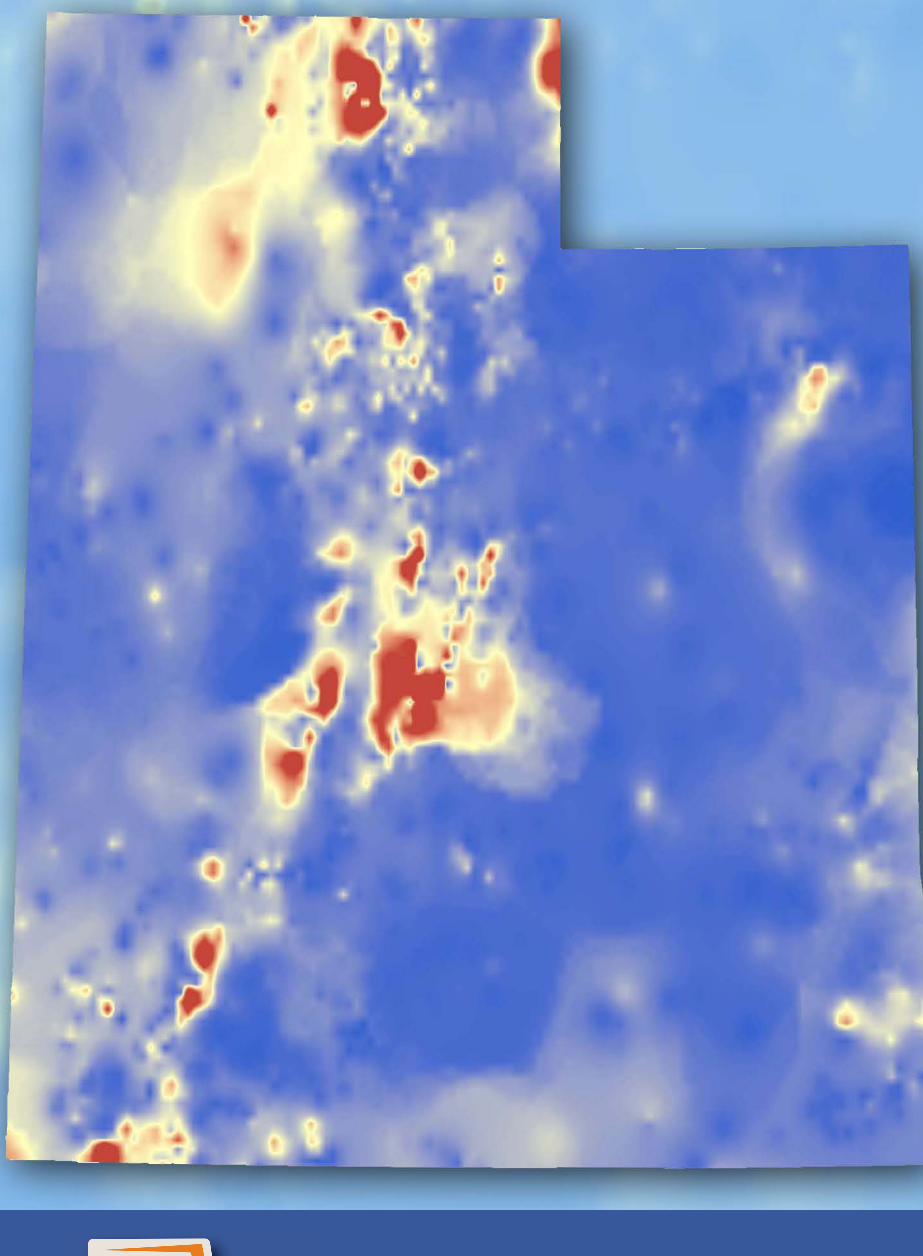
MAPPING TOOL TO SHOW TRENDS IN GROUNDWATER NITRATE CONCENTRATIONS IN UTAH

by Janae Wallace and Paul Inkenbrandt



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Cover photo: Bayesian kriging interpolation of groundwater nitrate data in Utah.

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MAPPING TOOL TO SHOW TRENDS IN GROUNDWATER NITRATE CONCENTRATIONS IN UTAH

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ABSTRACT

The Utah Division of Drinking Water has compiled water quality data for all public water supply systems in Utah. This is the first geographic synthesis of these data. This report uses extensive data to display statewide and temporal nitrate concentration trends in groundwater.

A database of Utah groundwater chemistry was compiled from data provided by the Utah Division of Drinking Water, the Utah Department of Agriculture and Food, the U.S. Geological Survey, the U.S. Environmental Protection Agency, and the Utah Geological Survey. A geographic information system tool created for this database automatically conditions and combines the data into a single database and interpolates the values in that database into a series of year-specific files.

INTRODUCTION

The Utah Division of Drinking Water (UDDW) wants to better understand spatial and temporal trends of regulated groundwater constituents, specifically nitrate, to better manage Utah's groundwater resource. Therefore, the Utah Geological Survey (UGS) created a series of time-capable ArcGIS maps showing interpolated variations in nitrate concentrations. We also created a set of adjustable tools that gives the UDDW the ability to periodically update and re-interpolate their data. The primary use of the maps is to recognize spatio-temporal trends in nitrate contamination to better manage the State's groundwater resources. This report describes the maps in detail, how they were constructed, and their limitations.

Background

Throughout the last century, several government entities have collected groundwater chemistry data in Utah. Some of these entities have maintained comprehensive databases of the information they collected. We compiled available data into a single dataset of groundwater-quality analyses, with an emphasis on nitrate (as nitrogen).

The databases we compiled include groundwater-quality information obtained from (1) UDDW Safe Drinking Water Information System (SDWIS) database, (2) the U.S. Geological Survey (USGS) National Water Information System (NWIS), (3) groundwater chemistry data from the U.S. Environmental Protection Agency (EPA) STOrage and RETrieval (STORET), (4) the Utah Department of Agriculture and Food (UDAF) State Groundwater Reports, and (5) the UGS.

SDWIS Data

The Utah Division of Drinking Water SDWIS contains millions of sample results from all public-supply sources in Utah. The SDWIS database follows database structure standards outlined by the U.S. EPA (EPA, 2007). The main database is maintained by UDDW in an Oracle platform.

USGS NWIS Data

The U.S. Geological Survey's NWIS (USGS, 2012) is a comprehensive and distributed dynamic dataset that supports the acquisition, processing, and long-term storage of water data. The USGS collects and analyzes chemical and physical properties of water (both groundwater and surface) throughout the United States. For the nitrate-mapper database, we used NWIS data from springs and wells, and excluded surface-water data.

STORET Data

U.S. Environment Protection Agency's STORET (EPA, 2012) database includes data from multiple sources compiled by the EPA for the entire country. STORET data are divided into two separate databases, defined by the date the data were provided. The current database is called the STORET Data Warehouse, and the older of the two is the STORET Legacy database.

Data provided to EPA before 1999 exist in the STORET Legacy database. This system, designed in the 1960s, was a pioneer in the long-term archival of field water monitoring results. The STORET Legacy database contains data of undocumented quality (sampling and analysis quality were not noted) and is a static data set (data here will not updated or replaced).

Since January 1, 1999, all new data have been entered into the modernized STORET Data Warehouse. The STORET Data Warehouse currently receives new data on a regular basis and will continue to do so for the foreseeable future; it is considered a dynamic database.

UDAF Data

The State Groundwater Program, administered by the Utah Department of Agriculture and Food, operated from 1996 to 2010. It was implemented for the UDAF staff to assist and educate private well owners about their groundwater quality. The UDAF database includes thousands of mostly rural Utah groundwater samples based on well owner requests. The program focused on inorganic water quality, salinity, toxic minerals, and pesticides. UDAF reports include maps available from 1999 to 2010; the program was discontinued after 2010. Reports prior to 1996 contain only data and no maps. Legal obligations between UDAF and well owners limit the release of some data, including geographic coordinates of sampling locations and well owner information.

UGS Data

The Utah Geological Survey has conducted groundwater-quality studies since 1996 (Lowe and others, 2002). For each groundwater-quality study, the UGS sampled water from wells and springs, and compiled data from other sources, including the UDDW, UDWQ, Weber Basin Water Conservancy District, the Weber-Morgan Health Department, USGS, EPA, and UDAF. Although the UGS staff have been collecting chemistry samples since 1996, some of these data include compilation from other sources prior to 1996.

METHODS

To create the time-series interpolation maps, we (1) prepare the data, (2) compile and format the data, and (3) interpolate and time-enable the data. Data preparation consists of manipulating raw data into a consistent reporting type and unit, with consistent field names. Compilation merges the data into a single file. Interpolation creates a smoothed interpolation surface representing nitrate concentration for each year of available data.

Data Preparation

We first prepared the data by creating a Microsoft Access database for each dataset. The SDWIS data are obtained through an Access database with a dynamic connection (direct, read-only link) to the Oracle database. Regional data from the NWIS (USGS, 2012) and STORET (EPA, 2012) databases were downloaded from the NWIS and STORET websites and transferred into respective Access databases. These databases can be periodically updated using scripts based on platforms from the NWIS Water-Quality Web Services.

Because the UDAF was legally obligated not to release geographic coordinates of sampling locations or well owner information, we were unable to obtain the original digital point shapefiles of sample locations from UDAF. However, UDAF maps in the State Groundwater Reports (UDAF, 2010) depict locations of each sample site. Also, courtesy of UDAF staff, we received chemistry data from each sample site (Mark Quilter written communication, January 2012).

To digitize the UDAF data points, maps (figures) from the reports (UDAF, 2010) were georeferenced to their respective areas to an accuracy of 15 meters or less. We matched layers in the figures, such as roads and land use, to layers from the Utah Automated Geographic Reference Center (AGRC) (2012) when available to ensure accurate georeferencing. We then centered our shapefile points on the points representing geographic sample locations on the figures. The geographic points on the original figures were created using ArcMap (ESRI, 2012a), so the center of the points should be the exact location of the point as recorded by UDAF staff (UDAF, 2010). Because we applied the nitrate mapping tool at a state-level scale, the accuracy of the UDAF locations is adequate at this scale. Error in this digitization method is from inaccuracy of the original data measurement device (GPS), inaccuracy of georeferencing, and inaccuracy in drawing the digitized points.

When possible, we matched the points we created to the locations of the Utah Water Rights (2012) points of diversion (WRPOD) records near the figure plot (within about 150 meters). To match the data points, we used the ArcGIS spatial join tool for WRPOD to UDAF points within 150 meters of each other. Although the WRPOD locations may not be exact, the well identification number (WIN) information, including well depth and depth to water, is valuable.

Maps were not available for UDAF reports from 1996 to 1998. In other UDAF reports, some map series had missing data, where the number of wells sampled did not match the number displayed on the maps.

After digitizing the points, we combined files containing tabulated chemistry and exported data into a Microsoft Access database. We then exported data from the digitized point shapefile database and added it to the Microsoft Access database. Some of the tabulated chemistry data were missing exact sample dates, so we assigned a year value based on the year of the report.

ArcGIS Tools

We used ArcGIS ModelBuilder (ESRI, 2012a) to create several tools to automate the time-series interpolation map making process. We chose ModelBuilder because of it allows the users to learn the mechanics of the tools. Once users understand the processes of scripts created by ModelBuilder, they can modify the scripts to accommodate the dynamic components associated with the data, technology, and field areas. We programmed a set of tools to extract data tables from the Access databases (see above), add and calculate fields to make field names consistent, and then convert data tables into point shapefiles.

Querying Databases

Ultimately, our goal is to compile a comprehensive point shapefile of most of the available groundwater chemistry in the State of Utah. Having a single shapefile facilitates interpolation of point data and ensures duplicate sample instances are eliminated. To combine all of the data into a single set of point data, we imported each dataset from Microsoft Access into ArcGIS and then assigned consistent field names for each dataset. We matched field names so that, upon merging datasets in ArcGIS, all of the data in field columns were properly aligned into consistent fields.

First, we extracted the data from each of the Microsoft Access databases. In each Microsoft Access database, we queried station identifier, sample identifier, latitude/longitude coordinates, sample date, constituent concentration, and parameter of constituents.

For all of the datasets, we designated a standard concentration of 0.1 mg/L for all non-detect data. Although minimum detection limits were available for some of the compiled data, they were not specified for much of the data. In some cases in the UDAF and UGS databases, some reported non-detects were unclear. Also, non-detect values can vary based on the analyzing laboratory's capabilities. Nitrate concentrations of great concern are concentrations that are near or exceed the U.S. EPA maximum contaminant level of 10 mg/L (nitrate as nitrogen) due to threat to groundwater supply and the discontinued use of public supply wells that do not meet standards. However, the nitrate mapping tool can be adjusted to accommodate other non-detect values, but the concentrations attributed to non-detect values need to be specified.

We created a series of dynamic links in ArcGIS (ESRI, 2012a) to the queries in the Microsoft Access databases for each chemistry dataset. We used the "Table to Table" tool in ArcGIS to export data into ArcGIS from the Access databases. After exporting the data from Access, we created permanent shapefile points if the data were stagnant, though we maintained a link between ArcGIS and Access if the data are dynamically (continuously) or periodically updated (sampling events and points periodically added to outside databases).

For stagnant databases (those that will not receive new data), we created a point shapefile from the query in the Access database to eliminate the need for future dynamic Microsoft Access connections. The databases having no periodic updates include the UGS, UDAF, and STORET Legacy databases. We stored a master copy of these points into a separate folder with the Nitrate ModelBuilder toolbox. The point creation tools in the ModelBuilder toolbox for UGS (figure 1), UDAF (figure 2), and STORET Legacy (figure 3) points extract data from the existing master point shapefiles and transfer those data to a temporary location. This ensures that the original shapefile points are not modified.

The data receiving periodic updates undergo a slightly more complex process through the ModelBuilder toolbox. These include the NWIS (figure 4), SDWIS (figure 5), and STORET (figure 6) databases. Because the dynamic data are directly from databases having different field formats, we create new fields with the common (matching) field names.

Once all data were consistent in point shapefile formats and all of the important fields (sample date, concentration, sample ID, and station ID) were made consistent, we merged them into a single shapefile.

Combining and Organizing Data

The resulting points from each database were combined using a merge tool that also removes remnant, inconsistent data fields. As a single point shapefile the merged data are much easier to interpolate and manipulate. The tool (figure 7) that merges the data also clips data points located outside of Utah's boundaries. This includes points with incorrect geographic coordinates and points from the STORET and NWIS databases that extend beyond the area of interest. We designed the clipping layer to include portions of surrounding states having nitrate data to ensure that the interpolation of nitrate values was valid across state lines.

We created unique point shapefiles for each year from the merged data. To perform moving-average smoothing, we created point shapefiles consisting of three-year windows with one-year time steps (figure 8). We also created a tool that creates a five-year (figure 9) window having one-year time steps, which increases the smoothing effect. The moving-average selection corrects for poor temporal coverage, where a high-nitrate data point is present one year, but not available the next. The moving-average selection makes year-to-year interpolation transitions more smooth. An option for selecting the no moving-average correction is also available (figure 10).

Interpolation

We created several tools to interpolate the sets of point shapefiles that we created in the last step described above. Interpolation predicts values over an area based on a finite number of values from data points, and can be used to predict unknown values for any geographic point data, including chemical concentrations (Longley and others, 2005). The interpolation tools interpolate each year's points into a smooth, variable surface. The result of the interpolation is a set of rasters,

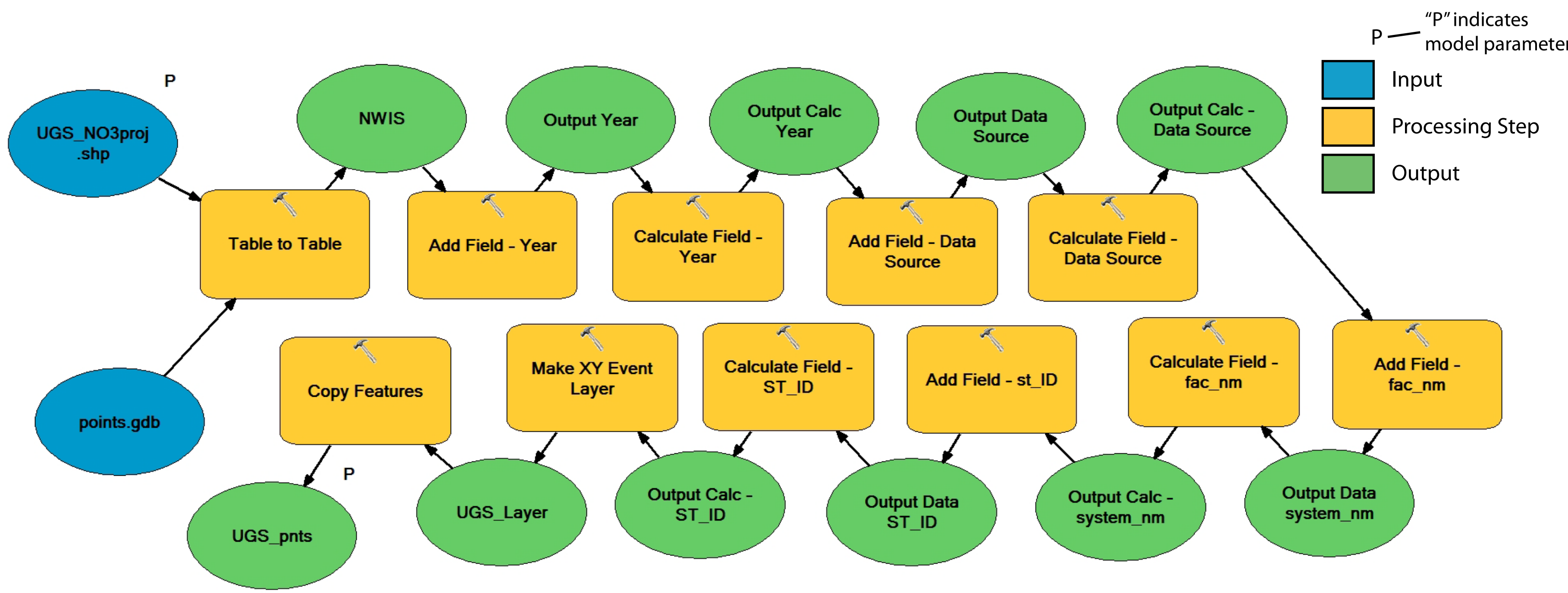

Figure 1. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the Utah Geological Survey groundwater nitrate point data consistent with other datasets, which allows for proper merging of the data.*

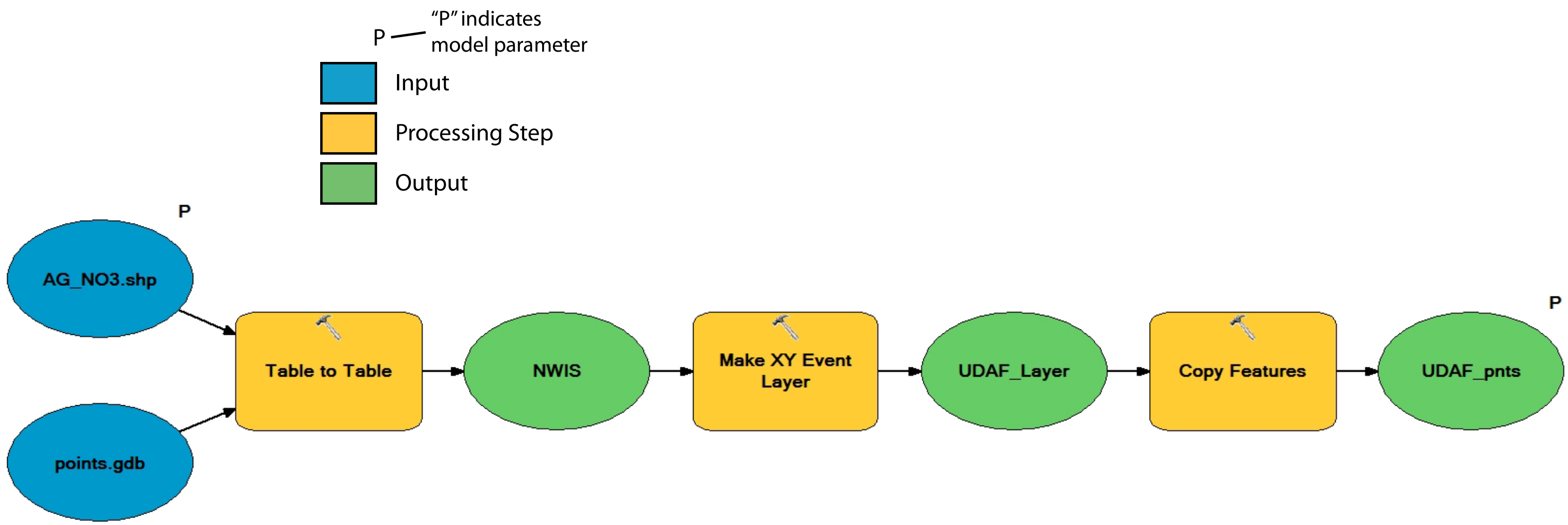

Figure 2. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the Utah Department of Agriculture and Food groundwater nitrate point data (UDAF, 2010) consistent with other datasets, which allows for proper merging of the data.*

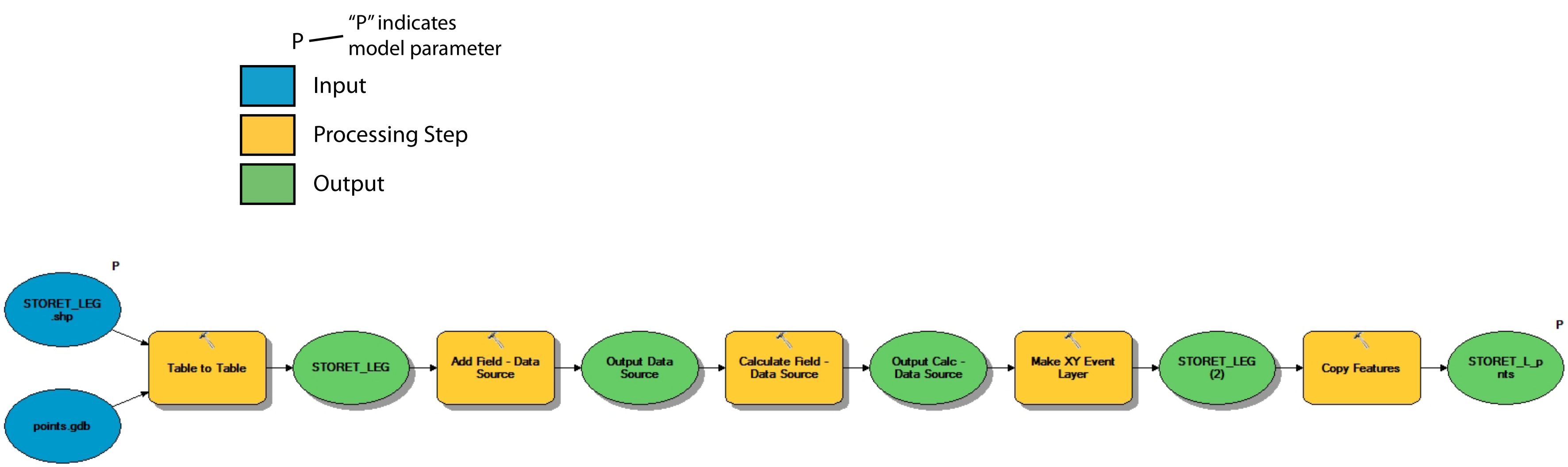

Figure 3. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the U.S. EPA (2012) STORET Legacy groundwater nitrate point data consistent with other datasets, which allows for proper merging of the data.*

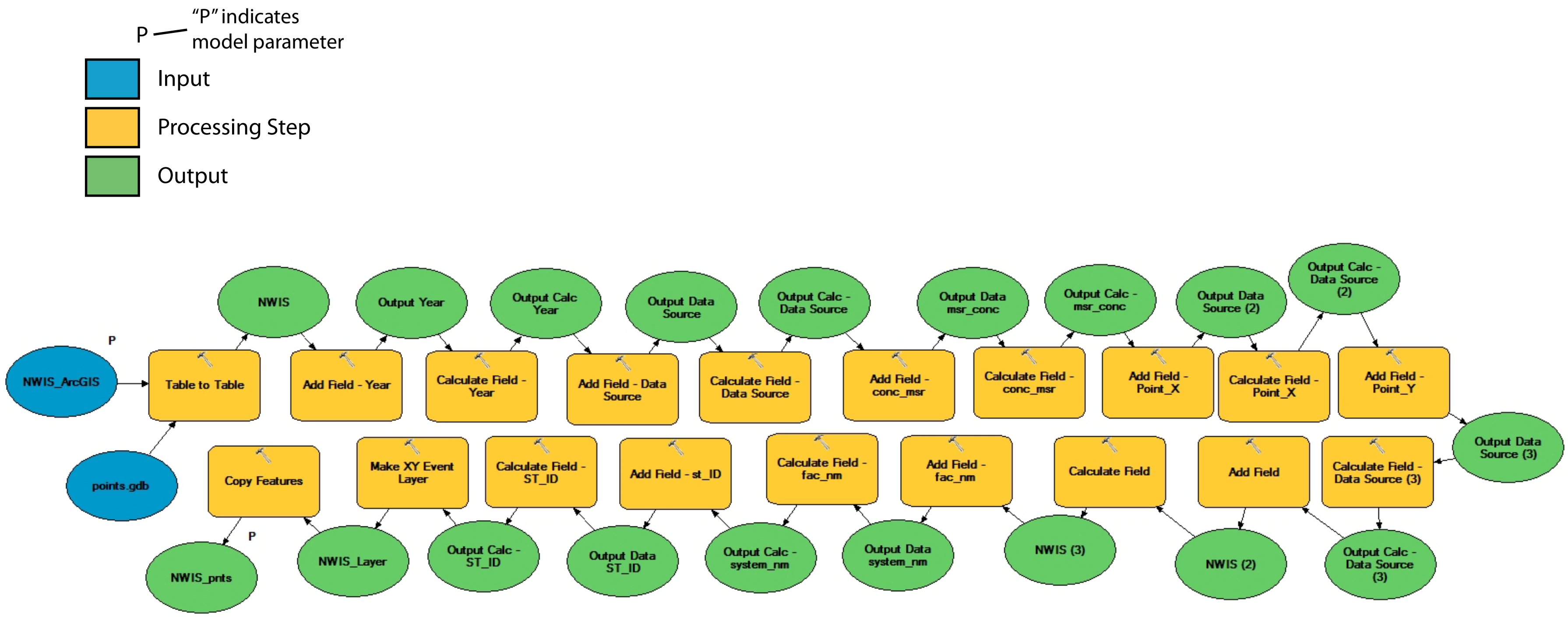

Figure 4. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the USGS (2012) NWIS groundwater nitrate point data consistent with other datasets, which allows for proper merging of the data.*

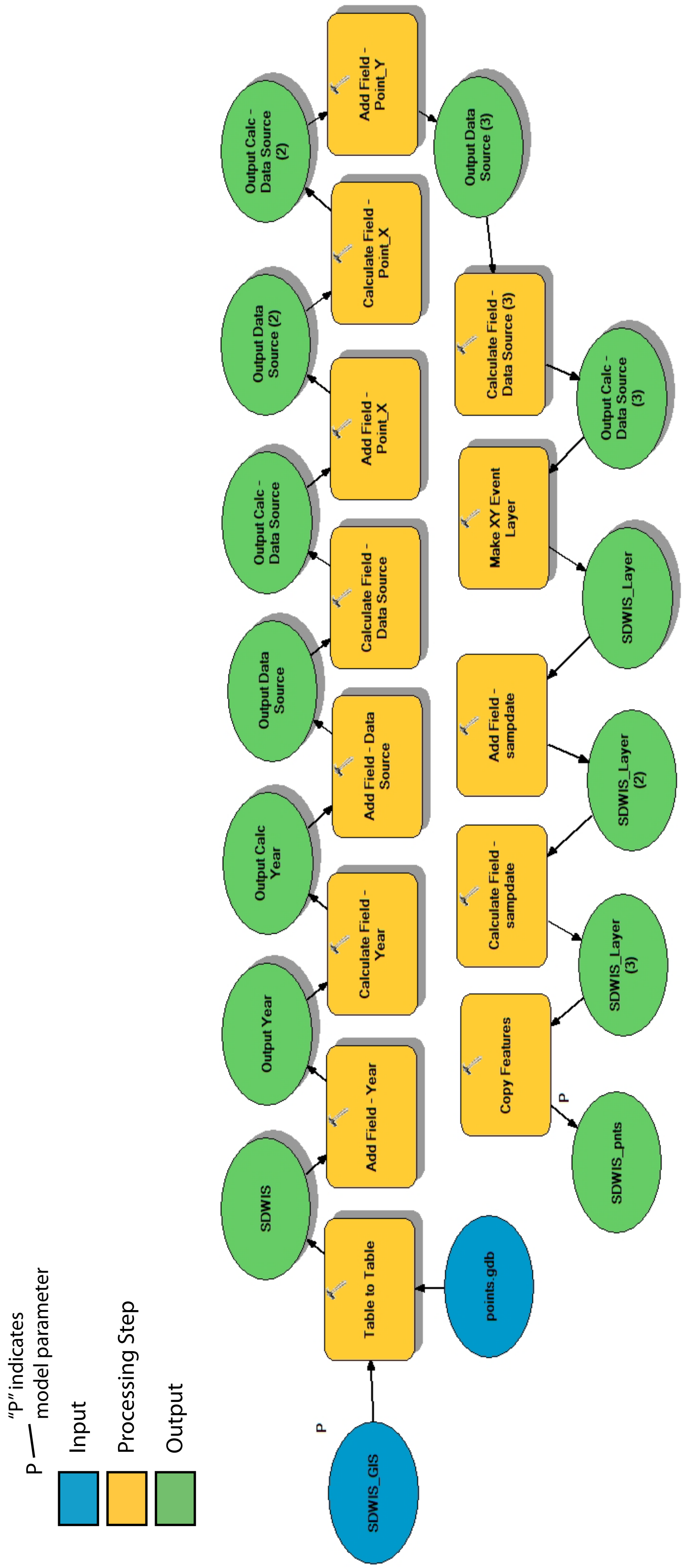

Figure 5. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the Utah Division of Drinking Water SDWIS groundwater nitrate point data consistent with other datasets, which allows for proper merging of the data.*

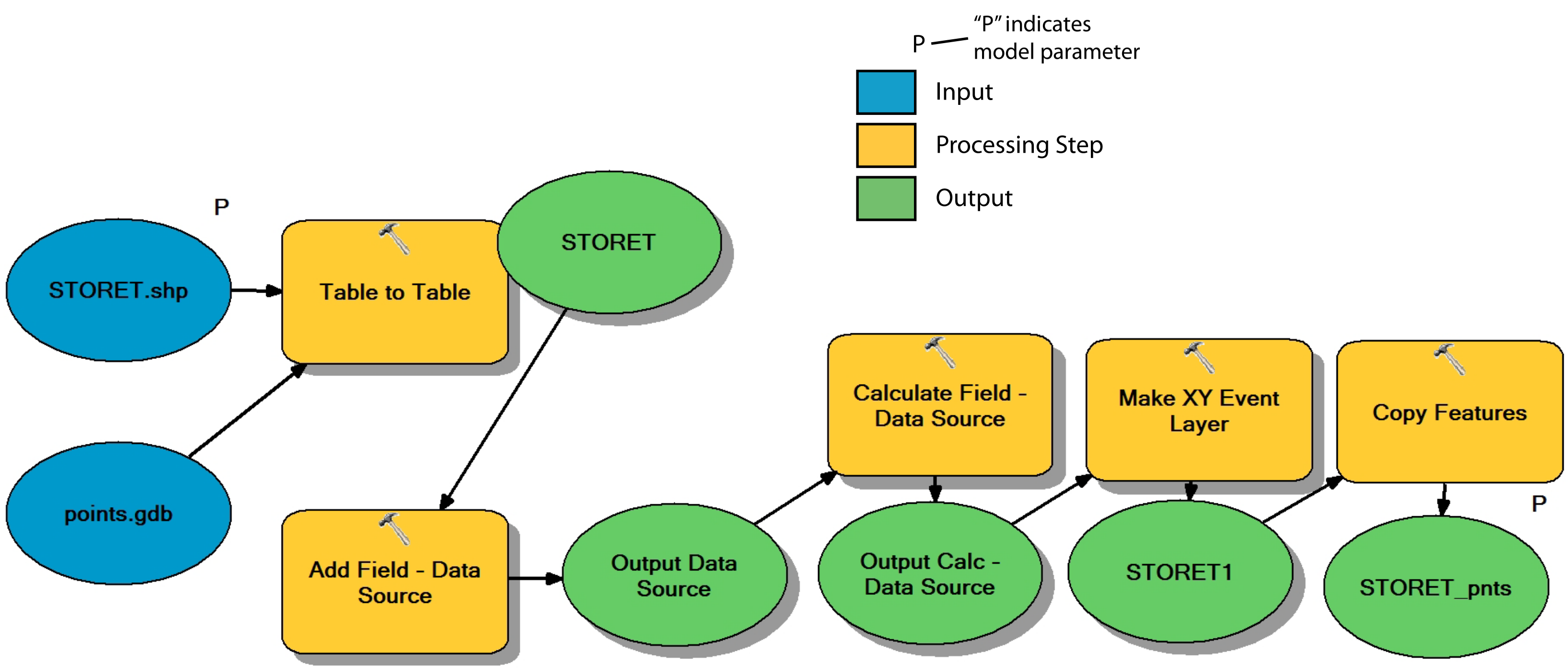

Figure 6. *ArcMap (ESRI, 2012a) ModelBuilder model used to make the U.S. EPA (2012) STORET groundwater nitrate point data consistent with other datasets, which allows for proper merging of the data.*

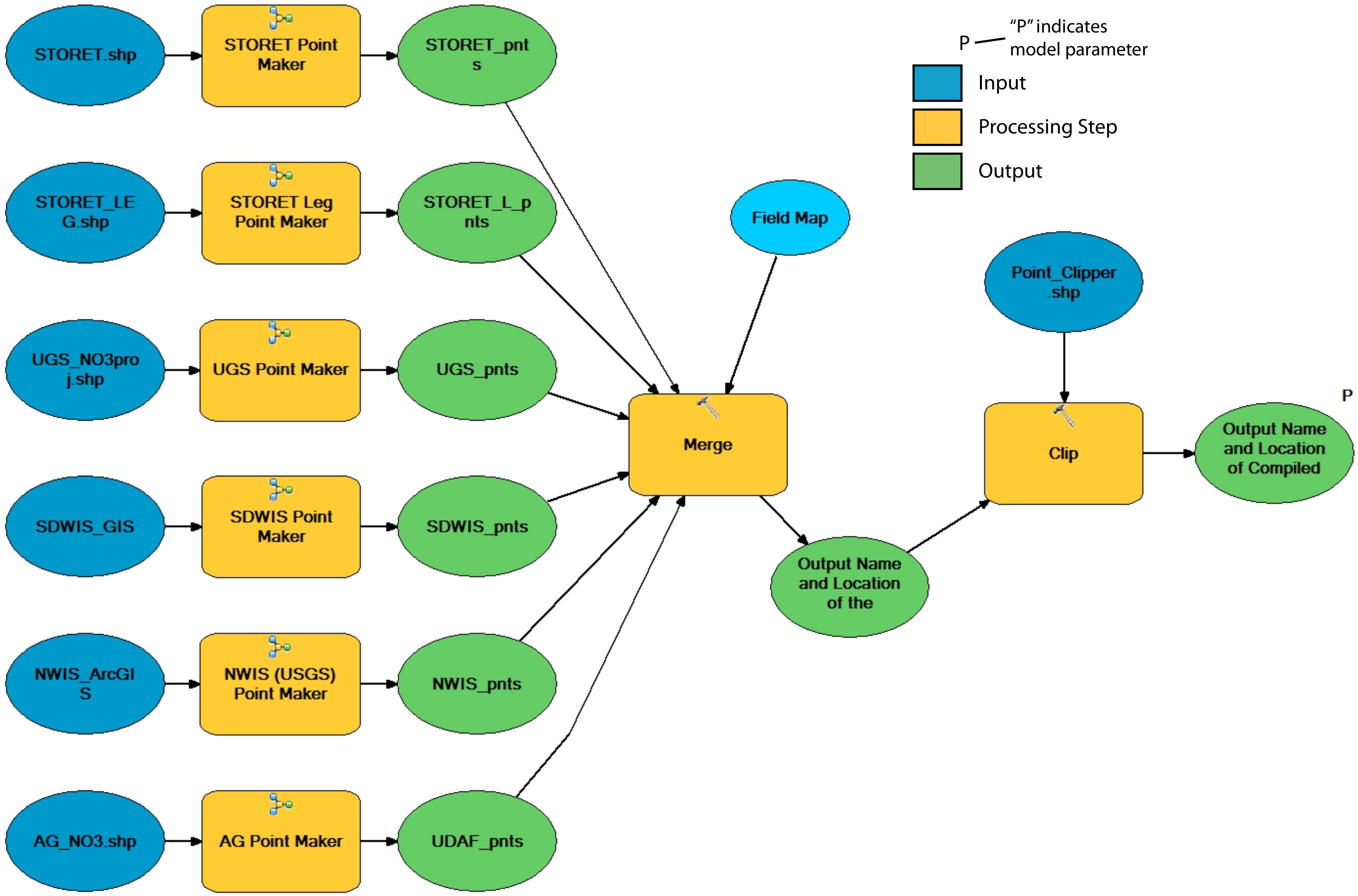

Figure 7. *ArcMap (ESRI, 2012a) ModelBuilder model used to merge nitrate point data from different sources into a single point shapefile. The "Field Map" determines which fields are included in the final shapefile.*

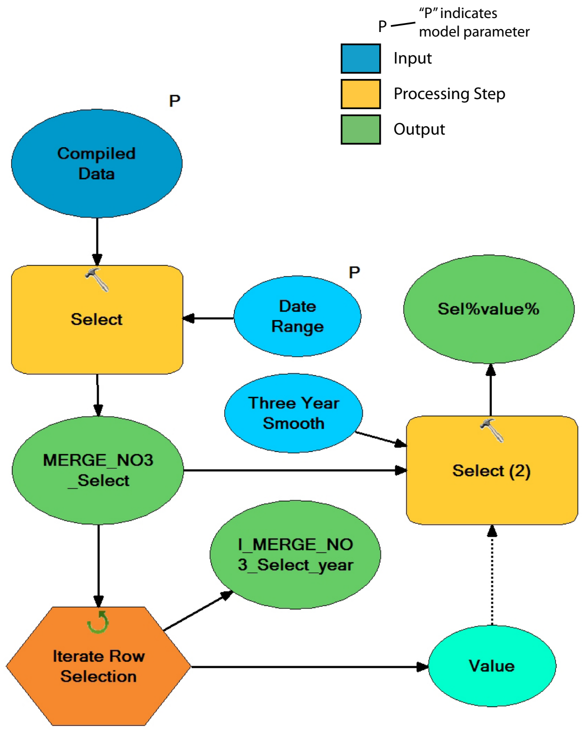

Figure 8. *ArcMap (Esri, 2012a) ModelBuilder model used to create a nitrate point dataset for each year within a selected date range. Using this tool, each yearly point dataset will include the labeled year, the year before, and the year after the label year (3-year window, 1-year timestep).*

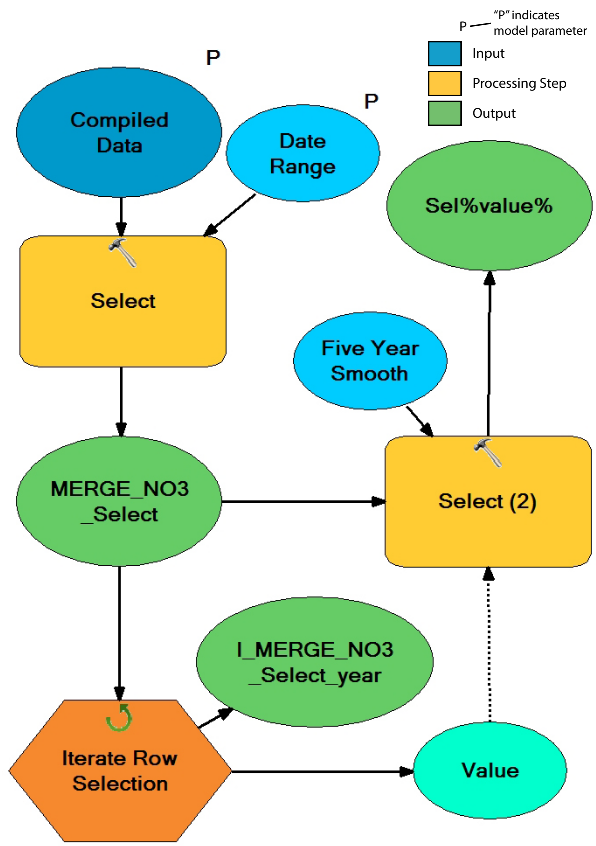

Figure 9. *ArcMap (Esri, 2012a) ModelBuilder model used to create a nitrate point dataset for each year within a selected date range. Using this tool, each yearly point dataset will include the labeled year and two years before and two years after the label year (5-year window, 1-year timestep).*

which we threshold and classify and then convert into a polygon shapefile. Thresholding decreases noise in the raster and allows for more consistent representation on how its displayed on the map (symbology) between years. Thresholding consists of grouping individual raster cell values into like areas. Resolution is reduced, but patterns are easier to identify when the cells are grouped. Also, thresholding around an anomalously high concentration (for example, a maximum contaminant level) can accentuate exceedence of that level, making it easier to identify. Thresholding allows for a single, consistent scale to be applied to every year's interpolated data, which allows comparison from year-to-year. Polygons work more effectively because they are highly compatible with the ArcMap (ESRI, 2012a) time slider and are easier to export into other file formats, such as Google Earth kml. Below, we summarize various interpolation methods used by each of the interpolation tools. The kernel method and the spline method can accommodate barrier features, such as the extent of valley fill.

Inverse Distance Weighted

Inverse distance weighted (IDW) interpolation assumes that points near each other are more alike than those farther apart. The values closest to the prediction location have more influence on the predicted value than those farther away (ESRI, 2012b). In IDW, the maximum and minimum values in the interpolation can only occur at actual sample points. IDW accounts for clustering of points and the presence of outliers in point data.

IDW is sensitive to the search neighborhood and the power value. Excluding distant points that have minimal influence on the resulting interpolation improves calculation rates. The number of measured values can be limited by specifying a search neighborhood, which restricts the distance and locations of measured values to be used in the prediction. The rate at which the influence or weight points have on an interpolated value decreases with distance and is dependent on the power value. As the value increases, points farther from the interpolated location are weighted less (ESRI, 2012b).

Kernel

Kernel interpolation is a type of local polynomial interpolation, where many polynomial functions are fit locally. Kernal interpolation reduces calculation instability using a regularization method to estimate regression coefficients. Kernel interpolation uses the shortest distance between points so that points on the sides of boundaries are connected by a series of straight lines (ESRI, 2012b).

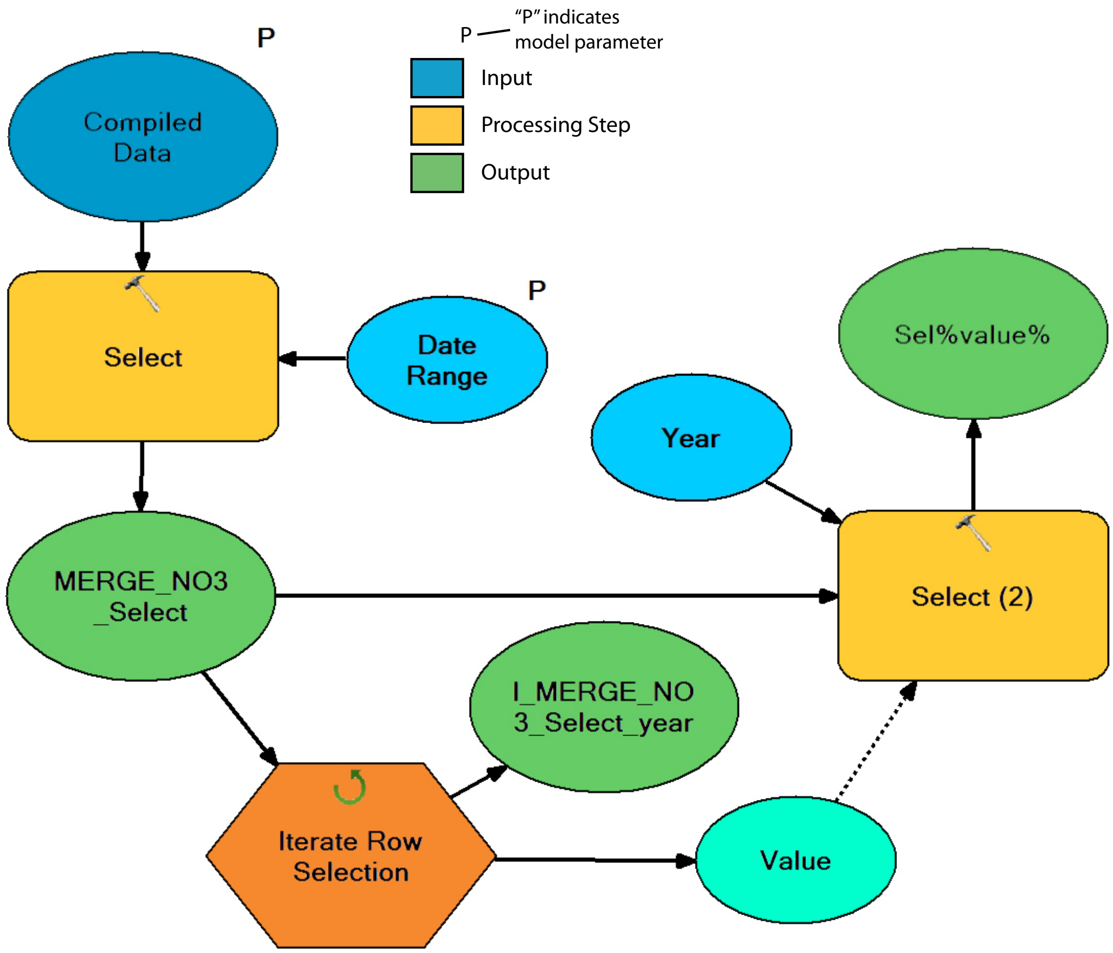

Figure 10. *ArcMap (Esri, 2012a) ModelBuilder model used to create a nitrate point dataset for each year within a selected date range. Using this tool, each yearly point dataset will include only the labeled year (1-year window, 1-year timestep).*

Kriging

Kriging models spatial variation observed in natural phenomena using spatial auto-correlation. Kriging techniques can be used to describe and model spatial patterns, predict values at unmeasured locations, and assess the uncertainty associated with a predicted value at the unmeasured locations. Kriging is a processor-intensive method, where processing time is dependent on the size of the input dataset and the size of the search window. Kriging works best when the user has an understanding of the distribution and spatial trends in the data.

Spline

Spline interpolation uses a function that minimizes interpolated surface curvature, resulting in a smooth surface that passes exactly through the input points. Because the interpolated surface passes exactly through every input point, abrupt changes in gradient or slope can occur in the vicinity of the data points. When a barrier is applied, the input barrier features constrain the resulting smooth surface. Spline is very effective for interpolating contaminant concentrations, such as nitrate (ESRI, 2012b).

TIN

Triangular irregular networks (TIN) are based on triangulation of a set of points, where the points are connected by lines to form a network of triangles. ArcGIS uses a Delaunay triangulation method to make the TIN triangles, which maximizes the minimum interior angle of all triangles, avoiding long, thin triangles as much as possible (ESRI, 2012b). TINs account for variations in point density. TINs fit exactly to point data, which allows a TIN to preserve precision of the input data while interpolating between known points.

RESULTS

The output of the toolset includes three types of GIS data (1) individual raster files for each year of data (these data are preserved in a raster geodatabase for optional analysis purposes), (2) point shapefiles, including individual point shapefiles for each database, a merged point shapefile for all data, and the moving average point shapefiles, and (3) polygon data representing the interpolated nitrate concentrations.

Points

Each database has varying degrees of spatial and temporal coverage. The following discussion is specific to nitrate data in the Utah.

Temporal Data Distribution

Good temporal data coverage consists of multiple measurements over time at the same point in space and has measurements that span several continuous years. High temporal resolution consists of continuous, frequently sampled measurements (e.g., monthly). Figure 11 shows the distribution of all of the compiled groundwater nitrate data from 1911 to 2012. The USGS NWIS database had the broadest time range of samples, spanning 1911 to 2012. However, data in the early years are sparse, with less than 100 data points available throughout the state for years prior to 1950. SDWIS data are so numerous that they obscure other datasets. Figure 12 shows the temporal distribution of the data excluding the SDWIS data.

SDWIS has excellent temporal distribution and resolution, having several hundred repeated samples in several instances, sometimes on a near monthly interval. Having over 70,000 data points for nitrate, SDWIS masks the other compiled data. Data collection years for nitrate data from SDWIS range from 1977 to 2012. The most advantageous temporal aspect of SDWIS data is that they have multiple samples at the same location, allowing for excellent temporal comparison of the same groundwater aquifer.

Spatial Data Distribution

Good spatial coverage is defined by datasets that have even geographic distribution throughout the state, without large areas lacking data. High spatial resolution means that the points are located near each other. Spatial and temporal distributions limit our ability to interpolate. Although a database may have over 10,000 points, it may only have 10 points for a given year (for example, 1963), which makes interpolation for the entire state fairly meaningless.

The NWIS database covers the entire country, and has good spatial distribution for Utah (figure 13). The STORET Legacy points are relatively spatially sparse (figure 14), having highest point densities in areas of higher population density. The STORET data (figure 15) have better spatial distribution than the STORET Legacy data, likely due to contributions from the U.S. Forest Service and increasing population. Unlike most of the datasets, the STORET dataset includes good spatial coverage of areas not densely populated. The UDDW SDWIS dataset (figure 16) is limited to within Utah's boundary. Because the UDDW SDWIS points represent public drinking water sources, they are concentrated in areas of moderate to high population density. The UGS dataset (figure 17) is focused in areas of studies conducted by the Utah Geological Survey. This dataset contributes a significant amount of data from western Utah, which is sparsely populated. The UDAF dataset includes many samples from rural parts of Utah (figure 18), filling in many spatial gaps in the other datasets.

Nitrate Concentrations

The nitrate data from all of the datasets show a lognormal distribution, skewed somewhat to the left (figure 19). The left skew is likely due to nitrate detection limits, where reported nitrate data concentrations are limited by the minimum concentration detection value of a sample analysis device. Figure 20 shows a comparison of the distribution of nitrate values for the different datasets. The average and median values do not match as well as expected, varying from about 0.4 mg/L to 2 mg/L.

We created time-capable polygon shapefiles using several different interpolation techniques.The polygons change shape as the time slider is moved to show changes in nitrate concentrations. The databases we made can be adjusted for other constituents. We semi-automated the process to make future interpolations easier. We also attempted other ways to display changes over time of groundwater constituent concentrations. An alternative presentation technique is to show arrows indicating changes in sample concentrations taken at different (consecutive) times at the same location, or by following the techniques outlined by Lindsey and Rupert (2012).

Interpolation Limitation

The nitrate point data have variable point density, both spatially and temporally. In some places, like some parts of western and southern Utah, data are spatially and temporally sparse. For some years, especially before 1980, data are spatially sparse over the entire state. The interpolations do not account for depth to groundwater, annual variations in recharge, or differentiate aquifer types (such as valley fill vs. bedrock). Because of this, interpolation may be invalid for areas not having known hydrologic characteristics. To help mitigate the lack of continuity between aquifers, we created a layer that only interpolates within alluvial valleys of the state. However, even the valleys can contain separate or multiple aquifers, and interpolations in these areas should be examined carefully. Due to the limitations of the interpolations, these data should only be used to help determine general trends in nitrate concentrations over time and to help focus on areas of potential nitrate contamination.

SUMMARY

This report is the first attempt to synthesize nitrate data compiled from several agencies to show regional trends and the current status of nitrate concentration in Utah. Data were com-

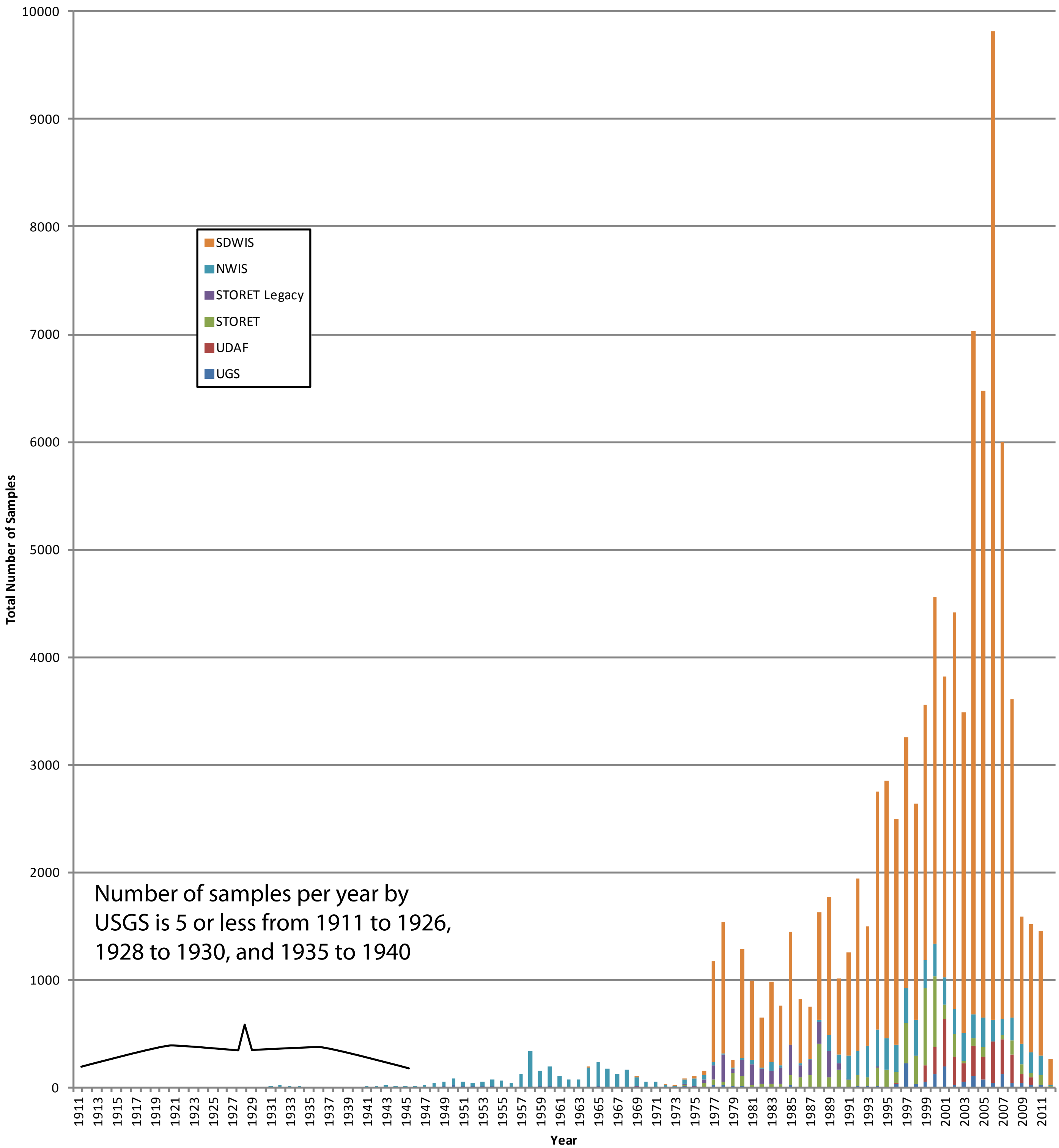

Figure 11. *Temporal distribution of all of the nitrate samples compiled for the nitrate mapping tool.*

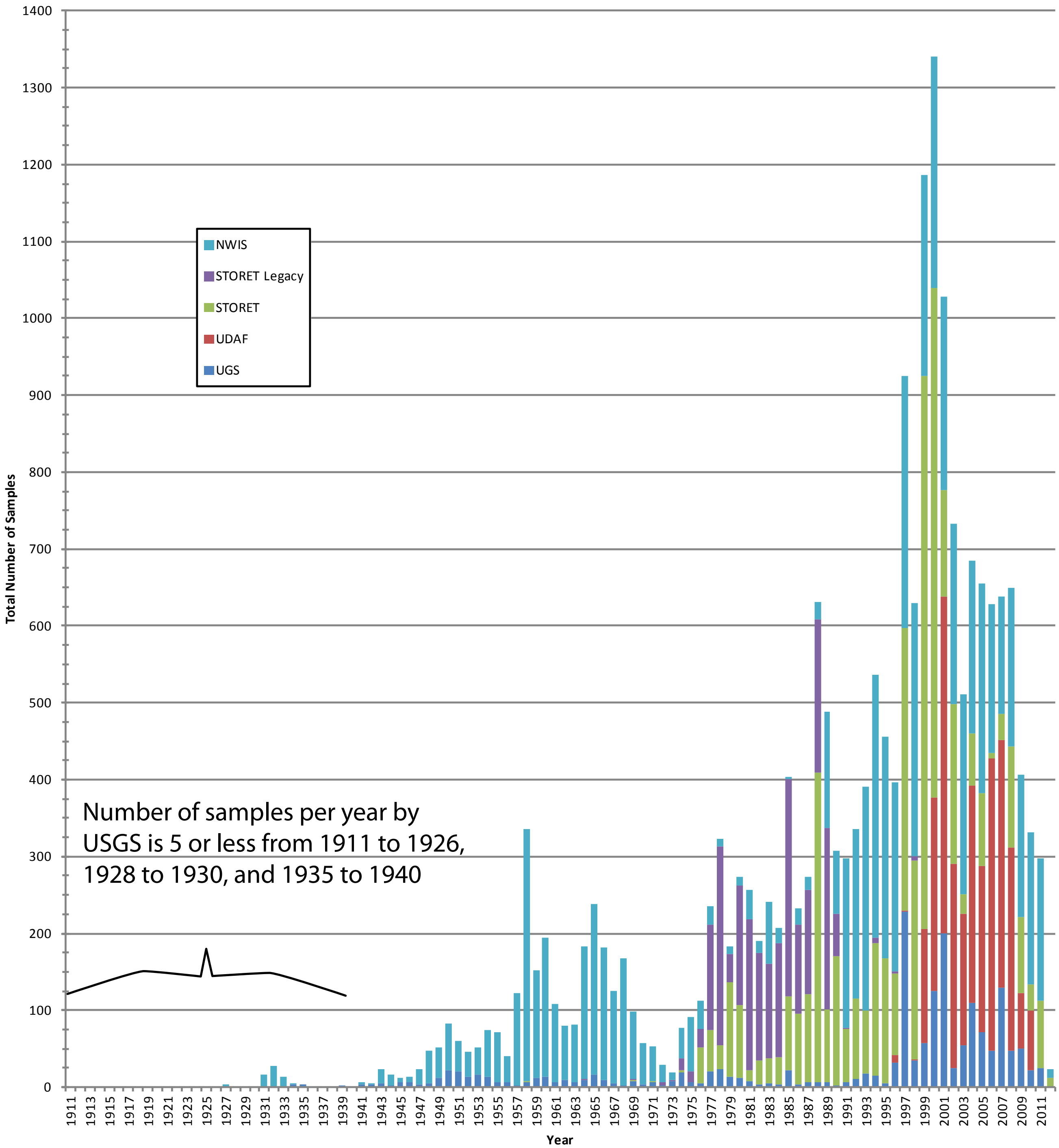

Figure 12. *Temporal distribution of nitrate samples (excluding SDWIS data) compiled for the nitrate mapping tool. See figure 16 for distribution of the data including SDWIS data. Note that NWIS samples extend back to 1911.*

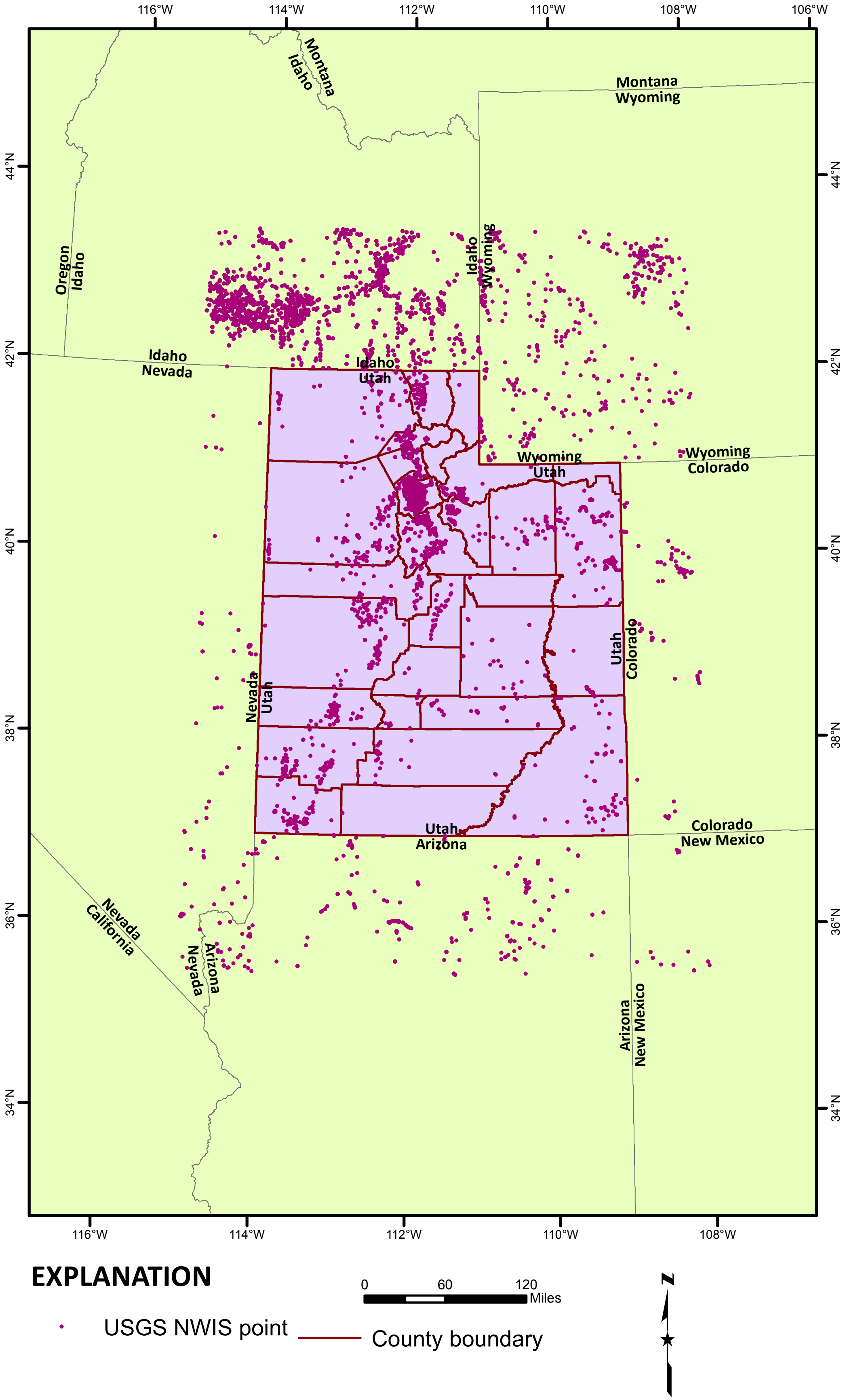

Figure 13. Spatial distribution of USGS (2012) NWIS nitrate point data. This point shapefile is the result of the NWIS pointmaker model tool presented in figure 4. The map area is the clipping area of the tool that merges all of the points.

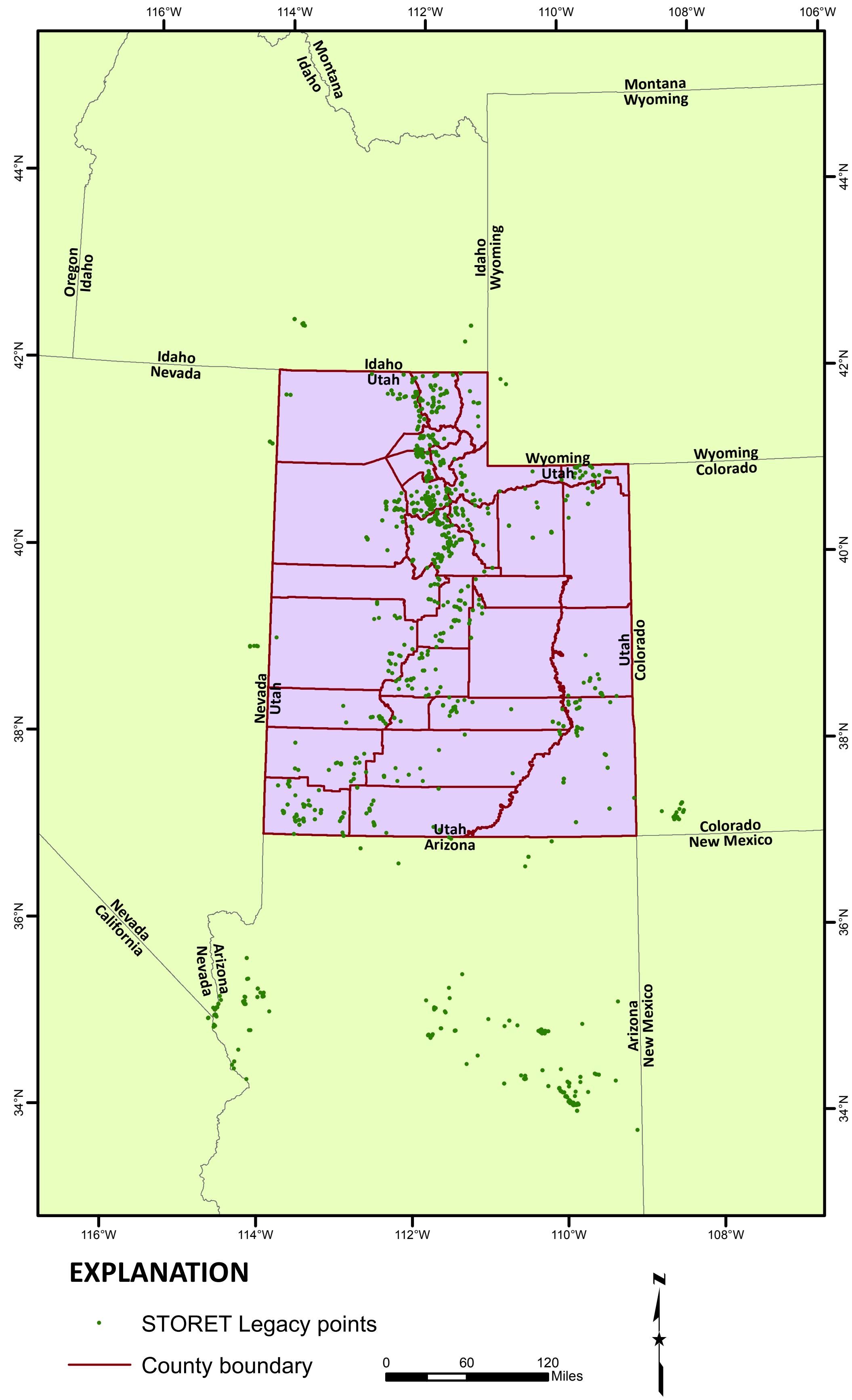

Figure 14. Spatial distribution of U.S. EPA (2012) STORET Legacy nitrate point data. This point shapefile is the result of the STORET Legacy pointmaker model tool presented in figure 3. The map area is the clipping area of the tool that merges all of the points.

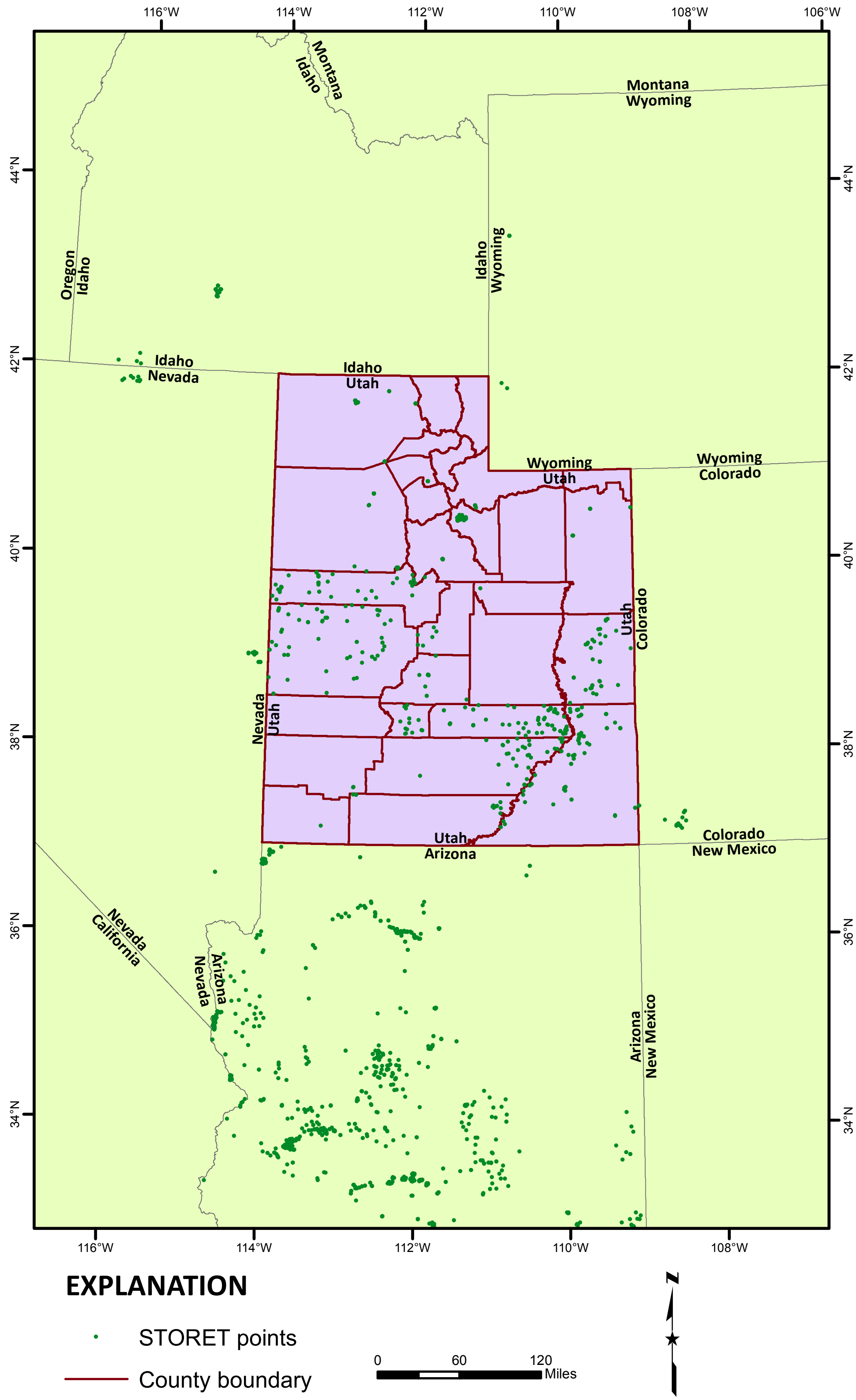

Figure 15. *Spatial distribution of U.S. EPA (2012) STORET nitrate point data. This point shapefile is the result of the STORET pointmaker model tool presented in figure 6. The map area is the clipping area of the tool that merges all of the points.*

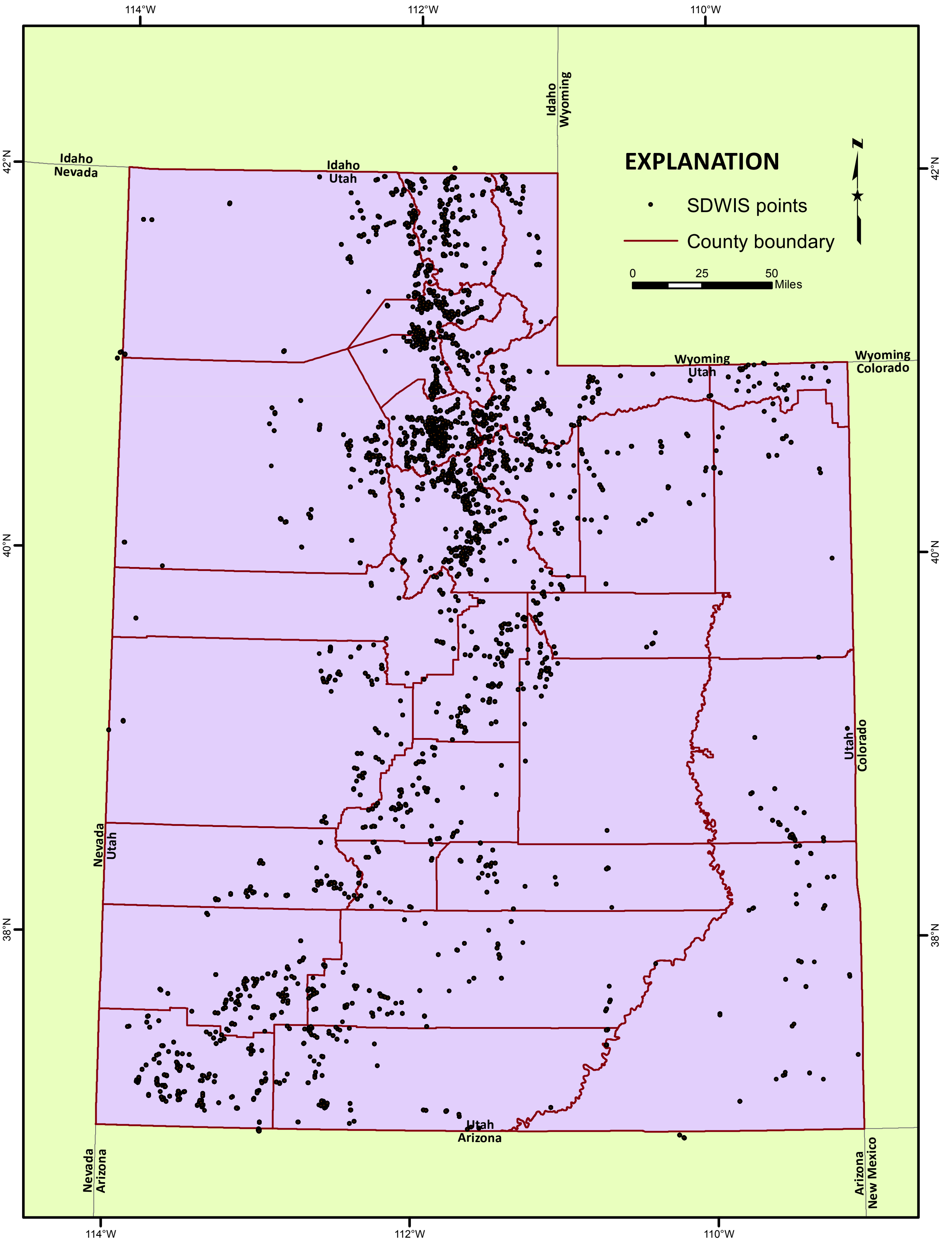

__Figure 16.__ Spatial distribution of Utah Division of Drinking Water SDWIS nitrate point data. The data are limited to within or near Utah's borders. This point shapefile is the result of the SDWIS pointmaker model tool presented in figure 5.

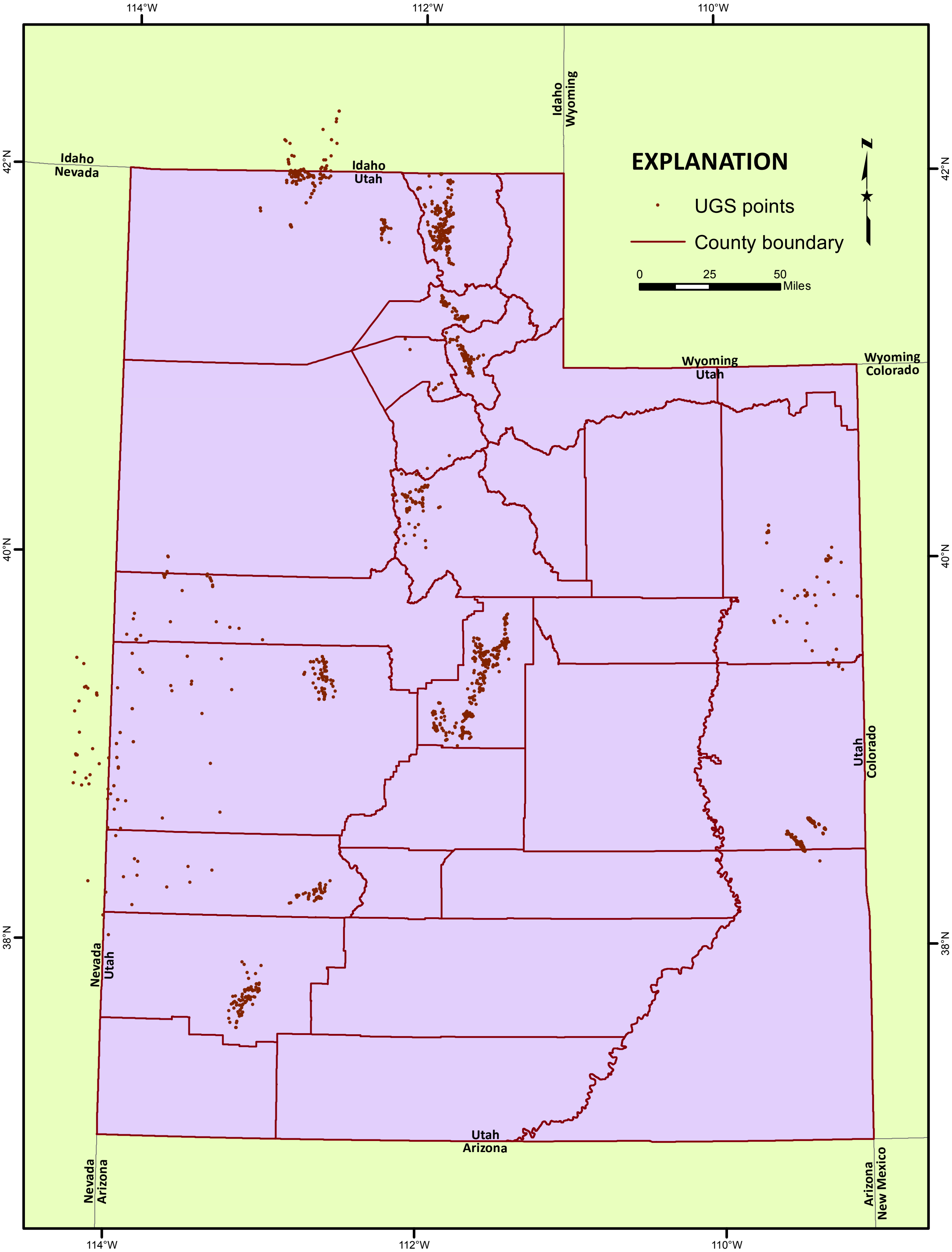

Figure 17. *Spatial distribution of Utah Geological Survey (UGS) nitrate point data. The data are limited to areas of studies conducted by the UGS near Utah's border with other states. This point shapefile is the result of the UGS pointmaker model tool presented in figure 1.*

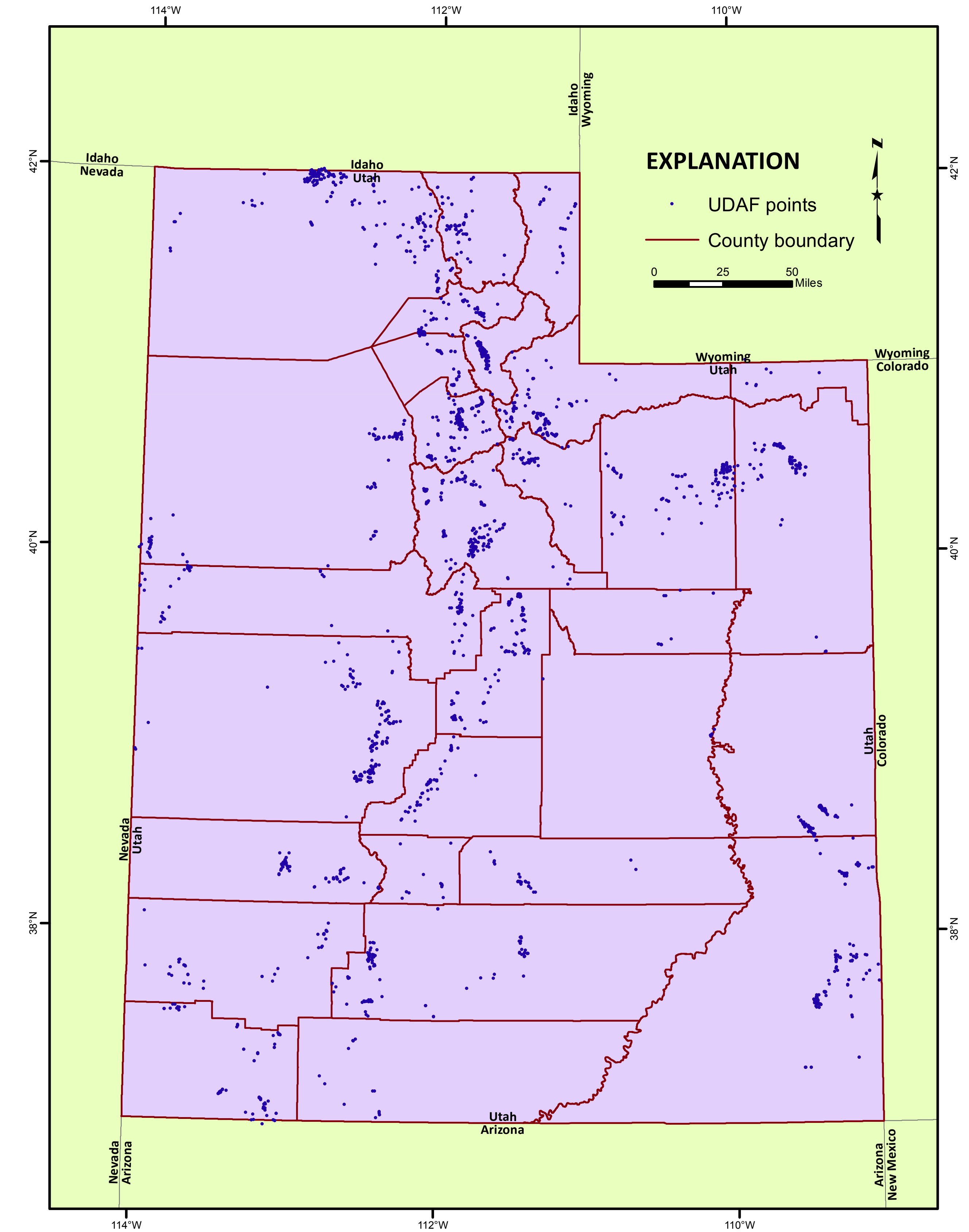

Figure 18. Spatial distribution of Utah Department of Agriculture and Food nitrate point data. The data are limited to areas very near Utah's border. This point shapefile is the result of the UDAF pointmaker model tool presented in figure 2.

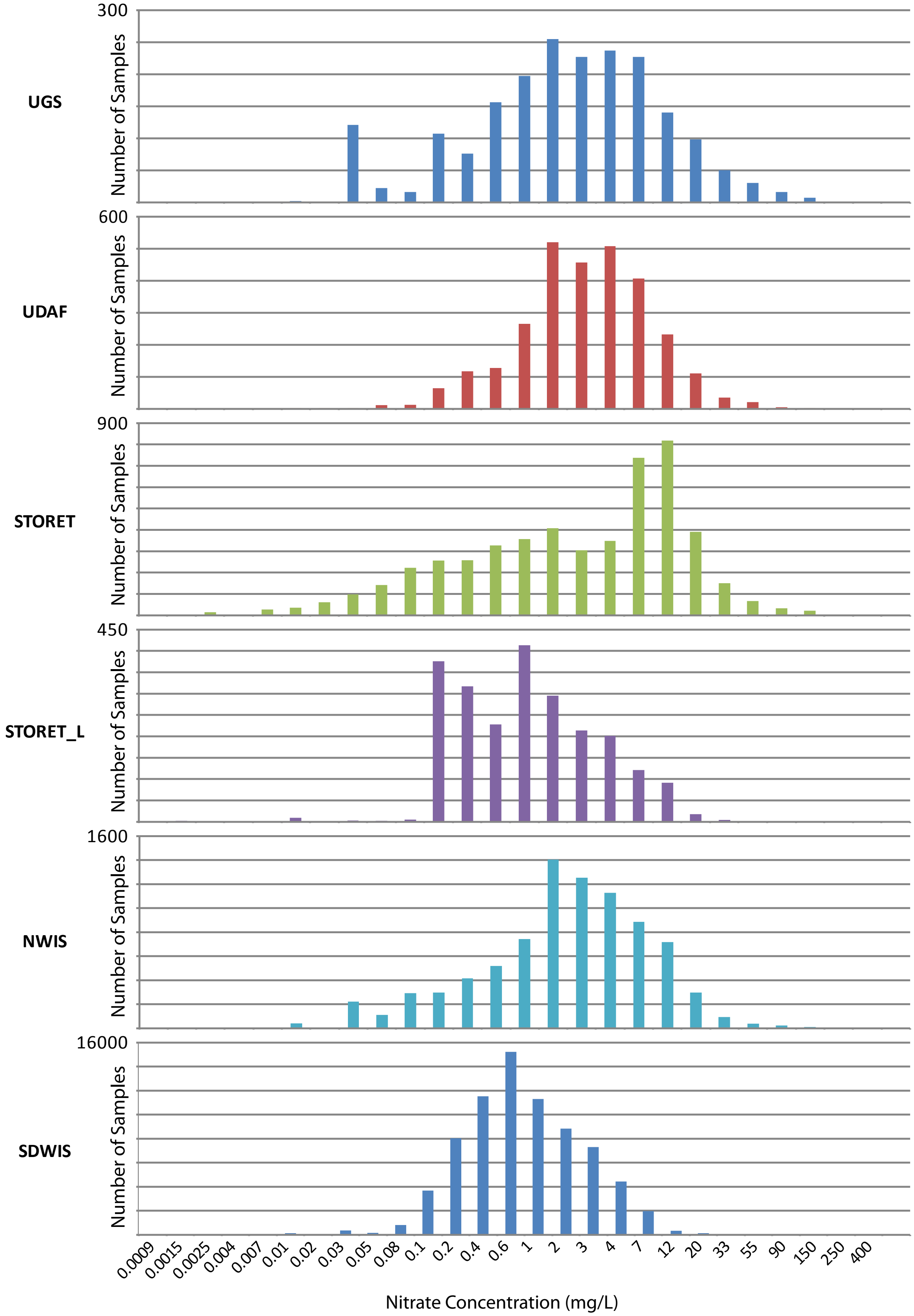

Figure 19. *Histograms of concentrations of nitrate samples for each of the databases compiled for the nitrate mapper tool. Note that the concentration bins have a natural log (ln) scale.*

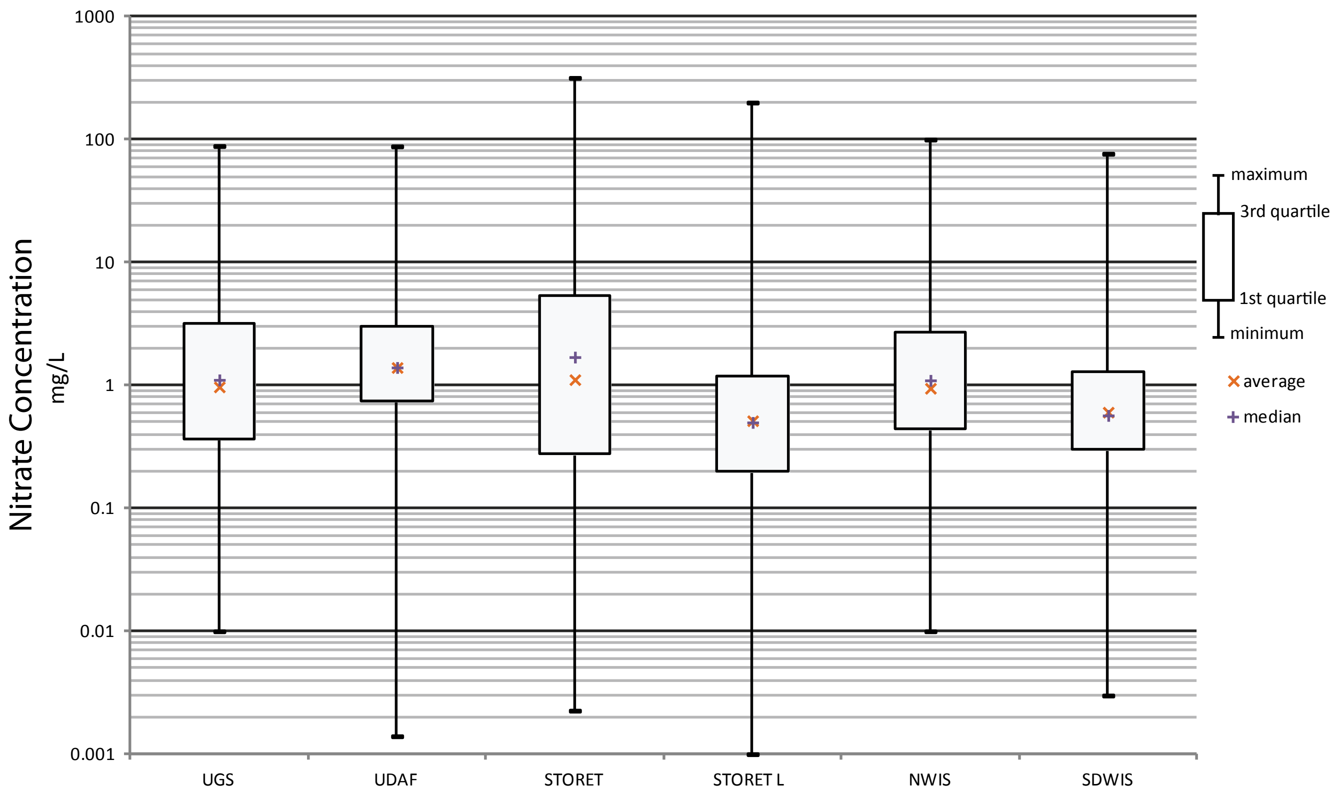

Figure 20. *Box and whisker plot of the nitrate concentrations for the datasets used for the nitrate mapper tool.*

piled from many sources including STORET, USGS, UDAF, UDDW, and the UGS. A set of ArcGIS tools was created to compile the various sources into a single point shapefile, then interpolate the points in that shapefile into a series of rasters. The tools are capable of interpolating data using a variety of techniques. The overall map product demonstrates the spatial and temporal trends in nitrate concentrations. However, limitations of the resulting interpolations include poor representation in areas having sparse data distribution. The interactive digital maps created by the tool show the most comprehensive compilation of groundwater nitrate concentrations for the State of Utah. Our goal is to continue to update and maintain the databases to incorporate other key water quality constituents.

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