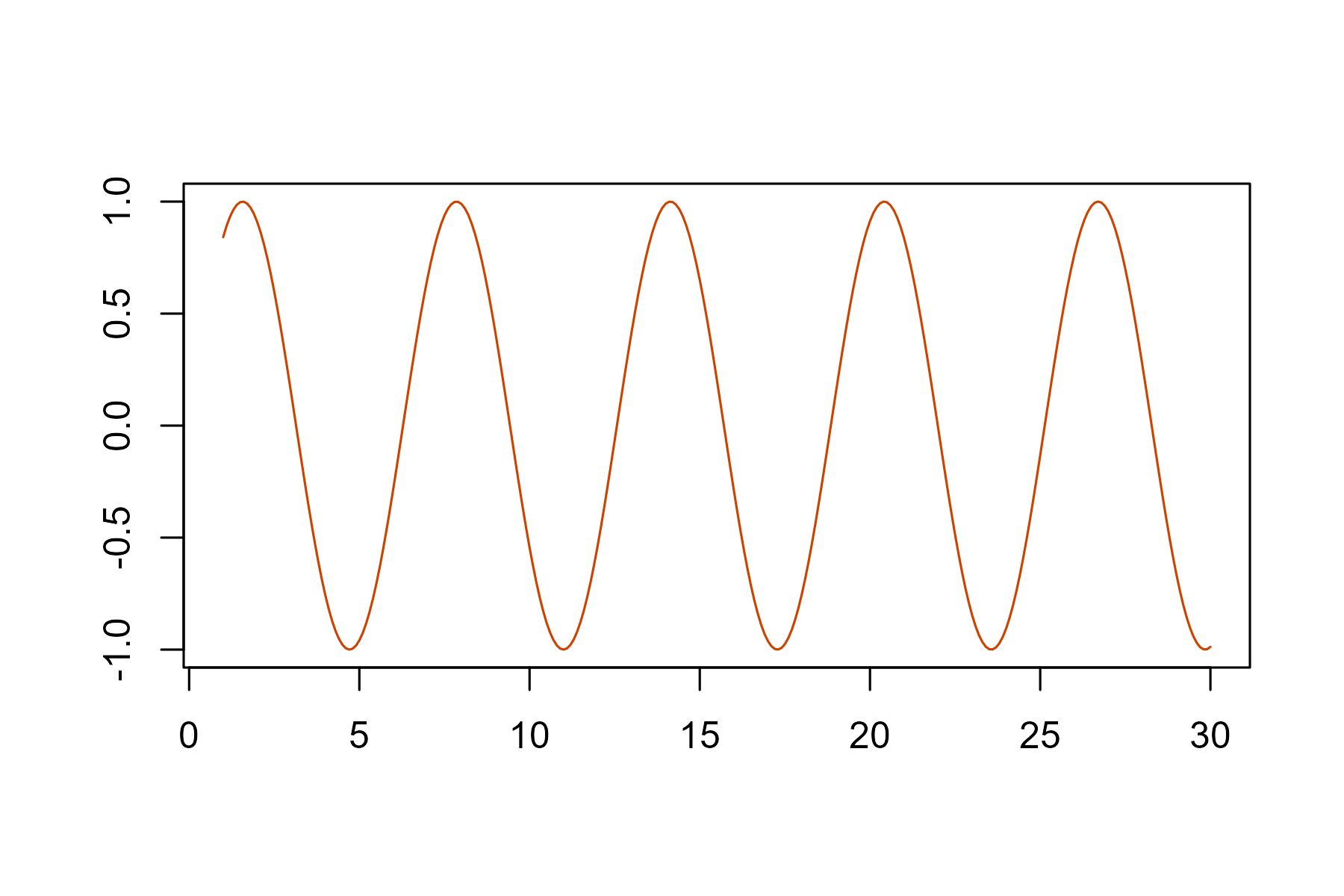


Figure . sin function

# Math

Wrap variables or math in a single $ to show math inline. For example, . Standalone equations are wrapped with $$.

If the equations need to be numbered and cross-referenced the format as:

\begin{equation}  
\left(\prod\_{i=1}^{n}y\_i\right)^{\frac{1}{n}} = \exp\left[\frac{1}{n}\sum\_{i=1}^n\log{y\_i}\right], \quad \textrm{when} \quad y\_1, y\_2, ..., y\_n > 0  
(\#eq:gmean)  
\end{equation}

Which renders as (Equation (8):

# References

In-text references and bibliography generation are handled automatically. It relies on creating a bibtex .bib file with your references. Software such as Zotero, Mendely, and even Google Scholar can generate the bibtex entries for you. The entries are stored in the bibliography.bib file inside the same directory as this .Rmd file. To make a in text citation, use the following syntax, [@helsel\_statistical\_2002] to generate the reference at the end of this sentence (**helsel\_statistical\_2002?**). Use a semicolon to include multiple references [@helsel\_statistical\_2002; @hirsch2010weighted] (**helsel\_statistical\_2002?**; **hirsch2010weighted?**). Or we might use @helsel\_statistical\_2002 without brackets to indicate (**helsel\_statistical\_2002?**) provide a fundamental overview of water quality statistics. The bibliography will populate automatically.

# Styling and fonts

This template uses Minion Pro for body fonts and Open Sans for headings following TWRI brand guidance and AgriLife brand guidance. I can’t bundle Minion Pro in this package because of licensing, but you can download and install both fonts from AgriLife (<https://agrilife.tamu.edu/wp-content/uploads/2021/03/AgriFonts.zip>). I recommend downloading and installing the fonts before knitting your documents. Note that Minion Pro won’t “embed” in Word documents because it is an OTF style font and currently Word only embeds TTF fonts. That means collaborators without the font installed on their system will see a different serif font on their system in Word. Once exported to pdf, both OTF and TTF fonts should be embedded correctly.

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# Appendix A

You can add more info, tables, and figures here.