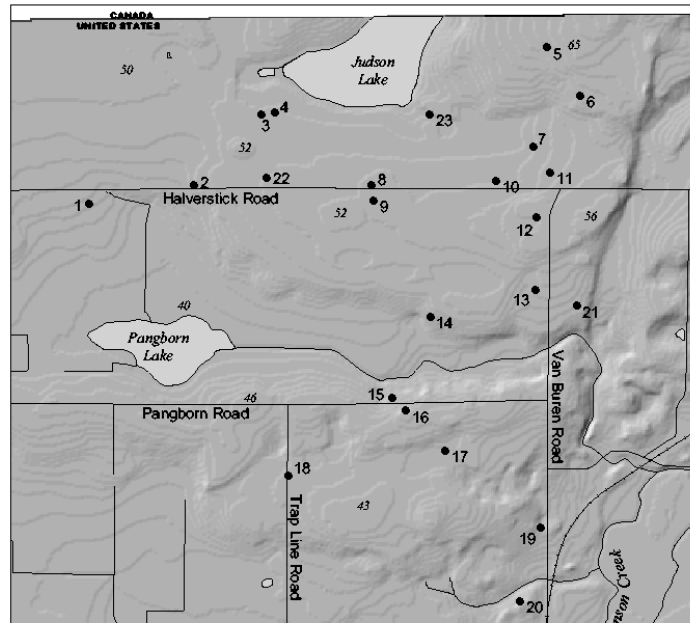


Abbotsford-Sumas Aquifer Monitoring Project Final Report



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1 Introduction

1.1 Background

The Abbotsford-Sumas aquifer is located in southwest British Columbia, Canada, and extends across the international boundary into Whatcom County in Washington State. The aquifer lies within the Fraser and Nooksack Lowlands and is comprised primarily of glacial sands and gravel deposited during the Pleistocene Epoch (East-erbrook, 1979). The aquifer occupies approximately 100 square miles and serves as a water supply for nearly 10,000 people in the U.S. and about 100,000 people in Canada. Due to extensive agricultural activity in Canada and Whatcom County, a continuing deterioration of water quality has occurred within the Abbotsford-Sumas aquifer over the past 40 years (Abbotsford/Sumas Aquifer 1996 Status Report).

Nitrate concentrations above the Canadian Drinking Water Guidelines (CDWG) and the United States Environmental Protection Agency (EPA) drinking water standards, both 10 mg/L, have been documented in the Abbotsford-Sumas aquifer (Leibsch-er et al., 1992; Gartner-Lee, 1993; Garland and Erickson, 1994). Previous ground water quality studies conducted by the Department of Ecology (Erickson, 1998), Environ-ment Canada (Wassenaar, 1995) and the U.S. Geologic Survey (Cox and Kahle, 1999) have shown that high concentrations of nitrate exist in British Columbia, just north of the border, and near Halverstick Road, south of the border in Whatcom County.

Nitrate concentrations vary considerably within the aquifer (Leibsch-er et al., 1992; Gartner-Lee, 1993; Garland and Erickson, 1994; Cox and Kahle, 1999). Exact sources of contamination and trends in concentration with time are poorly understood. Dairy farms and other agricultural activities in northern Whatcom County have been rec-ognized as contributing to the nitrate contamination of the ground water. Local agri-cultural practices may not, however, be the only sources of nitrate contamination. The direction of ground water movement in the study area is towards the southeast (Creahan, 1988; Kahle, 1990); therefore, poultry farming and agricultural practices in Canada may also be responsible for the elevated nitrate concentrations seen in the United States.

The purpose of the Abbotsford-Sumas Aquifer Monitoring Project was to determine the existing nitrate concentrations and sources of nitrate contamination in a portion of the aquifer and support community involvement by working with local schools to increase awareness of groundwater issues.

The objectives of the Abbotsford-Sumas Aquifer Project were to:

1. Monitor selected chemical constituents in a portion of the Abbotsford-Sumas aquifer (Figure 1, page 41) in order to establish temporal and spatial trends for nitrate concentrations.
2. Assess the relationship between ground water nitrogen, surface land use and hydrostratigraphy and the impact of agricultural management practices on ground water quality.
3. Develop a Geographical Information System (GIS) database of land use, soil, surface water, and ground water data.
4. Support community involvement by working with local high schools to develop research projects, establish a homepage on the Internet, and organize community information programs for student presentations.

Community Involvement: One of the objectives of this project was to educate the public about nitrate in drinking water and to support community involvement by establishing a research partnership with science students in local schools. To accomplish this, high school teachers David Tucker, at Mt. Baker High School and Donald McQuarrie, at Lynden High School, developed and managed projects for students in advanced science courses that involved the acquisition, analytical laboratory measurement, and interpretation of nitrate data from waters in Whatcom County. This active learning experience allowed students to bridge classroom theory and environmental concepts with field experiments designed for actual research. Furthermore, the students had a legitimate stake in addressing a community problem, which motivated them about the research and its outcomes.

Advanced chemistry students at Lynden High School focused on nitrate contamination in Bertrand Creek, which is located in the Nooksack River watershed in Whatcom County. The students, on a bi-weekly basis, sampled several sites along a reach on Bertrand Creek. The students were exposed to real scientific research and had the opportunity to experiment with secondary-level analysis tools such as a nitrate analysis kit distributed by Global Rivers Environmental Education Network (GREEN) and a Vernier Software colorimeter.

David Tucker managed two nitrate projects in his biochemistry class at Mt. Baker High School. In one project, students investigated nitrate contamination in several lakes in Whatcom County. After field sampling and laboratory analysis, the students compared nitrate values from the lakes, which allowed them to realize the impacts of localized sources, seasonality, and discover how lakes communicate with ground water. In a second project, students measured nitrate concentrations of duplicates of some

of the same water samples collected by the Western Washington University (WWU) research team working on the Abbotsford-Sumas Aquifer Project. In addition to learning about spatial distributions of nitrates in Whatcom County, the students developed an understanding of quality assurance by comparing their results with those from the Water Quality Lab at WWU.

The students involved in the projects at Mt. Baker High School also shared the exciting experience of presenting their research results at a poster session at the annual open house at the Institute for Watershed Studies at WWU. The acknowledgment of their efforts by professors, laboratory staff, and community visitors at the open house was a proud moment for the students. And, after interacting with faculty and staff and visiting WWU laboratories, the students left energized about learning more science.

Students at Nooksack Valley Middle School, under the direction of Joyce Perkins, analyzed drinking water samples from their homes. Using test strips, pH and nitrate were determined and compared with existing standards for water quality. The students were enthusiastic about designing their own water quality analysis program and had requests to do additional analyses from friends and neighbors.

In addition to preparing final project reports, the students at both Lynden and Mt. Baker High Schools developed web sites. The web sites allow the students to share their nitrate projects with members of the community and with students investigating nitrate contaminated waters in similar agricultural settings in other community high schools across the country. The web site addresses are:

http://www.lynden.wednet.edu/community/Bertrand_Creek/index.html.

http://www.mtbaker.wednet.edu/science/biochem_index.htm.

2 Study Area Description

The study area for this project consisted of approximately 4 square miles in Northern Whatcom County, west of the city of Sumas and bordering on Canada (See Figure 1, 41). The township Sections and Ranges include: T41N, Sec. 36, R3E; T41N, Sec. 31, R4E; T40N, Sec. 1 & 12, R3E and T40N, Sec. 6 & 7, R4E.

2.1 Climate

The temperate climate in the Abbotsford-Sumas area is influenced by Pacific maritime air and the Cascade and Rocky Mountains, which prevent cold air masses from moving into western Washington. The average summer temperature is 61° F and the average

winter temperature is 38° F. Extreme temperatures may occur during the summer or winter due to the intrusion of continental air masses from the east. Seventy percent of the annual rainfall occurs from October to March. During the summer, rainfall is light, so crops actively growing during this period may need irrigation. Snow is uncommon in the study area, averaging ≤ 2 days with ≥ 1 inch of snow on the ground (Goldin, 1992).

The average monthly temperature¹ and precipitation values for the sampling period were plotted along with 30-year averages (Figures 2 and 3, pages 42 and 43). The 30-year average precipitation was 45.8 inches. The 1997 and 1998 precipitation totals were higher than average, measuring 61.4 and 46.2 inches, respectively. The 30-year average temperature was 49.8° F, which was cooler than the 1997 and 1998 averages (51.7 and 52.0° F, respectively).

2.2 Topography

The gently rolling (hummocky) topography within the study area is typical of a glaciated terrain. The regional land surface slopes southward from a maximum elevation of about 200 ft above average sea level (ASL) near the Canadian border to an elevation of about 60 ft ASL in the southeast corner of the study area (Figure 4, page 44). Associated with the hummocks are a number of depressions that characterize the lakes, bogs, and wetlands. These depressions range in elevation from about 150 ft ASL (Judson Lake) to as low as 60 ft ASL in the southeast portion of the study area. Pangborn Bog and Pangborn Creek typify a regional low within the middle of the study area of about 130 ft ASL.

2.3 Geologic History

The Sumas-Abbotsford Aquifer lies within the Fraser and Nooksack Lowlands which is part of a major structural trough that has subsided repeatedly since late Cretaceous time (Halstead, 1986). The same tectonic activities responsible for this subsidence also produced the Coast and Cascade Mountain Ranges, which have undergone continuous weathering and erosion supplying enormous quantities of sediment to the Fraser and Nooksack Lowlands. These sediments were deposited along with plant and organic matter in fluvial, glacial and marine environments. Post-depositional lithification and consolidation of these sediments produced sandstones, siltstones, mudstones, shales, conglomerates, and hydrocarbon deposits including coal. Post-depositional deformation resulted in folding and faulting of the sedimentary rock units, producing

¹Climate data were obtained from the National Climatic Data Center's Clearbrook COOP gauging station in Washington State, latitude 48° 58'N, longitude 122° 20'W. Historical climate data were compiled from the Western Regional Climate Center.

an irregular bedrock surface topography (Cox and Kahle, 1999). The Lowland was repeatedly invaded by glaciers during the Pleistocene Epoch which further shaped the topography prior to depositing thick variable sequences of both glacial and nonglacial sediments. These comprise some of the most productive aquifers in this region. Test drilling for coal and gas, and geophysical surveys indicate that bedrock is beneath 1,000 to 2,000 ft of Pleistocene deposits throughout much of the Fraser-Nooksack Lowlands (Cox and Kahle, 1999). However, one well log located less than 3 miles north of the Canada - U.S border (north end of the study area), encountered bedrock at approximately 400 ft below land surface (Halstead, 1986).

Little is known about the oldest and deepest deposits in the study area because they are relatively inaccessible due to depth. The recent deposits of the last major glaciation known as the Fraser Glaciation, have been relatively well characterized (Figure 5, page 45). The Fraser Glaciation began approximately 20,000 years ago and had a 10,000-year duration (Easterbrook and Hansen, 1974). Three phases, or stades, have been defined, each representing a different time period during the advance and retreat of glacial ice. The first stade, known as the Evans Creek Stade, was the advance of alpine glaciers in the North Cascades and did not affect the study area.

The Vashon Stade (20,000 to 13,000 years ago) was the second stade which began with the advance of glacial ice southward across the Canada - U.S. border. Meltwater streams from the advancing glacial ice deposited outwash sand and gravel south of the glacier terminus. Outwash deposits were soon covered with glacial till (Vashon till) as the ice thickened and moved farther southward. Vashon till is usually a compact, poorly sorted mixture of clay, silt, sand, pebbles, cobbles, and boulders which has a texture somewhat resembling concrete (Easterbrook, 1979). The ice responsible for depositing the Vashon till is believed to have been more than a mile thick in the vicinity of Bellingham, WA (Easterbrook, 1979).

The Everson Interstade followed the Vashon Stade and began approximately 13,500 years ago when the massive ice sheet retreated and thinned in response to global climate changes. Relative sea level at that time was several hundred feet higher than at present due to a depressed land surface caused by the overlying weight of glacial ice and the large influx of water from melting glaciers. The continental ice was buoyed up by rising sea water levels and floated as the ice continued to thin and retreat. As the ice melted, an unsorted mixture of clay, silt, sand, and gravel fell to the sea floor burying clams and various other mollusks creating a deposit resembling glacial till with shells, known as glaciomarine drift. In the Nooksack Lowland and in the region westward to Bellingham, the Everson Interstade is represented by two glaciomarine units separated by fluvial sand and peat. Elsewhere, a single glaciomarine unit (Bellingham Drift) represents the Everson Interstade. According to Easterbrook (1976), the Kulshan Drift consists of an unsorted, blue-gray mixture of silt, clay, sand, and pebbles. The Deming Sand overlies the Kulshan Drift and generally consists of stratified,

brown, well sorted, medium to coarse sand deposited on flood plains and beaches when sea level dropped relative to land surface. The Bellingham Drift overlies the Deming Sand and consists of blue-grey, unsorted, pebbly, sandy silt and pebbly clay.

The Sumas Stade (10,000 to 11,000 years ago) represented the last phase of Pleistocene glaciation in the area. During that time, the main glacial terminus was just north of the present-day international border with a lobe extending south into Whatcom County Washington, near Sumas. Three Sumas Stade units were identified by Easterbrook (1976) including till and ice contact deposits, outwash sand and gravel, and silt and clay sediments. Glacial meltwaters deposited large quantities of sand and gravel forming an outwash plain sloping southward from the border to the modern Nooksack floodplain near Lynden, Washington. The sand and gravel deposits of the Sumas outwash makes up the unconfined aquifer within the study area. The outwash makes an excellent a high yield aquifer that supplies water for both residential use and irrigation. The Sumas outwash is also an important natural resource that has been and continues to be mined for sand and gravel.

2.4 Surface Water Hydrology

Surface water lakes in the study area consist of two small peat-filled depressions known as Judson Lake and Pangborn Bog (Figure 1, page 41). Both Judson Lake and Pangborn Bog occupy deep kettles surrounded by very permeable outwash sand and gravel. Judson Lake lies in the northern portion of the study area and crosses the international boundary into Canada. The Lake is approximately 32 acres in size and shallow (2-5 ft in depth). A small lake of unknown depth occupies the center of Pangborn Bog and is only visible from aerial photographs. Much of Pangborn Bog is heavily vegetated making the lake virtually inaccessible. There are two surface water streams in the study area: a small perennial stream that originates in Canada and flows into the west side of Judson Lake; and Pangborn Creek, which flows year round from the east side of Pangborn Lake. Two small springs feed Pangborn Bog from the north and west as well as several man made drainage ditches to the north and east. Pangborn Creek is the only source of surface water drainage in the study area as there is no outflow stream associated with Judson Lake. Because of the hummocky, glaciated topography in the study area there are numerous wetlands. The wetlands, as classified by the national wetlands inventory, are shown in Figure 6 (page 46).

2.5 Soils

The soil survey of Whatcom County Area, Washington (1992) outlines the soil types within the study area (Figure 7, page 47). The soils are, in general, poorly developed and thin. Silt loam and gravelly loam soils are the most productive and widespread

soils in the study area. These soils are primarily used for growing raspberries with some areas used as pasture for dairy cows and for spreading manure. The silt loams formed in a mixture of loess and volcanic ash over glacial outwash; therefore, the substratum of this unit is very gravelly to extremely gravelly. Permeability is moderate in the upper portions of this unit and very high in the substratum. Pangborn muck is also an abundant soil type located within the study area. This is a very deep, very poorly drained soil formed in depressions on outwash terraces and in abandoned outwash channels. It has moderate permeability and has been artificially drained. Open drainage ditches are commonly used to drain the Pangborn muck.

2.6 Land Use

The land use in the study area was divided into 17 distinct land use codes. These included: blueberries, cemetery, corn silage, dairy, flowers, forest, gravel pits, hazelnuts, house/building, no farm use, other crops, pasture, poultry barn, ranch, raspberries, cabbage in 1997 or rhubarb in 1998, and surface water. The map in Figure 8 (page 48) was created by comparing field observations performed in October 1997 and August 1998 to a digital parceled County land-use base map. In many cases the actual land use did not correspond with the County land-use code. In those instances the land use observed in the field was identified and recorded on the map as the current land use. The major change in land use between 1997 and 1998 was a decrease in the number of raspberry fields and an increase in the number of fields used for corn silage, especially north of Halverstick road. The total study area included 9,624,647 m² (4 mi²). Of that, 2,691,552 m² (28%) was designated as berry fields and 1,780,256 m² (18.5%) was designated dairy/cattle. In 1997 61% of the land use in the study area was comprised of berry fields, dairy and pasture lands. In 1998 only 57% of the study area was comprised of berry field, dairy and pasture lands. There was a 1.5% increase in cornfields between 1997 and 1998. Five percent of the land in the study area was surface water. The total number of cows in the study area reported by the Whatcom County Conservation District in 1995 was 2141 (see Figure 9, page 49). More than 50% of the reported number of cows were from a single dairy on Halverstick Road. Table 1 (page 32) shows the predominant land use 100 m, 500 m, and 1000 m up gradient from each sampling well. The majority of the wells selected for this study were located down-gradient from berry fields and dairies.

2.7 Ground Water Nitrogen Cycle

Nitrates can enter the ground water system by natural or anthropogenic sources. Natural sources include soil nitrogen, nitrogen rich geologic deposits and atmospheric deposition. Anthropogenic sources include fertilizers, farm animal manure, septic

tank drainage, and leaching of the soil due to irrigation (Madison and Brunett, 1985).

When nitrates enter the soil, a number of hydrologic, chemical or biological processes take place to convert nitrogen into nitrate, nitrite, ammonia, N_2 gas, or nitrous oxide. This process is called the nitrogen cycle and includes five stages (Canter, 1997):

1. **Nitrogen fixation**, which is the process of combining gaseous nitrogen, by aerobic or anaerobic bacterial conversion, into ammonium that can be used by plants and animals;
2. **Ammonification**, or the altering of organic nitrogen into ammonia during the decomposition of plants, animals and animal fecal matter;
3. **Assimilation**, a biochemical process that uses ammonium or nitrate to form nitrogen-containing compounds;
4. **Nitrification**, which is the biologically mediated oxidation of ammonium ions into nitrite and nitrate; and
5. **Denitrification**, which occurs when bacteria respire anaerobically and convert nitrate into nitrite, and possibly into nitrous oxide, nitrogen dioxide and finally nitrogen gas.

A decrease in nitrate concentrations in ground water may result from dilution, denitrification, or assimilatory reduction to ammonia or ammonium. The assimilation process of transforming nitrate or ammonium into organic nitrogen is reversible, the organic nitrogen can later be transformed back into nitrate. As a result, assimilation alone will not cause significant, long-term increases or decreases in nitrate concentrations in the soil. Denitrification is the only mechanism that results in a significant, long-term reduction of nitrate concentrations because the reactants are unlikely to be transferred back into nitrate (Wassenaar, 1995). The environmental conditions necessary for denitrification to occur include availability of organic carbon, the presence of denitrifying bacteria, and reducing (anoxic) conditions (Starr and Gillham, 1993).

3 Methods

3.1 Field Sampling

Twenty domestic wells were sampled monthly from April 1997 to January 1999 (Figure 1, Wells 1–5 and 7–21). Six additional domestic wells (Wells 6, 22, 23, 24, 26, and

27²) were sampled intermittently during this time period. Well 16 was replaced by a deeper well, Well 28, in August, 1998. Exact well addresses, elevations, and GPS locations are shown in Appendix A.

The static water level (depth to water) was measured at accessible wells, using a depth-to-water meter with an electrical sounding tape before any water was removed from the well. The well was then purged at the standpipe for approximately 10 minutes, or until the conductivity stabilized, in order to remove any stagnant water.

Ground water parameters were then measured through a one-liter flow-through cell in order to get a representative ground water sample. Dissolved oxygen, temperature and conductivity were measured using the YSI model 85 water analyzer. Dissolved oxygen was calibrated to the nearest 100 ft in elevation. Temperature and pH were measured using a calibrated Orion 250A meter. A pH standard of 6 was checked at each well to assure that the meter was working properly.

Ground water samples were taken directly from the flow-through cell. Two water samples were collected from each well sampled. One sample was collected using a 500 ml acid washed Nalgene bottle, to be analyzed in the lab for total nitrogen, nitrate+nitrite³, nitrite, and ammonia. The second sample was collected in a 250 ml plastic Nalgene bottle to be analyzed for chloride. All bottles were rinsed three times with the sample prior to collection and then placed in an iced cooler for transport. Nitrite lab tests were conducted within 48 hours of sampling. Nitrate + nitrite and total nitrogen samples were frozen and ammonia was acidified and were analyzed in the lab within 30 days of sampling. Field notes in Appendix B include observations of fertilization and irrigation events.

3.2 Analytical Methods

The methods for each chemical analysis are summarized in Table 3 (page 34). All parameters were analyzed by the Institute for Watershed Studies (IWS), which is accredited by the Washington State Department of Ecology. All water quality data are listed in Appendix C.

Limits of detection for ammonia nitrogen, nitrate+nitrite nitrogen, nitrite nitrogen, and total nitrogen were estimated using blanks or low concentration standards in the following formulas:

$$s_{wb} = \frac{\sqrt{\sum d_i^2}}{2m}$$

²Well 27 was sampled only once, and was not included in the data analysis for this report; Well 25 was never sampled.

³Nitrate+nitrite will normally be referred to as “nitrate” in the text.

$$LD = 2.83 \times t_{0.1, n} \times s_{wb}$$

$$CD = 1.41 \times t_{0.1, n} \times s_{wb}$$

where:

s_{wb} = the estimated within batch standard deviation of the blank,

d_i = the difference between the two blanks run during one batch,

m = number of duplicate blank determinations or batches,

LD = limit of detection,

CD = criteria of detection, and

$t_{0.1, n}$ = the 2-sided 10% t statistic (n = # pairs of duplicates).

If the calculated concentration was less than the criteria of detection, then the value was reported as less than the limit of detection for that analyte. If the calculated concentration was located between the criteria and the limit of detection, then the calculated value was reported. For example, if the criteria of detection was 10 mg/L and the limit of detection was 20 mg/L for an analyte, then a calculated value of 9 mg/L would have been reported as <20 mg/L, while a calculated value of 15 mg/L would have been reported as 15 mg/L.

3.3 Quality Control

The IWS laboratory is accredited through the Washington State Department of Ecology. The student staff are trained and supervised by IWS staff using standard operating procedures that describe the applicable methods. The student staff analyzed double-blind performance evaluation samples semi-annually during this project with acceptable results.

To assure accuracy of the analytical results, the following procedures were used to help assess the quality of the data being produced.

1. At least 5% of all samples collected in the field were field duplicates in order to test the precision associated with sample collection.
2. In the laboratory, 10% of the samples were analyzed in duplicate and the results used to check for errors associated with analytical procedures.
3. Two internal check standards (20% and 80% of the calibration curve) were analyzed with each analytical run for nutrients. The results were used to verify that analytical precision and calibration bias was acceptable using control charts.

Check Standards: The purpose of analyzing check standards was to verify the accuracy of the calibration standards. The data from the check standards for ammonia, nitrate+nitrite, nitrite, total nitrogen, and chloride were entered into control

charts. The control limits were established by calculating the standard deviation of the 20 previous data pairs and multiplying that number by three. These charts were updated using the most recent data.

The control limits are listed in Table 4 (page 35) for two check standards at approximately 20% and 80% of the analytical range for the method. After establishing the limits, each subsequent check standard result was compared to the limits to verify that the analytical run was producing data in a similar range of accuracy. When check standards fell outside the region, the samples were re-analyzed when possible. If re-analyzing the samples was not possible, then the laboratory manager decided whether to accept the results, depending upon the distance of the excursion and comparison to other quality control measures such as blanks, spikes, laboratory duplicates, and the other check standard.

Duplicate Laboratory Analyses: Duplicate laboratory analyses check the precision of the analytical method. The 10% duplicate laboratory analyses were analyzed for all laboratory parameters. The control chart limits were established in the same manner as for the internal check standards. Duplicate laboratory analyses were compared to the control chart limits to identify analytical problems. The control chart limits were calculated by multiplying the standard deviation for 20 previous sample pairs by three. Table 5 (page 36) lists the control chart limits that were set for each analyte.

Field Replicates: To assess the precision associated with sample collection, relative standard deviations were calculated for the field replicates. Table 6 (page 37) lists the standard deviations of the field replicates for samples collected monthly. Standard deviation was not calculated for ammonia and nitrite data because most of the data were below detection. Appendix D shows the field replicate data.

4 Water Quality Results

4.1 Nitrogen compounds:

The total nitrogen and nitrate+nitrite results were very similar (Figures 11 and 12, pages 51 and 52). The similarity between total nitrogen and nitrate+nitrite was expected because total nitrogen is predominantly nitrate in most aerobic environments. The median concentrations of total nitrogen and nitrate+nitrite concentrations were higher than the 10 mg/L drinking water standard in about half of the wells tested. Very high concentrations were measured in Wells 14, 18, and 24. There was an

unusually wide range of concentrations in Wells 9, 14, 18, and 24.

Ammonia and nitrite concentrations were often lower than their detection limits of 21 $\mu\text{g-N/L}$ and 6 $\mu\text{g-N/L}$, respectively (Figures 13 and 14, pages 53 and 54). Notable exceptions include Wells 5, 11, 12, 24, and 28, which had unusually high concentrations of ammonia on more than one sampling date, and the high nitrite concentrations at Well 28.

Nitrite concentrations were usually below the detection limit of 0.9 $\mu\text{g-N/L}$ (Figure 14, page 54). The nitrite distribution is skewed due to the higher concentrations found in Well 28 and several other outliers and the numerous undetectable concentrations.

4.2 Chloride:

The chloride concentrations were fairly low ($<10 \text{ mg/L}$) at most sites (Figure 15, page 55). Well 21 had noticeably high concentrations, but this was probably because the water at this site had gone through a residential chlorination and filtration system to remove excess iron. High concentrations of chloride were also measured at Wells, 5, 9, 14, and 26. These higher concentrations may have been caused by agricultural practices (chloride is frequently found with nitrates in fertilizers).

4.3 Conductivity, pH, Dissolved Oxygen and Temperature:

There was a large variation between conductivities at different wells. Median conductivities in samples at individual wells ranged from $<50 \mu\text{S/cm}$ (Well 23) to $>250 \mu\text{S/cm}$ (Wells 14 and 22). Wells that had high chloride concentrations also had high conductivities. Temperature changes, dilution from precipitation, and ions in fertilizer were also likely factors in the variation.

The pH values fell within the range of 5.0–7.5 (Figure 17, page 57). Many of the wells had pH levels lower than the EPA secondary standards for drinking water (6.5 - 8.5); however, the ranges were fairly typical for ground water.

The dissolved oxygen concentrations were highly variable at almost all sites (Figure 18, page 58). The wide range in ground water oxygen concentrations is not unusual. Low oxygen concentrations are common in ground water due to bacterial respiration. Similarly, high oxygen concentrations are common as temperatures decrease (less bacterial activity, and more oxygen dissolved in the colder water), or the ground water becomes aerated from pumping activities and the influx of aerated water.

The average air temperature of well water for the study area was 11.4°C and the median was 11.2°C (Figure 19, page 59). The temperature at Wells 17 and 19 had more extremely cold and warm temperatures. Because the water elevation at Well

19 is closer to the surface, a greater fluctuation in temperature would be expected. However, the water elevations at Well 17 were similar to other wells that had smaller temperature ranges. The extreme temperatures at this site may be the result of permeability and flow conditions.

5 Hydrogeology

5.1 Geologic Units

Information from approximately 50 drillers' well logs and outcrops from two gravel pits were used to characterize the geologic stratigraphy in the study area. Synthesis of this information allowed for the identification of six geologic units. Descriptive names for these units are the same as those used by Easterbrook (1979). These units are discussed below and are shown in the cross sections in Figures 20–24 (pages 60–64).

Sumas Outwash Gravel and Sand: The primary geologic unit within the study area is the Sumas Outwash, consisting of fine to coarse gravel with varying amounts of sand, pebbles, cobbles, and boulders (in some locations). The outwash is identified as “Sand and Gravel” in the cross sections (Figures 20–24). Six samples of the Sumas Outwash were collected and sieved to determine average grain-size distribution (Figure 25). Results from the analyses of the six samples yielded the following average values: 5.4% cobbles, 67.8% gravel, 26.1% sand, and 0.72% silt and clay.

Sumas Outwash Sand: Distributed throughout the Sumas outwash are numerous sand lenses. The majority of the sand lenses are on the order of 5 to 20 ft thick. However, one larger sand lens, approximately 40 ft thick, was located in the southwest portion of the study area (Figure 23). Two samples from a sand lens representative of the outwash were extracted from the gravel pit south of Pangborn Road and sieved to determine the grain-size distribution. The sample was identified as a fine sand having the following grain-size distribution: 5.2% sand, 86.4% fine sand, and 8.4% silt and clay.

Ice Contact Deposits: A different assemblage of lenses of sand, gravel, and clay or silt and were identified near the eastern margin of the study area. These deposits are interpreted as ice contact deposits and coincide with the general location of the Sumas ice margin as interpreted by Easterbrook (1979). Most of these ice-contact sand, gravel, and clay lenses within the study area range from a few feet to 10 or 15 ft in thickness with the exception of two thick lenses along the eastern boundary of the

study area averaging 65 ft in thickness (Figures 20, 23, and 24). A sample of what appeared to be a silty clay, representative of an ice-contact deposit, was collected from the base of the gravel pit south of Pangborn Road and sieved to determine a grain-size distribution. The sample contained 9.0% fine gravel (rounded to sub-rounded), 40.3% sand (3.4% coarse, 7.7% medium, and 29.2% fine), and 50.8% silt and clay.

Peat Deposits: Peat is found within the study area in and around Pangborn Lake and Judson Lake (Figure 20, 21, and 22). Core samples of peat in and around Pangborn Lake were taken by Riggs (1958) and Easterbrook (1999). The peat ranges from a few feet thick on the fringes of the bog, which occupies an area much larger than the current lake, to over 30 ft thick closer to the center of the lake (Riggs, 1958). The peat around Judson Lake is not as extensive as Pangborn Bog. A core towards the western edge of the lake taken by Easterbrook (1999) found the peat to be approximately 10 ft thick. Pleistocene lake sediments consisting of blue-gray clay, silt and sand are found beneath the peat in both Pangborn Lake and Judson Lake (Riggs, 1958; Easterbrook, 1999). To date, the lake sediments beneath the peat of Pangborn and Judson lakes have not been fully penetrated and the relative depths remain unknown (Figure 22).

Glaciomarine Deposits: Two distinct glaciomarine units are thought to exist within the study area. The evidence for these units is based on drillers' well logs and literature review of glacial chronology. The oldest of these units is found 340 ft below land surface with a thickness of 20 ft in the northernmost portion of the study area. This unit may correlate to the Kulshan Drift of the Everson Interstade, which is encountered in southern areas of the Nooksack Lowland. The second, younger unit was identified in the same well log, 213 ft below land surface and has an approximate thickness of 21 ft (Figure 24). This is probably the Bellingham Drift. Fine sand (116 ft) separate the two units in this well log. Possible correlations exist between the younger glaciomarine drift unit found in the northern portion of the study area and clay units encountered in the southern portion of the study area (Figures 20 and 24).

5.2 Hydrostratigraphy

Hydrogeologic units are geologic units grouped together on the basis of similar hydraulic conductivity (Fetter, 1994). The six distinct geologic units identified within the study area were grouped into two hydrogeologic units, the Sumas Aquifer and the Sumas Aquitard.

Sumas Aquifer: The Sumas Aquifer is an unconfined aquifer consisting of three hydraulically similar geologic units: the Sumas outwash gravel and sand and Sumas outwash sand lenses. In general, the Sumas Aquifer is characterized by a heterogeneous mixture of highly conductive gravel and sands. Distributed throughout the Sumas Aquifer, however, are numerous lenses of silt and clay having much lower hydraulic conductivities. These less-conductive lenses are grouped within the Sumas Aquitard material discussed below. Ground water is assumed to move freely through the hydraulically connected gravels and sands of Sumas Aquifer and around the discontinuous less-conductive lenses. The thickness of the Sumas Aquifer ranges from approximately 180 ft in the northeast portion of the study area, near the international border, to approximately 80 ft in the southeastern portion of the study area (Figure 24). Outside of the study area, the Sumas Aquifer tends to increase in thickness to the north and east. Several drillers' logs north of the study area, in Canada, indicate that outwash deposits of the Sumas Aquifer are inter-layered with at least one clay deposit of glaciomarine origin (Halstead, 1986). Based on available well log data, the Sumas Aquifer is the only source of ground water currently being used for domestic and irrigation purposes within the study area.

Sumas Aquitard: The Sumas Aquitard consists of three geologic units encountered in the study area having very low hydraulic conductivities. They include the glaciomarine drift deposits, lenses of ice contact clays with sand and gravel and or till, and lacustrine deposits. As seen in all of the cross sections (Figure 20–24), there are numerous lenses of lower conductive material that are distributed throughout the Sumas Aquifer. Because of their low hydraulic conductivities, the lenses are grouped with the Sumas Aquitard material. The lenses range between 5 and 20 ft thick. Some thicker clay lenses and or layers in excess of 30 ft are found beneath Pangborn Bog (Figure 22) in the southern portion of the study area (Figure 20) and in the eastern portion of the study area (Figure 24). The Sumas Aquitard also includes the thick, underlying layer of Bellingham Glaciomarine Drift (GMD), which is thought to form the confining unit that underlies the unconfined Sumas Aquifer. The Bellingham GMD is believed to be continuous at depth and stratigraphically connected with the Hampton Clay to the south and the stony clays described by Halstead (1986), to the north in Canada. This scenario fits the glacial chronology, which has been well documented by Easterbrook (1963; 1976; 1979) and Armstrong and Brown (1953; 1954). However, this scenario is not conclusive given the distance between drillers' well logs and lack of deep descriptive drillers' well logs.

5.3 Static Water Level/Depth Below the Water Table:

The corrected static water level was calculated by subtracting the casing height from the measured surface water level. This gives the depth of the water below ground surface. The static water levels ranged from <5 ft to nearly 70 ft, and showed considerable differences between and within sites (Figure 10, page 50). These differences were due to variations in precipitation and ground water removal for irrigation, and residential use.

The depth below the water table was calculated by subtracting the static water level from the well depth. The depth below water table levels ranged from < 1 ft to over 70 ft. Variations in the depth below the water table were due to fluctuations in the static water level.

5.4 Ground Water Flow

Water Table Contours: Monthly water level readings were taken consistently at 18 point locations in the study area (17 residential wells and one piezometer) for ground water flow analyses. The residential wells that were eliminated from the analyses, because of inconsistent measurements, were 4, 9, 13, 16, 22, 23, 24, 26, and 28 (see Figure 1, page 41). A depth-to-water meter and standard measurement techniques were used to determine water levels. Accurate elevations of well locations were surveyed to the nearest 0.01 ft using laser survey equipment from a United States Geological Survey bench mark located at the intersection of Halverstick and Holmquist roads. During field sampling periods each month, water samples and water level readings were taken over the course of two days. Therefore, whenever possible, alternating wells were measured on both days to ensure water levels did not change drastically over a 24 hour period. Water level data and well casing elevations are in Appendices A and D.

Water table contour maps were developed within the study area to aid in the determination of ground water flow directions, residence times, and to examine correlations between ground water flow and nitrate distributions. Due to the subtle changes in water levels from month to month, the monthly water level values were averaged into eight seasonal blocks (spring 1997 to winter 1999). Spring includes March, April, and May; summer includes June, July, and August; fall includes September, October, and November; and winter includes December, January, and February. Sampling began in April of 1997, so the spring season data set of 1997 consists only of April and May. Sampling ended in January of 1999. Therefore, winter 1999 season data set consists of December, 1998 and January, 1999. Water table contours were generated using the seasonal water level averages at the 18 point locations in the study area and a geostatistical gridding method known as kriging within Surfer software version 6.0,

Golden Software. Given that the 18 wells used in the analyses had variable well-screen depths and, in some cases, large lateral distances between them, the water table contours depict an approximate surface. The eight water table maps representing the seasonal averages are given in Figures 26–33 (pages 66–73). The maps indicate a general ground water flow direction from the northwest to the southeast, with a steeper gradient in the southeast corner. The water table did not change dramatically throughout the duration of the study.

To examine seasonal water table fluctuations, water table profiles were generated along a Northwest-Southeast diagonal traverse through the study area (Figure 34, page 74). Profiles representing four seasonal extremes are shown in Figure 35 (page 75). Note that the profiles in Figure 35 start at Well 3, not the Canadian border. Water table levels along this traverse were highest during the fall of 1997 and the spring of 1998. Water table levels were lowest during the winter of 1998 and winter of 1999. The winter lows may indicate that it may take weeks for the water table to respond to the fall and early winter precipitation. The largest difference in water table heights occur in the southeast portion of the traverse. This is believed to be caused by topography and heavy irrigation during the summer and fall months.

Ground Water Flow Velocities and Residence Times: Average linear ground water flow velocity represents the average rate at which ground water moves along a flow path. The quantity is important because it can be used to estimate the residence time of nitrate in a parcel of water as it migrates the distance of a flow path between two points. To examine the travel times of nitrates in the study area, an average linear ground water velocity and residence time was estimated along the Northwest-Southeast traverse (starting at Well 3) using the average of the four seasonal extremes in Figure 35. The average linear ground water velocity is estimated by dividing the Darcy flux by the porosity, as follows

$$\frac{q}{n} = v = \frac{K_G}{n} \left(\frac{\Delta h}{\Delta l} \right)$$

where q is the Darcy flux, v is the average linear ground water velocity, K_G is the average hydraulic conductivity, $\frac{\Delta h}{\Delta l}$ is the hydraulic gradient, and n is the porosity.

The hydraulic gradient was approximated from Figure 35 by taking the average change in head ($\Delta h = 85$ ft) divided by the horizontal distance over which the change in head occurred ($\Delta l = 11,500$ ft). An estimate for the average hydraulic gradient along the profile was determined to be 0.0074 (Stasney, 2000). Theoretically, the hydraulic gradient should be determined using horizontal distances that are perpendicular to contours representing the head change. Therefore, given that the Northwest-Southeast traverse, as shown in Figure 35, is not always perpendicular to

the contours, the hydraulic gradient determined here is an approximation. An average hydraulic conductivity was determined using the geometric mean of hydraulic conductivities estimated from six gravel and sand samples collected within the study area. The hydraulic conductivities of the six samples were estimated from grain-size distribution data and the application of the Hazen method (Fetter, 1994). The geometric mean (K_G) was determined by Stasney (2000) to be 930 ft/day. Porosity for well-sorted sand or gravel sediments ranged from 25-50% (Fetter, 1994). An estimated porosity (n) of 35% or 0.35 was assumed to be representative of the glacial sediments. Using these values in the above equation, an average linear ground water velocity close to 20 ft/day was determined. Therefore, the residence time for a parcel of water traveling the length of the profile (11,500 ft) would be about 575 days. If nitrate is advecting along the flow path (ignoring dispersion and other transport phenomena), then the nitrate travel times will be equivalent to the ground water travel times. These values should be used with the caveat that they reflect an ideal system based on many approximations and assumptions.

Nitrate Contours: Nitrate contour maps were developed for the same seasonal blocks of time as the water table contour maps to examine nitrate spatial and temporal trends within the study area, and correlations with ground water flow. The eight seasonal contour maps (spring 1997 to winter 1999) are shown in Figures 36–43 (pages 76–83).

The nitrate contour maps were generated using the same techniques as those used to develop the water table contour maps (i.e., Surfer software). Although the contour maps provide a means by which to view the data, in some cases they do not accurately reflect nitrate plumes because of artifacts that result from contouring a limited data set with the Surfer software. The study area lacked wells along the boundaries; therefore, some contours flaired out at the boundaries due to interpolation techniques employed by the software. Another example of an unrealistic nitrate distribution is represented by the converging contours near well 18 in Figures 36–38 (pages 76–78). During the first few seasons of the study, the nitrate concentrations were anomalously high in well 18 (20–30 mg/L). Therefore, the contours were forced to converge at well 18 because of a lack of wells in the vicinity of well 18, and those wells that were in the localized region yielded lower nitrate values. The contouring around well 18 became more realistic when the nitrate concentrations dropped in the well after the first few seasons to values closer to the surrounding wells. The addition of well 26 to the sampling set aided in the contouring because it yielded concentrations similar to those produced by well 18. Well 26 is located very close to well 18 (Figure 1, page 41).

6 Water Quality, Hydrology, and Land Use Relationships

6.1 Correlation Analysis

Correlation analysis was used to identify relationships between water quality, hydrology, and land use variables. The variables measured in this study are not normally distributed, and many were categorical rather than discrete. Therefore, non-parametric statistical methods were employed. Kendall's τ correlations were used to determine the overall processes taking place in the study area. The correlation matrix for all sites combined is shown in Appendix E. Correlations with greater than a 5 percent significance level were considered to represent processes occurring in the aquifer.

Well Depth: The significant, inverse correlation between the well depth or depth below the water table and nitrate concentration (Kendall's $\tau = -0.152$ and -0.273 , respectively) may indicate that there is direct leaching of nitrates from the soil. Figures 44 and 45 (page 84 and 85) shows that in general, shallower wells have higher nitrate concentrations than deeper wells. Contamination by fertilizers can also be inferred from high conductivity values.

Denitrification: Denitrification is an anaerobic microbial process that requires the presence of nitrate and organic carbon. The residence time of infiltrating water in the unsaturated zone influences the amount of organic carbon available to support the denitrification process. In shallow unconfined aquifers with well-drained soils, organic carbon can be transported from the unsaturated zone to the ground water before oxidation occurs (Hiscock et al., 1991). In theory, static water level could be used to estimate residence time, if soil types and land use are similar (Starr and Gillham, 1993). If so, and if denitrification was a major factor in determining the species of nitrogen present in well water, we would expect a negative correlation between static water depth and nitrate. The fact that such a correlation was not evident in the Abbotsford-Sumas data (Figure 46, page 86, and Appendix E), suggests that denitrification rates are slow compared to the nitrate inputs.

Another indicator of denitrification is the chloride/nitrate ratio. Nitrates can be reduced by assimilation or by denitrification, but chloride is a conservative ion in that it cannot be metabolized (Obenhuber and Lowrance, 1991), so active denitrification should result in a negative correlation between chloride and nitrate. In the Abbotsford-Sumas data, we found a significant, positive correlation between chloride and nitrate (Kendall's $\tau = +0.306$), and a plot of the two parameters confirms that there is no reduction in nitrate in high chloride samples (Figure 47, page 87).

Denitrification is an anaerobic process (Atlas and Bartha, 1987), so a positive correlation between nitrate and oxygen would be expected. The Abbotsford-Sumas data did have a significant, positive correlation between nitrate and dissolved oxygen (Kendall's $\tau = +0.194$), but Figure 48 (page 88) shows that the data points are scattered. Dissolved oxygen concentrations were low enough in several wells to permit denitrification if the rest of the environmental conditions are being met (presence of bacteria, organic carbon, and nitrates). Denitrification is probably also occurring in anaerobic microhabitats, but these would be difficult to quantify. Low concentrations in shallow wells down gradient from peat deposits (well 4 and 15) indicated denitrification in the peat.

Precipitation: In order to relate precipitation data to nitrate concentrations, the cumulative precipitation for the 30 days before sampling was calculated (Appendix F). The data were examined initially using all sites grouped together. There was no obvious relationship between precipitation and nitrate concentrations (Figure 49, page 89). Similarly, month of the year and nitrate concentrations were not correlated (Figure 50, page 90), indicating that there was less of a seasonal effect that we had expected. A scatterplot of all nitrate concentrations over time (on a 24-month scale) shows that a small subgroup of wells had considerably higher concentrations of nitrate during the first year of sampling (Figure 51, page 91), after which, the range of nitrate concentrations measured was fairly uniform for each month. Once again, the absence of a strong seasonal pattern was unexpected.

Nitrate concentrations were plotted by month (24-month) for each well to check for site-specific, seasonal patterns (Figures 52–77, pages 92–117). Wassenaar (1995) concluded that nitrification in the Abbotsford-Sumas aquifer occurred during the summer months; in the fall and winter, nitrates would be flushed through the unsaturated zone due to high precipitation rates. This process produces low nitrate concentrations in the summer and a peak in nitrate concentrations in the fall. Fewer than half of the wells sampled in 1997–1988 followed this seasonal pattern. Those wells that did were 7, 11, 15, 16, 18, and 22.

Among the remaining wells, many other patterns were evident in the nitrate data. Wells 1, 4, and 10 had higher concentrations in the spring than any other time of year. This could have been due to precipitation, fertilization, or irrigation events. Other trends included a decrease in nitrates at Wells 2, 8, 9, 13, 14, and 19; an increase in nitrates at wells 5 and 6; no detectable concentrations in Wells 3, 12, and 21; and no significant nitrate pattern in Wells 17, 20, 23, 24, 26, and 28.

The wells that had the greatest amount of variation were Wells 8, 9, 13, 14, 15, and 18. Among these, Well 15 was the only one that had an increase during the second year of sampling. The others had extremely high concentrations at the beginning of the sampling program, but decreased throughout the study. This decrease occurred

most rapidly at Wells 8 and 18, and more gradually at 9, 13 and 14.

Land Use: Land use at 100 m, 500 m, and 1000 m up gradient from a well site (Table 1, page 32) was used to examine relationships between land use and nitrate concentration. Average nitrate concentrations were calculated using wells with similar up gradient land use categories. Table 2 (page 33) shows the average nitrate concentrations in wells according to land use classification. Wells 100 m down gradient from raspberry fields had relatively high average nitrate concentrations, particularly among the land use classes represented by more than one well. However, One-Way Analysis of Variance (ANOVA) indicated that there were no significant differences between mean nitrate concentrations based on land use class.

6.2 Nitrogen Isotope Analysis:

A total of twenty seven ground water samples were collected from 9 wells in the study area in February, June, and October 1998 for Nitrogen isotopes analyses. Nitrogen isotopes can be a powerful tool for distinguishing between synthetic fertilizers, septic field leaks, soil nitrogen, and animal wastes (Igbal et al., 1997). Stable isotope ratios are usually expressed in a δ -format, which for nitrogen indicates the relative value of the isotopic ratio $^{15}\text{N}/^{14}\text{N}$ as compared with a standard, and is expressed as:

$$\delta^{15}\text{N} = \frac{\frac{^{15}\text{N}}{^{14}\text{N}_{\text{sample}}} - \frac{^{15}\text{N}}{^{14}\text{N}_{\text{standard}}}}{\frac{^{15}\text{N}}{^{14}\text{N}_{\text{standard}}}} \times 10^3$$

The widely accepted ranges for synthetic fertilizers vary between -3‰ and $+2\text{‰}$, for natural soil nitrate between $+2\text{‰}$ and $+8\text{‰}$, and for human/animal waste nitrate between $+10\text{‰}$ and $+20\text{‰}$ (Kohl et al., 1973; Freyer and Aley, 1974; Igbal et al., 1997; Kreitler et al., 1978; Gormly and Spalding, 1979; Berndt, 1990; Exner and Spalding, 1994; Wassenaar, 1995). According to Igbal et al. (1997), difficulties arise when there is a possibility of the mixing of nitrate from more than one source. Igbal et al. (1997) studied seasonal source variability of ground water nitrogen isotope indicators and concluded that nitrogen isotope signatures can be used to determine the effects of local soil type, rainfall, and land-use practices on the fate of nitrate in the subsurface.

The 9 well locations (Wells 2, 5, 7, 9, 10, 13 14, 17, and 18) were selected because they represent a spatial distribution in the study area and had high nitrate concentrations, which would improve the likelihood of identifying the source of contamination. The ground water samples were collected in 1-liter nalgene bottles, acidified prior to collection to fix the solution, and were shipped to Coastal Science Labs, Inc. (Texas) for analyses.

The method for nitrogen isotope analysis in water used by Coastal Science Laboratories, Inc. is based on a methodology developed by several institutes including the Geophysical Laboratory of the Carnegie Institute, Washington D.C. and the Marine Biological Laboratory, Woods Hole, Massachusetts. Nitrate in solution is reduced to ammonia by Devarda's alloy (Cu:Al:Zn) under alkaline conditions so that NH_3 can be distilled to an acid trap (HCl). The ammonium ion in the trap is captured on an artificial zeolite molecular sieve then filtered and dried under mild conditions (60°C for 2 days). The zeolite is loaded in Pyrex tubes with CuO and Cu, evacuated, sealed and heated to 590°C to produce nitrite for direct analysis on an isotope ratio mass spectrometer. Mass spectrometers used for nitrogen analysis are VG SIRA models 10 and 12. Both are triple collector, dual inlet instruments which have been modified for continuous flow capability. Precision and accuracy for nitrogen isotope ratios are quoted by Coastal Science Laboratories, Inc. according to sample type and refer to the reproducibility (as described by the standard deviation) of the total preparation and measurement of general case samples. Coastal Science Laboratories, Inc. estimated a standard deviation for ground water nitrogen measurement to be 0.8 to 1.0% for samples of commonly encountered nitrogen concentration (0.5-5 mg/L N).

The results of the isotope analyses of the samples from the 9 wells are plotted in Figure 78 (page 118) and are shown in Table 7 (page 38) with the respective nitrate concentrations. The results are also shown as bar plots at well locations on the land-use map in Figure 79 (page 119). Sixty-six percent of the ground water samples had average $\delta^{15}\text{N-NO}_3^-$ values less than $+6\text{‰}$ and 23% had average $\delta^{15}\text{N-NO}_3^-$ values greater than $+7\text{‰}$. Eleven percent of the ground water samples had average $\delta^{15}\text{N-NO}_3^-$ between $+6\text{‰}$ and $+7\text{‰}$. Most striking is the apparent lack of high values associated with animal waste. The highest $\delta^{15}\text{N-NO}_3^-$ values were those measured at Well 9, which had nitrogen isotopic signatures of 11.0, 9.6, and 9.5‰ in February, June, and October 1998, respectively. These values probably correspond to animal waste, considering that Well 9 is down gradient of fields where dairy waste spreading has taken place. Consistently low values of $\delta^{15}\text{N-NO}_3^-$, which are typical of signatures of synthetic fertilizers, were measured from water samples from Wells 2, 7, and 10 (Table 7 and Figure 78). These wells are all in the vicinity of intense berry production where synthetic fertilizers are predominant. The rest of the wells yielded $\delta^{15}\text{N-NO}_3^-$ values in the natural and mixed sources region of Figure 78. Given the agricultural setting of most of these wells, it is unlikely that the isotope values are indicative of natural soil nitrate and probably correspond to a mixture of animal and synthetic sources. As indicated by the bar plots in Figure 8, only two wells (2 and 18) show a significant change in nitrogen isotope values from February, 1998 to October, 1998. The $\delta^{15}\text{N-NO}_3^-$ values drop from magnitudes in the mixed zone (3.4 to 6.8‰), to magnitudes below 1‰. The drop in magnitudes could be the result of a change in land use to one where synthetic fertilizers are dominant, or the larger values in February and June could be the result of animal waste application events.

6.3 Multivariate Analysis

To quantify the multiple underlying processes that are affecting the nitrate concentration trends in the study area, Factor Analysis, a multivariate statistical method, was employed using SPSS for Windows, Version 8.0.0. Factor Analysis defines relationships between variables, which are represented by a few underlying, but unobservable terms, called factors. Sets of variables that have strong associations with one another are called common factors (Suk and Lee, 1999). These common factors are thought to represent underlying processes. The first factor accounts for as much variance in the variables as possible. The second factor accounts for as much of the residual variance as possible and each subsequent factor accounts for as much of the residual variance of the preceding factor as possible. For this study Principle Components Analysis (PCA) was used to determine the common factors or components.

Missing data were not replaced due to the non-random quality of the data. The initial component matrix was transformed by Varimax rotation with Kaiser normalization in order to reveal the structure of the matrix more clearly. Varimax rotation is a type of orthogonal rotation used in PCA to maximize the variance of the factor loadings, making high loadings even higher, and low loading even lower (Tabachnick and Fidell, 1996). A transformation matrix is used to determine the rotated factor matrix.

Table 8 (page 39) shows that 80% of the variance in the data set is explained by the first six factors. Due to the large number of missing values in the data set, only 35% of all the cases were used in the computation of the final component matrix. A variable loading greater than 0.5 was considered to have a significant effect on the component. The first component explained 19.6% of the variance and was represented by total nitrogen, nitrate, pH, and depth below the water table. This could mean that the nitrate plume was located near the top of the aquifer or that there was shallow aquifer contamination. The second component explained 16.7% of the residual variance and was represented by chloride and conductivity, both of which are associated with agricultural contamination of groundwater. The third and fourth components were represented by a variety of physical characteristic of the wells. The third component explained 14.3% of the residual variance and was represented by static water level and well depth. The fourth component explained 10.7% of the residual variance and was represented by ground water temperature and the month of sampling, which could be related to seasonal influences. The fifth and sixth components explained 9.6% and 9.4% of the residual variance, respectively. These two components did not seem to represent any underlying processes. Based on these results, we concluded that nitrate concentrations and the depth below the water table provided the best characterization for the wells, followed by chloride, conductivity, static water level, and well depth.

6.4 Well Summary

Well 1: Nitrate concentrations were higher in the spring at this site. The mean nitrate concentration was 12.01 mg/L. The higher spring concentrations could have resulted from application of fertilizers during the growing season. The mean depth of the unsaturated zone at this site was 5.24 ft and the mean depth below the water table was 24.68 ft. Fields around this well have been excavated to elevations lower than the original topography for agricultural purposes; therefore, the water table was occasionally at the land surface.

Well 2: There was a gradual decrease in nitrate concentrations in Well #2. The mean nitrate concentration was 14.36 mg/L. The mean depth of the unsaturated zone was 23.24 ft and the mean depth below the water surface was 16.01 ft.

Well 3: Nitrate concentrations were below detection at this well. Iron was reported to be in the water by the resident, but no evidence of orange coloration was apparent in water samples collected at this site. The mean depth of the unsaturated zone was 24.13 ft and the mean depth below the water surface was 65.11 ft.

Well 4: Nitrate concentrations were higher in the spring at this site. The mean nitrate concentration was 1.78 mg/L. The mean depth of the unsaturated zone was 24.13 ft and the mean depth below the water surface was 4.07 ft. Because this well is shallow, there may be upgradient denitrification occurring as ground water flows through the peat beneath Judson Lake.

Well 5: Nitrate concentrations increased gradually during most of the study period, decreasing after October 1998. The mean nitrate concentration was 11.77 mg/L. Ammonia concentrations also increased during the sampling period. The mean depth of the unsaturated zone was 62.72 ft. The well depth was approximated at 70 ft making the mean depth below the water table approximately 13 ft.

Well 6: Nitrate concentrations increased gradually until May 1998, at which time sampling was discontinued at this site because of property owner objections. The mean nitrate concentration was 12.53 mg/L. The depth of the unsaturated zone was 50.42 ft and the mean depth below the water table was 50.58 ft.

Well 7: Nitrate concentrations increased during the fall of 1997, after which no consistent patterns were observed. The mean nitrate concentration was 8.67 mg/L.

The mean depth of the unsaturated zone was 37.74 ft and the mean depth below the water table was 38.68 ft.

Well 8: Well 8 had nitrate concentrations that began high, then dropped quickly. After the initial drop, there were no consistent trends. The mean nitrate concentration was 2.15 mg/L and ranged from 0.39 mg/L to 13.00 mg/L. The mean depth of the unsaturated zone was 31.01 ft. The well depth was unknown.

Well 9: Well 9 had decreasing nitrate concentrations. The mean nitrate concentration was 12.48 mg/L and ranged from 4.14 mg/L to 26.67 mg/L. Nitrite and ammonia concentrations were also detectable in ground water samples. The well depth was 71 ft. The depth of the unsaturated zone and the depth below the water table were unknown.

Well 10: Nitrate concentrations were higher during the spring of 1997. There was a slight decrease in nitrate concentrations from October 1997 until July 1998, after which the concentrations increased. The mean nitrate concentration was 10.73 mg/L. The high nitrates that were measured during the spring could have been due to precipitation or irrigation events that leached nitrates into the ground water. The mean depth of the unsaturated zone was 30.60 ft and the mean depth below the water table was 18.23 ft.

Well 11: No consistent patterns were evident, although higher nitrate concentrations were measured during the fall and winter of 1998. The mean nitrate concentration was 2.43 mg/L. The water had noticeable iron coloration, which cleared up during the winter of 1998. The mean depth of the unsaturated zone was 42.43 ft and the mean depth below the water table was 17.28 ft.

Well 12: Nitrate concentrations were below detection at this well. Ammonia concentrations were detectable and ranged from 0.038 mg/L to 0.685 mg/L. The mean depth to the unsaturated zone was 42.95 ft and the mean depth below the water table was 29.80 ft.

Well 13: Nitrate concentrations decreased over time at this site. The mean nitrate concentration was 12.51 mg/L. Nitrate concentrations ranged from 8.36 mg/L to 25.48 mg/L. A nitrate peak was measured during the spring of 1997 and a smaller peak was measured during the spring of 1998. The well depth was 40 ft. The unsaturated zone and depth below the water table are unknown.

Well 14: Nitrate concentrations decreased over time at this site. The mean nitrate concentration was 24.29 mg/L and ranged from 18.18 mg/L to 32.43 mg/L. This well was located on a dairy farm and was very shallow. The mean depth of the unsaturated zone was 23.86 ft and the mean depth below the water was 7.56 ft.

Well 15: Beginning in the summer of 1998, nitrate concentrations increased at this site. This increase may have been caused by nitrification in the summer, leaching in the fall due to precipitation, or possibly a combination of both. The mean nitrate concentration was 4.65 mg/L and ranged from 2.03 mg/L to 9.86 mg/L. The mean depth of the unsaturated zone was 24.98 ft and the mean depth below the water table was 8.52 ft. There may have been denitrification occurring due to upgradient peat.

Well 16 : Well 16 had nitrate concentrations that were higher in the fall and winter. The mean nitrate concentration was 8.79 mg/L. The nitrate concentrations could have been experiencing nitrification in the summer and leaching during the fall. The well depth was 60 ft. The unsaturated zone and depth below the water table were unknown.

Well 17: No consistent patterns were evident at this site. The mean nitrate concentration was 10.44 mg/L. The mean depth of the unsaturated zone was 28.82 ft and the mean depth below the water table was 9.18 ft.

Well 18: Nitrate concentrations at this site were higher in the late summer and fall of 1997 compared to the rest of the sampling period. The nitrate concentrations decreased rapidly in the spring of 1998, followed by a gradual increase during the summer and fall of 1998. The mean nitrate concentration was 21.09 mg/L and ranged from 13.38 mg/L to 32.35 mg/L. The mean depth of the unsaturated zone was 25.52 ft and the mean depth below the water table was 16.94 ft.

Well 19: Nitrate concentrations decreased gradually over time at this site. The mean nitrate concentration was 2.38 mg/L. The mean depth of the unsaturated zone was 12.72 ft. The well depth was approximated at 25 ft, making the mean depth below the water table approximately 11.61 ft.

Well 20: No consistent patterns were evident at this site. The mean nitrate concentration was 2.23 mg/L. The mean depth of the unsaturated zone was 13.92 ft and the mean depth below the water table was 31.58 ft.

Well 21: Nitrate concentrations were below detection at this site. The well was being treated for high iron by a chlorination and filtration process, so chloride concentrations were high at this site. There were also detectable concentrations of nitrite and ammonia. The mean depth of the unsaturated zone was 19.23 ft and the mean depth below the water table was 35.44 ft.

Well 22: Well 22 had no consistent trends in nitrate other than high concentrations during the winter of 1997/1998 and fall of 1998. The mean nitrate concentration was 5.92 mg/L. The well depth was 34 ft. The unsaturated zone and depth below the water table were unknown.

Well 23: Nitrate concentrations increased gradually at this site. The mean nitrate concentration was 0.97 mg/L. The unsaturated zone was approximately 12.21 ft, but the static water level was only measured a few times. The well depth was 75 ft, making the depth below the water table approximately 63 ft.

Well 24: Well 24 was only sampled four times; however, three of the four samples collected at this site had unusually high nitrate concentrations. The mean nitrate concentration was 19.88 mg/L. High ammonia concentrations were also measured. The mean unsaturated zone was 24.04 ft. The well depth was 27 ft, making the depth below the water table was approximately 3 ft.

Well 25: No samples were collected at this site.

Well 26: No consistent patterns were evident at this site. The mean nitrate concentration was 7.85 mg/L. High chloride concentrations were also noticed at this site. The mean depth of the unsaturated zone was 26.61 ft and the mean depth below the water table was 52.72 ft.

Well 27: This site was only sampled once. The site is identical to Well 21, except that the Well 27 sample was untreated (no filtration or chlorination).

Well 28: Well 28 was sampled infrequently, so the data are insufficient to establish seasonal patterns. The mean nitrate concentration was 13.19 mg/L. Nitrite and ammonia concentrations were also high. This well was at the same location as Well 16, but was deeper and had higher nitrate concentrations. The well was 100 ft deep. The unsaturated zone and the depth below the water table were unknown.

7 Conclusions

7.1 Hydrogeology

The wells within the study area are withdrawing groundwater from Sumas Aquifer. The Sumas Aquifer in the study area is an unconfined aquifer characterized by a heterogeneous mixture of highly conductive gravels and sands. Underlying the Sumas Aquifer and defining the confining aquitard, is a thick clay deposit of glacial marine drift. Distributed throughout the Sumas Aquifer are numerous lenses of silt and clay having much lower hydraulic conductivities. Ground water is assumed to move freely through the hydraulically connected gravels and sands and around the discontinuous lower conductive lenses within the aquifer.

Water table contours indicate that the general ground water flow direction is from the northwest toward the southeast. The water table did not fluctuate significantly over the duration of the study period. The largest differences were in the middle of the study area where irrigation practices were common during the summer.

A mean hydraulic conductivity of the Sumas Aquifer sediments was determined to be 930 ft/day. The average hydraulic gradient along the flow direction was estimated to be 0.0074. An average linear flow velocity was approximated to be about 20 ft/day. A residence time of 575 days was estimated along a 11,500 ft flow path, which indicates that groundwater moves rapidly through the aquifer.

7.2 Hydrogeochemistry

Contouring identified several “hot spot” (elevated nitrate concentrations superimposed on a regional gradient) in the study area. Nitrogen isotope data indicated that dairy waste spreading and over-application of synthetic fertilizers were the most probable sources of loading for these hot spots. The hot spots are associated with Wells 9, 14, and 18.

A vertical gradient in nitrate contamination was seen in Wells 15 and 16. Both wells showed unusually low nitrate values in the middle of a hot spot, with the lowest values in the shallower well (15). When Well 16 was redrilled to a depth of 100 ft, higher nitrate concentrations were measured.

There is an apparent trend of decreasing nitrate values in the study area from April 1997 to January 1999. This trend was primarily due to a decrease in nitrate concentrations at the hot spot well locations. This evidence documents the impact of local nitrate sources on the aquifer and the importance of identifying local agricultural management practices. Despite the overall decreasing trend, 11 of 26 wells produced

median nitrate concentrations above the drinking water standard of 10 mg/L. An additional 5 wells produced median concentrations between 3 and 10 mg/L, indicating probable contamination.

The only wells showing an increasing trend were the relatively deep wells in the north-west corner of the study area (primarily well 5). Given that the general direction of ground water flow is south, it is likely that the contamination observed in the wells is related to sources north of the border. If we assume that the nitrate concentrations in wells near the Canadian border are representative of a uniform background across the northern border of the study area of 10–12 mg/L, it is apparent that the anomalously high concentrations measured south of Judson Lake were related to local sources. Wells that had low or no nitrate contamination were either associated with large unsaturated zones, located far below the water table, had high iron concentrations, or were shallow wells down gradient from peat deposits that were sources of denitrification.

Nitrogen isotope values indicated an association between land use and nitrate source. Wells with high ratios indicating animal waste sources were generally down-gradient from dairy farms; whereas those wells with low isotope ratios indicating synthetic fertilizer sources were in the vicinity of berry fields

There was no consistent pattern of seasonal nitrate variation observed. The expected increase in fall and winter values due to leaching of soil nitrates, occurred in only 6 of the 26 wells. Three of the wells showed the opposite relationship, with higher nitrate values in the spring and summer. Part of this inconsistency is undoubtedly due to variable waste spreading and fertilization, well depth, and the input from Canada. Until specific information is available on land management practices, it will be difficult to interpret the data available.

Although denitrification was undoubtedly occurring in the unsaturated zone and the aquifer, there was no evidence that suggests it significantly affects nitrate concentrations in the study area.

8 Recommendations

- A more thorough characterization of nitrate sources in the aquifer should be undertaken using nitrogen isotope data combined with better information on loading practices.
- A detailed investigation of nitrate fate and transport through the unsaturated zone should be conducted to evaluate the mechanism and magnitude of loading to the water table. This should include a study of the effect of different soil types on nitrogen transformation processes (especially denitrification).

- Nested monitoring wells should be installed near “hot spot” locations and the Canadian border to define vertical and lateral distributions of contaminant plumes.
- A ground water model should be developed to predict flow and contaminant transport in the aquifer.
- The wells around Judson Lake should be studied. This area seems to be less contaminated than southern portions of the study area. A new study should be conducted to determine whether exfiltration from Judson Lake, or denitrification processes, are affecting ground water quality in that area.
- The wells around Pangborn Road should be studied. Amounts, types and times of fertilization and irrigation events should be determined in order to see if nitrate concentrations are directly related to the amount of fertilizer applied.
- The effect of iron and peat on denitrification should be studied.

9 Tables

Well	100 m	500 m	1000 m	Land Use Code
1	1	2	1	1 = raspberries
2	3	4	4	2 = corn
3	5	6	na	3 = other crops
4	5	6	na	4 = hazelnuts
5	1	1	na	5 = dairy/cattle
6	1	1	7	6 = pasture
7	2	1	7	7 = Judson Lake
8	8	7	na	8 = house/building
9	8	1	7	9 = Pangborn Creek
10	8	1	7	10 = rhubarb
11	2	1	1	11 = no farm use
12	1	1	1	12 = flowers
13	6	1	1	13 = gravel pit
14	5	5	2	na = not available
15	9	5	6	
16	8	5	6	
17	6	9	5	
18	1	10	1	
19	6	11	5	
20	5	13	11	
21	6	2	2	
22	1	5	na	
23	2	7	na	
24	12	1	6	
26	1	10	1	
28	8	5	6	

Table 1: Land use category within 100 m, 500 m, and 1000 m up gradient from each sampling site. Well 27 is omitted because it is redundant with Well 21.

Land use category	100 m up gradient		500 m up gradient		1000 m up gradient	
	Ave. NO ₃	# sites	Ave. NO ₃	# sites	Ave. NO ₃	# sites
Raspberries	10.2	7	10.1	9	9.4	6
Corn	4.0	3	6.0	2	12.2	2
Other Crops	14.4	1	—	—	—	—
Hazelnuts	—	—	14.4	1	14.4	1
Dairy/Cattle	7.1	4	11.4	5	6.4	2
Pasture	6.3	4	0.9	2	11.6	4
Judson Lake	—	—	1.6	2	11.1	4
House/Building	9.5	5	—	—	—	—
Pangborn Creek	4.7	1	10.4	1	—	—
Rhubarb	—	—	14.5	2	—	—
No Farm Use	—	—	2.4	1	2.2	1
Flowers	19.9	1	—	—	—	—
Gravel Pit	—	—	2.2	1	—	—

Table 2: Average nitrate concentrations in wells grouped by land use category (Well 27 omitted).

Parameter	Method	Description	Det. Limits
Ammonia	Limnol. Ocenogr 14:799-801	Phenate method	0.021 mg-N/L
Nitrate+nitrite	EPA 353.2	Automated Cd. Red.	0.006 mg-N/L
Nitrite	EPA 354.1	Spectrophotometric	0.0009 mg-N/L
Total nitrogen	Water Res. 17:1721-1729	Persulfate digested, automated Cd reduction	0.129 mg-N/L
Chloride	EPA 300.0	Ion chromatography	na
Conductivity	EPA 120.1	YSI 85 meter	2 μ S/cm
pH	EPA 150.1	ORION 250A meter	na
Dissolved oxygen	EPA 360.1	YSI 85 meter	0.1 mg/L

Table 3: Analytical methods used in Abbotsford-Sumas project.

Check Standard	Std Dev	Mean	Lower Control Limit	Upper Control Limit
Ammonia (50 $\mu\text{g N/L}$)	4.7	48.0	34	62
Ammonia (200 $\mu\text{g N/L}$)	6.5	198.5	179	218
Nitrite (25 $\mu\text{g N/L}$)	0.4	24.9	23.6	26.1
Nitrite (62.5 $\mu\text{g N/L}$)	0.5	62.1	60.6	63.7
Nitrate+nitrite (250 $\mu\text{g N/L}$)	7.0	250.8	230	272
Nitrate+nitrite (625 $\mu\text{g N/L}$)	13.9	629.4	588	671
Total nitrogen (500 $\mu\text{g N/L}$)	25.4	508.4	432	585
Total nitrogen (1500 $\mu\text{g N/L}$)	79.7	1270	1039	1500
Chloride (5 mg Cl/L)	0.1	4.6	4.3	4.9
Chloride (12.5 mg Cl/L)	0.2	12.4	11.8	12.9

Table 4: Control limits for check standards.

Parameter	Control Limit
Ammonia	$\pm 16.2 \mu\text{g-N/L}$
Nitrite	$\pm 0.86 \mu\text{g-N/L}$
Nitrate+nitrite	$\pm 13\%$
Total nitrogen	$\pm 42\%$
Chloride	$\pm 0.32 \text{ mg-Cl/L}$

Table 5: Control limits for laboratory duplicates

Parameter	Number of Batches (n)	Relative Standard Deviation
Total nitrogen	43	9%
Chloride	8	1%
Nitrate+nitrite	42	5%

Table 6: Relative standard deviation of field duplicates.

Site	Date	Isotope	Nitrate (mg/L)
		Ratio	
2	February 1998	3.4	14.90
5	February 1998	8.3	11.31
7	February 1998	1.2	9.63
9	February 1998	11.1	12.45
10	February 1998	1.7	9.06
13	February 1998	5.0	9.66
14	February 1998	5.6	25.48
17	February 1998	5.3	10.27
18	February 1998	6.8	21.74
2	June 1998	4.3	14.02
5	June 1998	7.7	13.83
7	June 1998	0.3	9.35
9	June 1998	9.0	8.81
10	June 1998	1.3	7.93
13	June 1998	5.0	10.70
14	June 1998	4.6	20.66
17	June 1998	7.3	10.59
18	June 1998	5.5	13.38
2	October 1998	0.7	13.81
5	October 1998	5.3	16.14
7	October 1998	0.3	8.69
9	October 1998	9.5	5.35
10	October 1998	1.5	11.91
13	October 1998	7.5	8.77
14	October 1998	7.8	19.88
17	October 1998	6.9	9.78
18	October 1998	0.9	14.99

Table 7: Nitrogen isotope analysis results, Abbotsford-Sumas Aquifer.

Variable	PCA Component					
	1	2	3	4	5	6
Total nitrogen	0.818	0.426	-0.002	0.099	0.058	0.245
Nitrate	0.822	0.425	-0.009	0.092	-0.066	0.239
Nitrite	-0.079	-0.060	0.137	0.324	0.623	-0.338
Ammonia	-0.167	-0.373	0.453	-0.091	-0.343	-0.450
Chloride	-0.028	0.910	-0.008	-0.064	-0.031	-0.133
pH	-0.747	0.044	0.021	0.094	-0.016	-0.122
Conductivity	0.279	0.925	0.001	-0.127	0.012	0.004
Dissolved oxygen	0.209	-0.173	-0.002	0.008	0.047	0.847
Temperature	-0.127	0.252	-0.051	-0.800	0.336	-0.062
Month	0.030	0.001	-0.011	-0.120	0.869	0.214
Precipitation	-0.098	0.040	-0.064	0.824	0.267	-0.015
Static water level	0.209	-0.066	0.859	-0.005	0.059	-0.122
Well depth	-0.411	0.081	0.891	0.011	0.035	0.068
Depth below water table	-0.668	0.218	0.488	0.036	-0.034	0.254

Table 8: Principle components rotated component matrix.

10 Figures

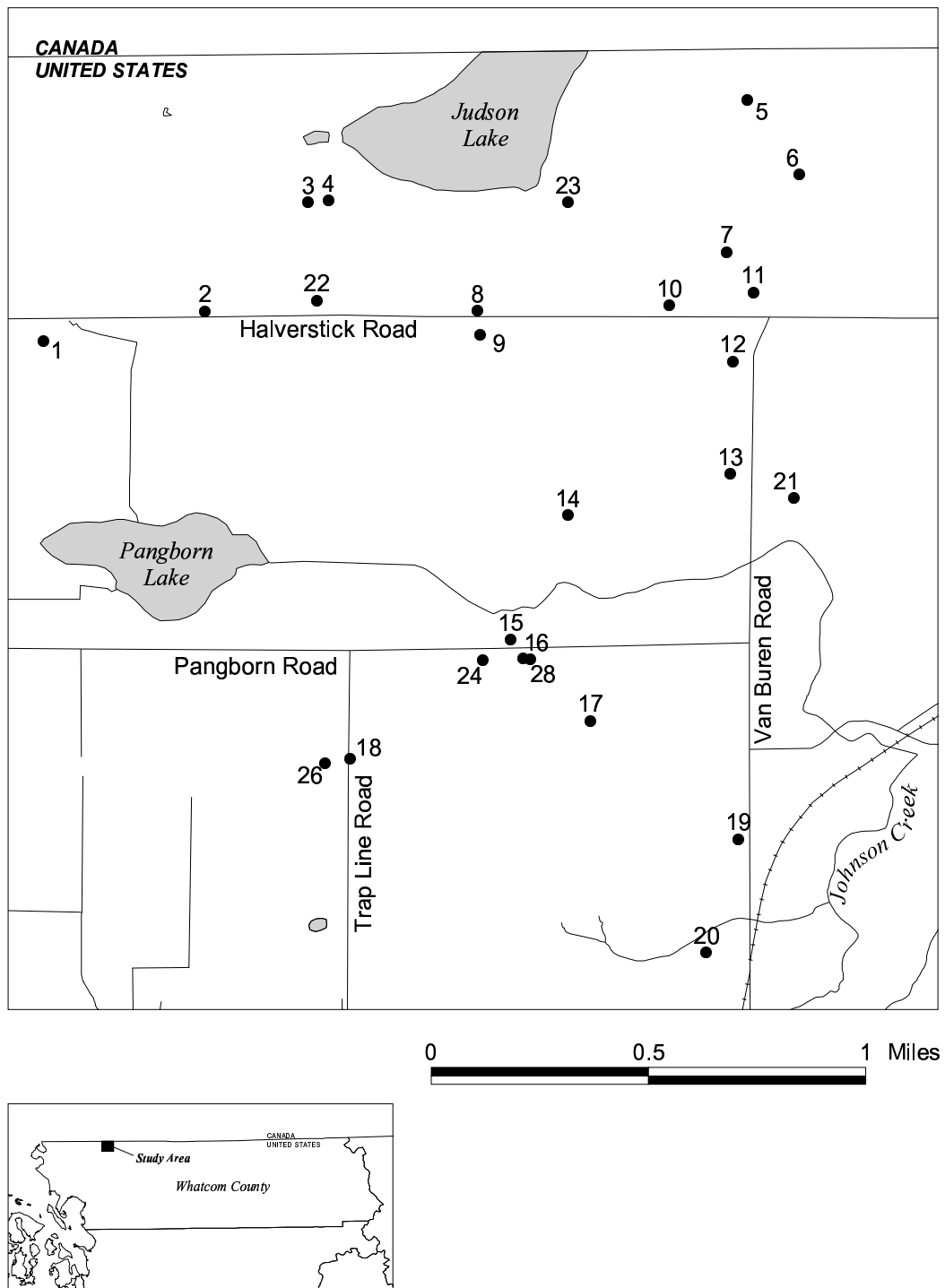


Figure 1: Location of the Abbotsford-Sumas study area and monitoring wells.

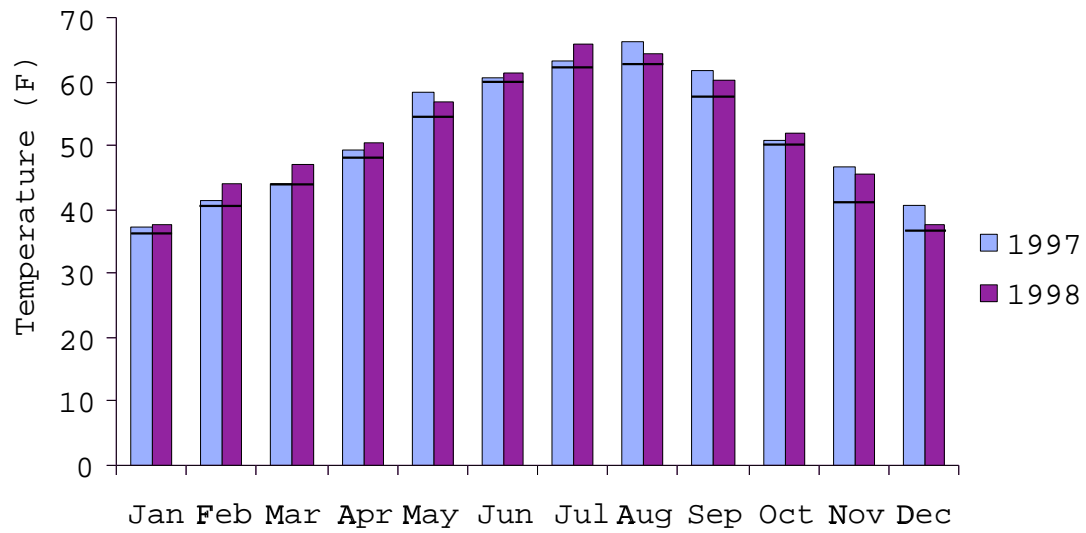


Figure 2: Monthly temperature averages for 1997 and 1998 compared to 30-year averages (1961-1999; solid line).

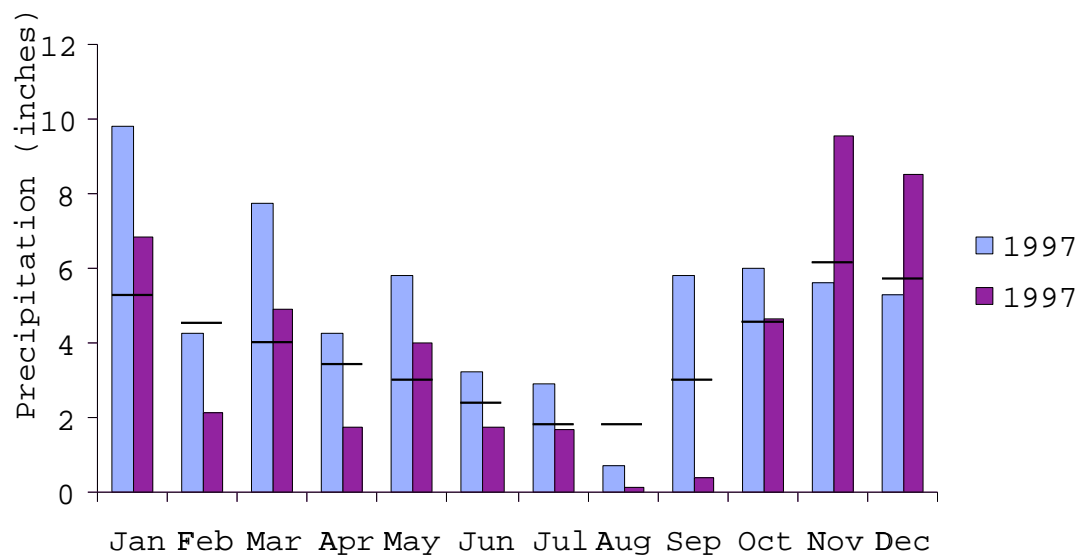


Figure 3: Monthly precipitation averages for 1997 and 1998 compared to 30-year averages (1961-1999; solid line).

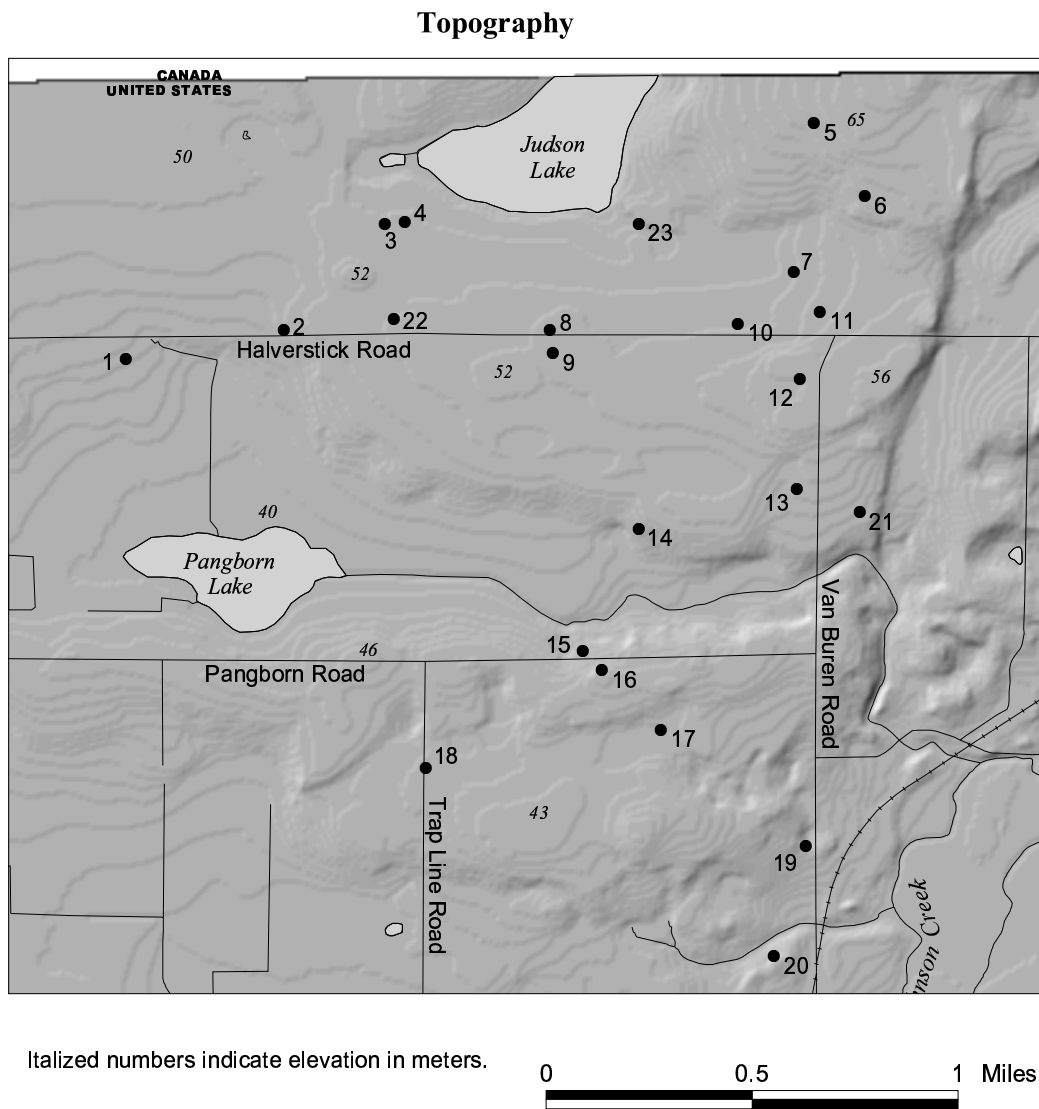


Figure 4: Topographic map of the Abbotsford-Sumas study area. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.

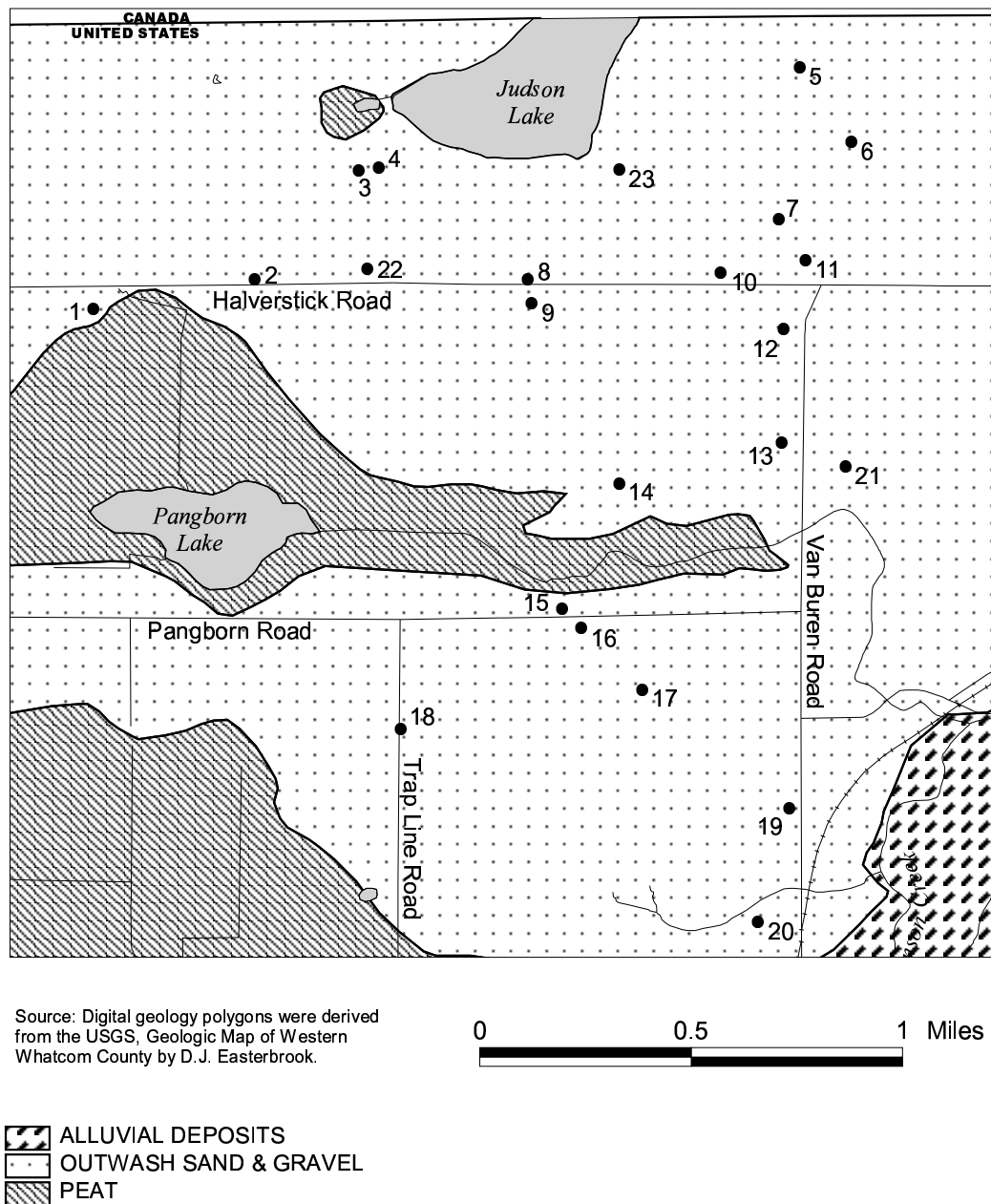


Figure 5: Geological overlay of the Abbotsford-Sumas study area. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.

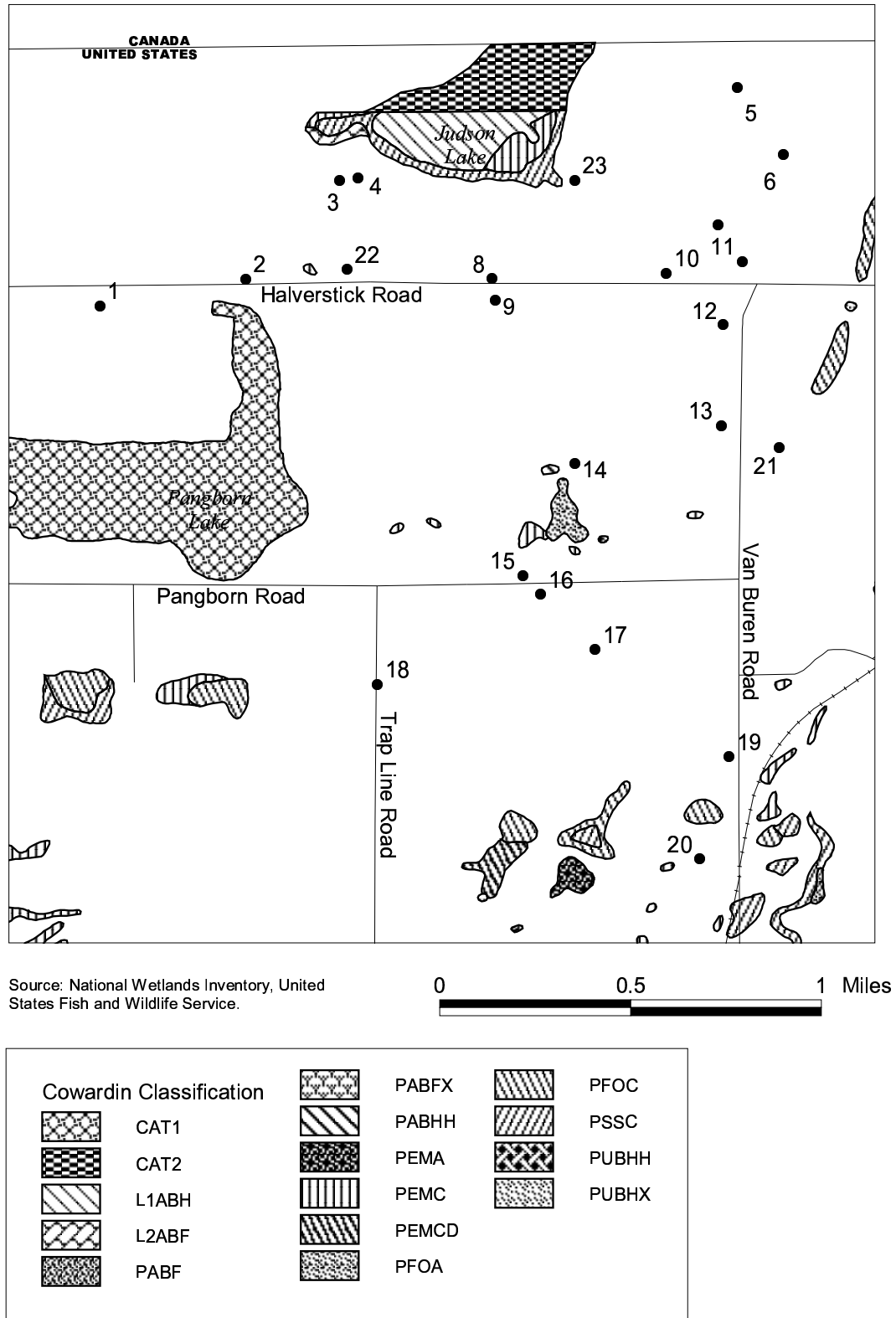
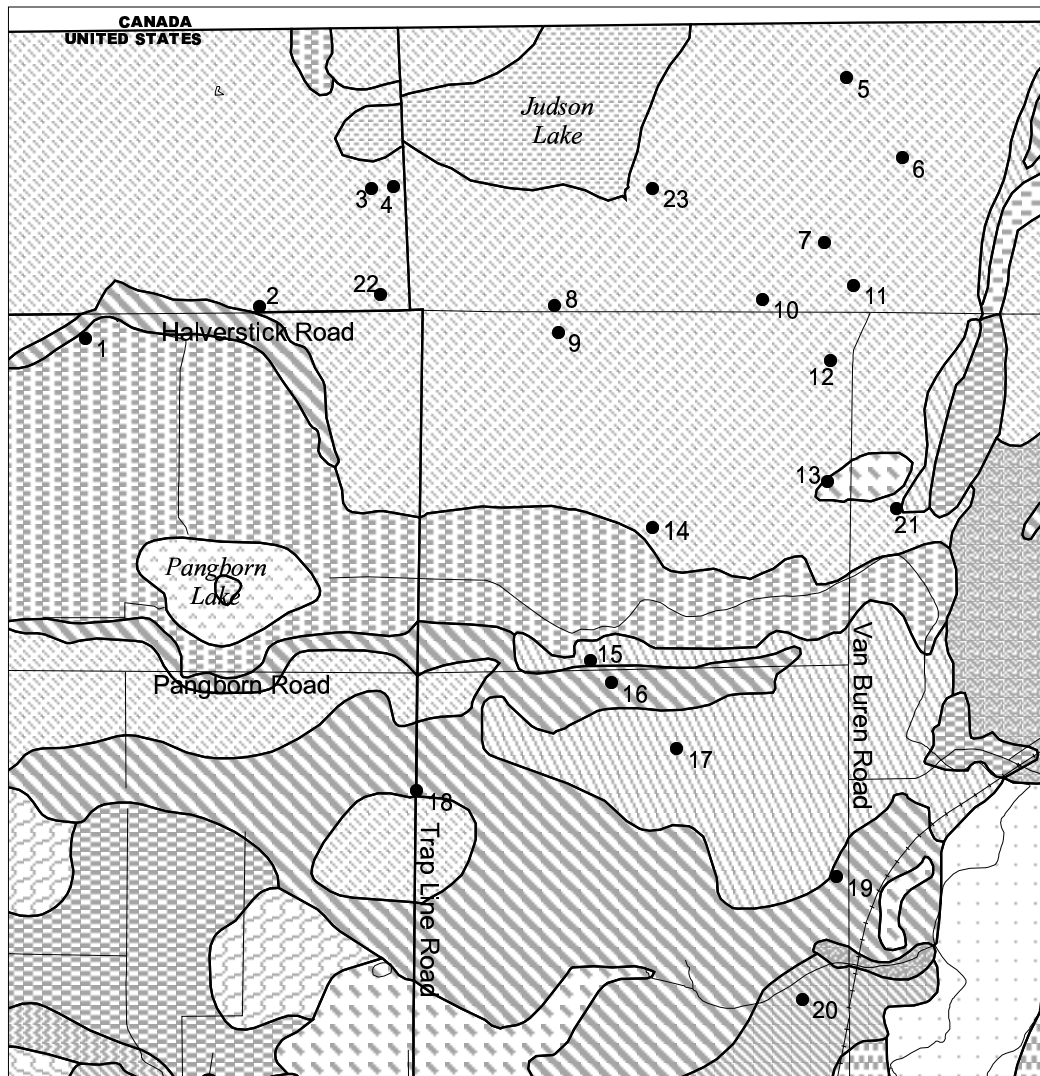


Figure 6: National wetlands inventory for the Abbotsford-Sumas study area. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.



Source: Derived from Natural Resources Conservation Service Soil Survey for Whatcom County and The Private Forest Land Grading project by the State of Washington. Managed by Whatcom County Planning & Development.

0 0.5 1 Miles

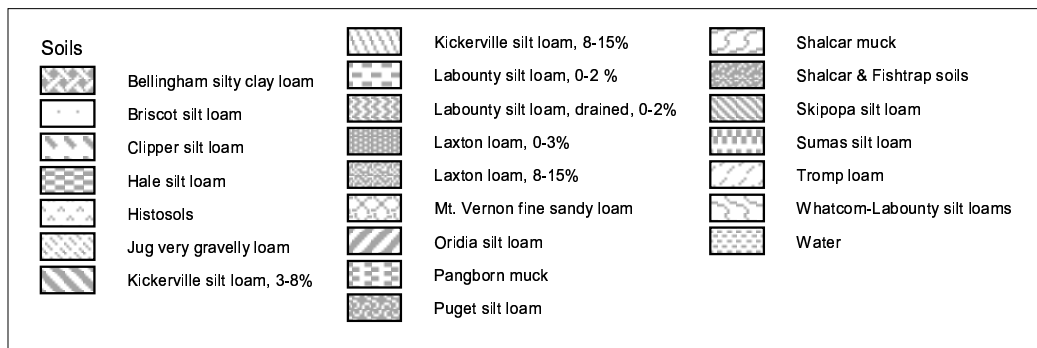
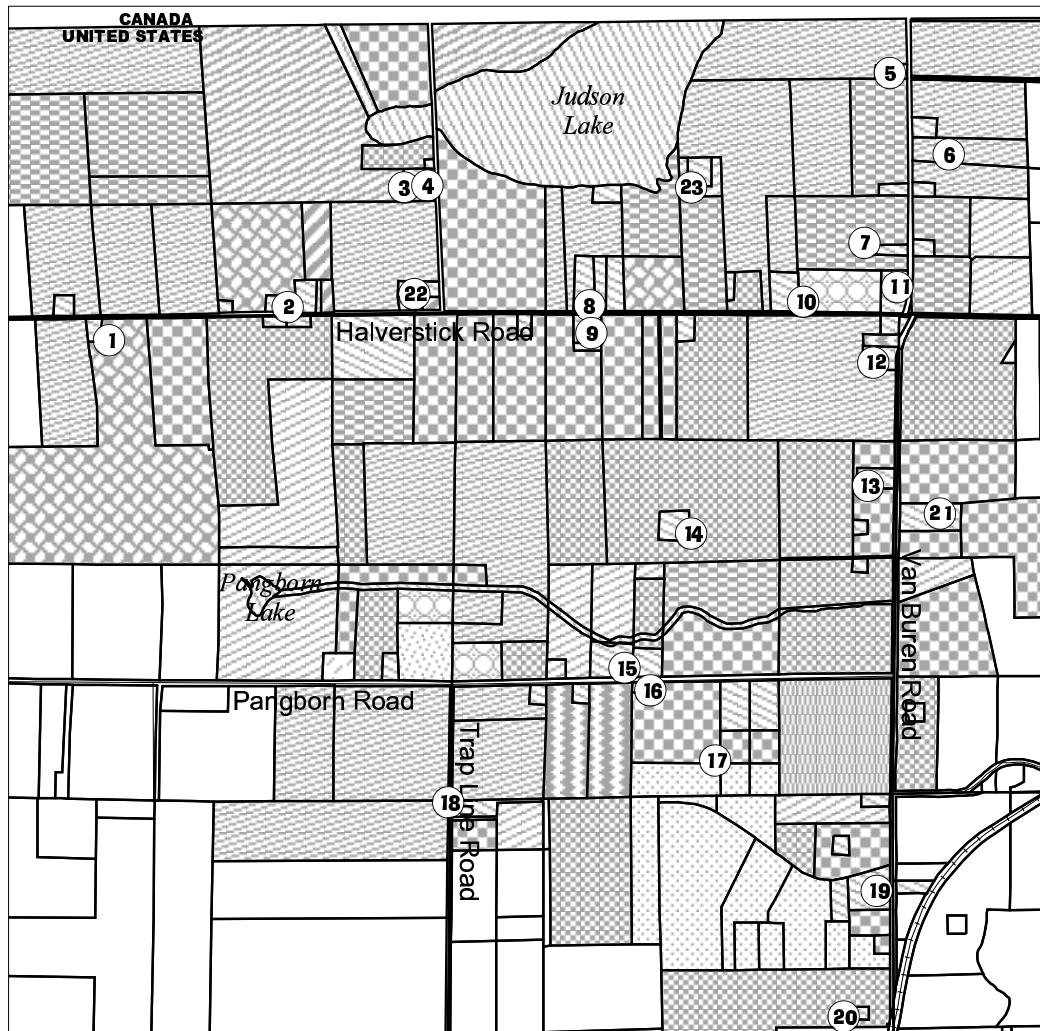


Figure 7: Soils map for the Abbotsford-Sumas study area. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.



Source: Field survey conducted Summer 1997. Base parcel layer from Whatcom County Planning and Development.

0 0.5 1 Miles

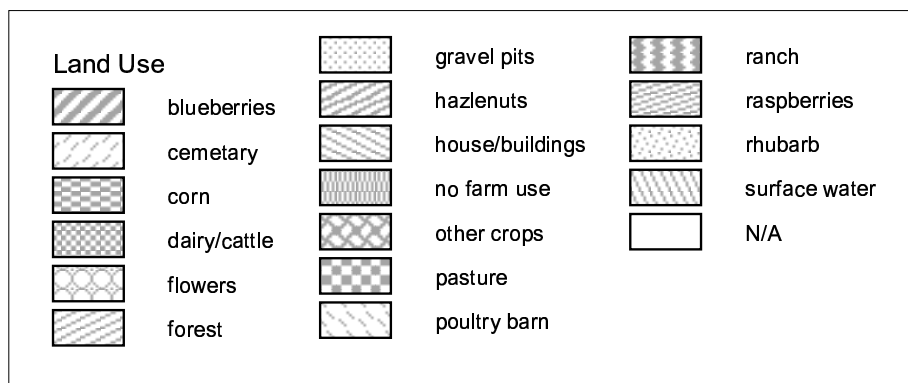


Figure 8: Land use map of the Abbotsford-Sumas study area. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.

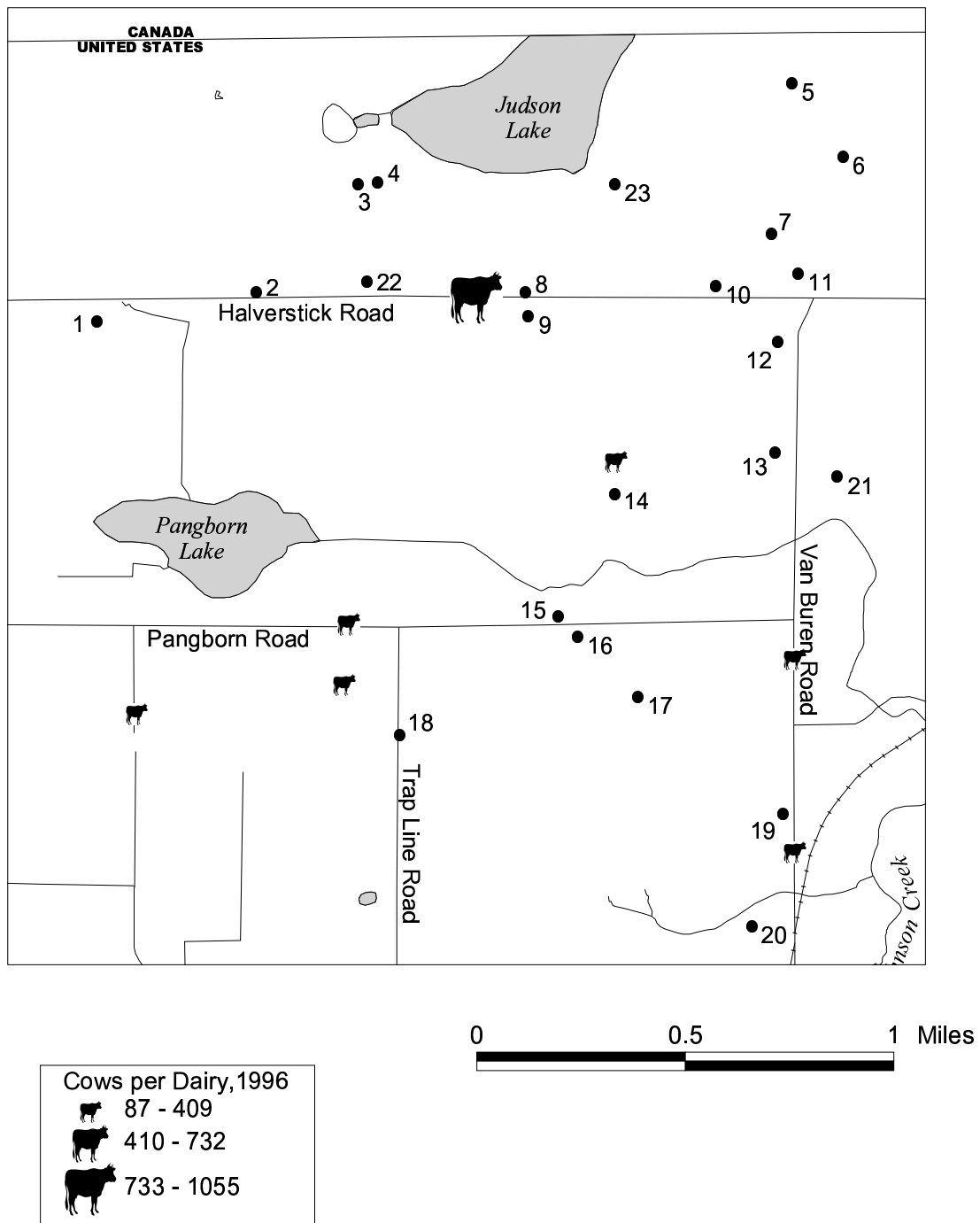


Figure 9: Number of cows per dairy in the Abbotsford-Sumas study area in 1996. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.

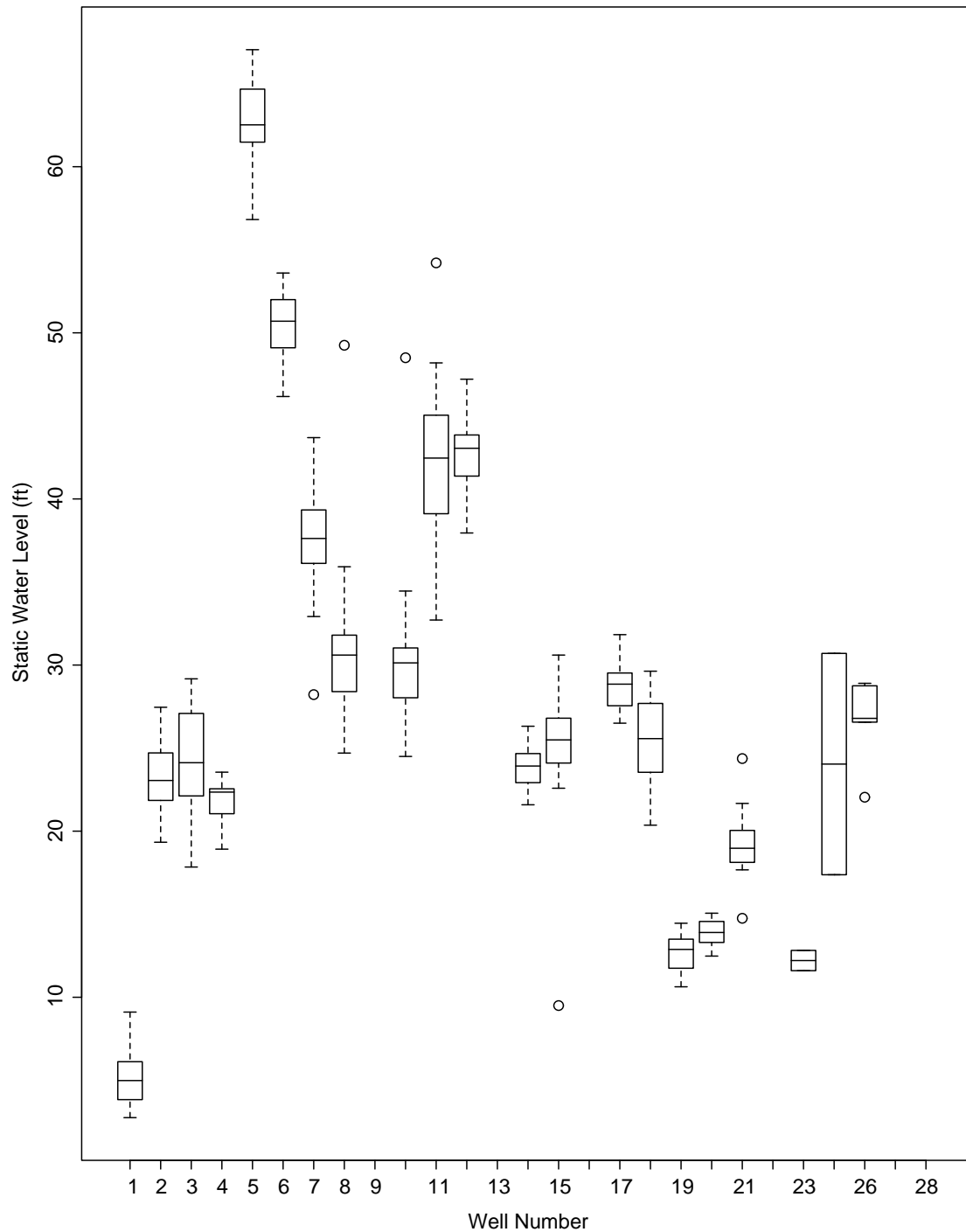


Figure 10: Boxplot of static water levels. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

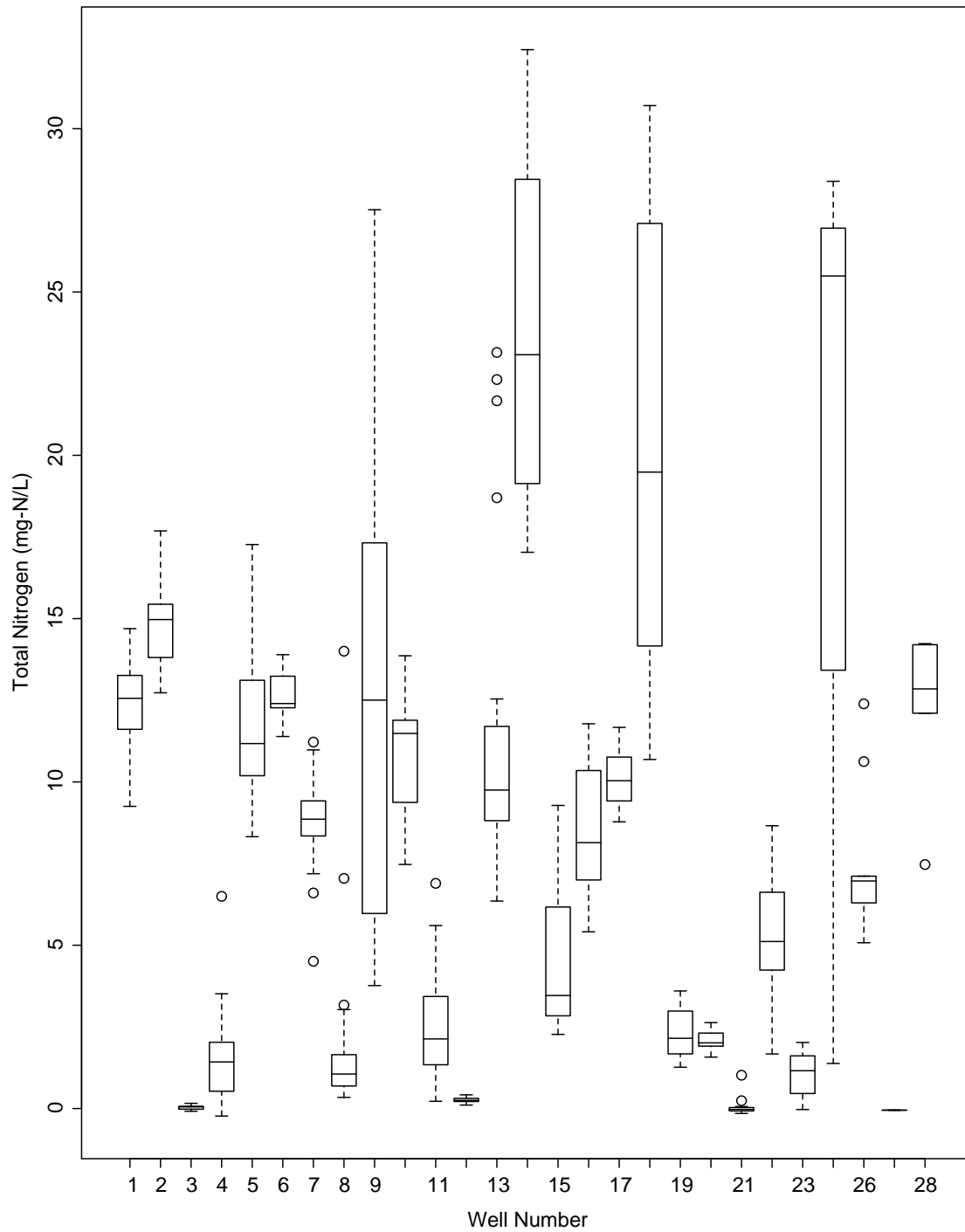


Figure 11: Boxplot of total nitrogen concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

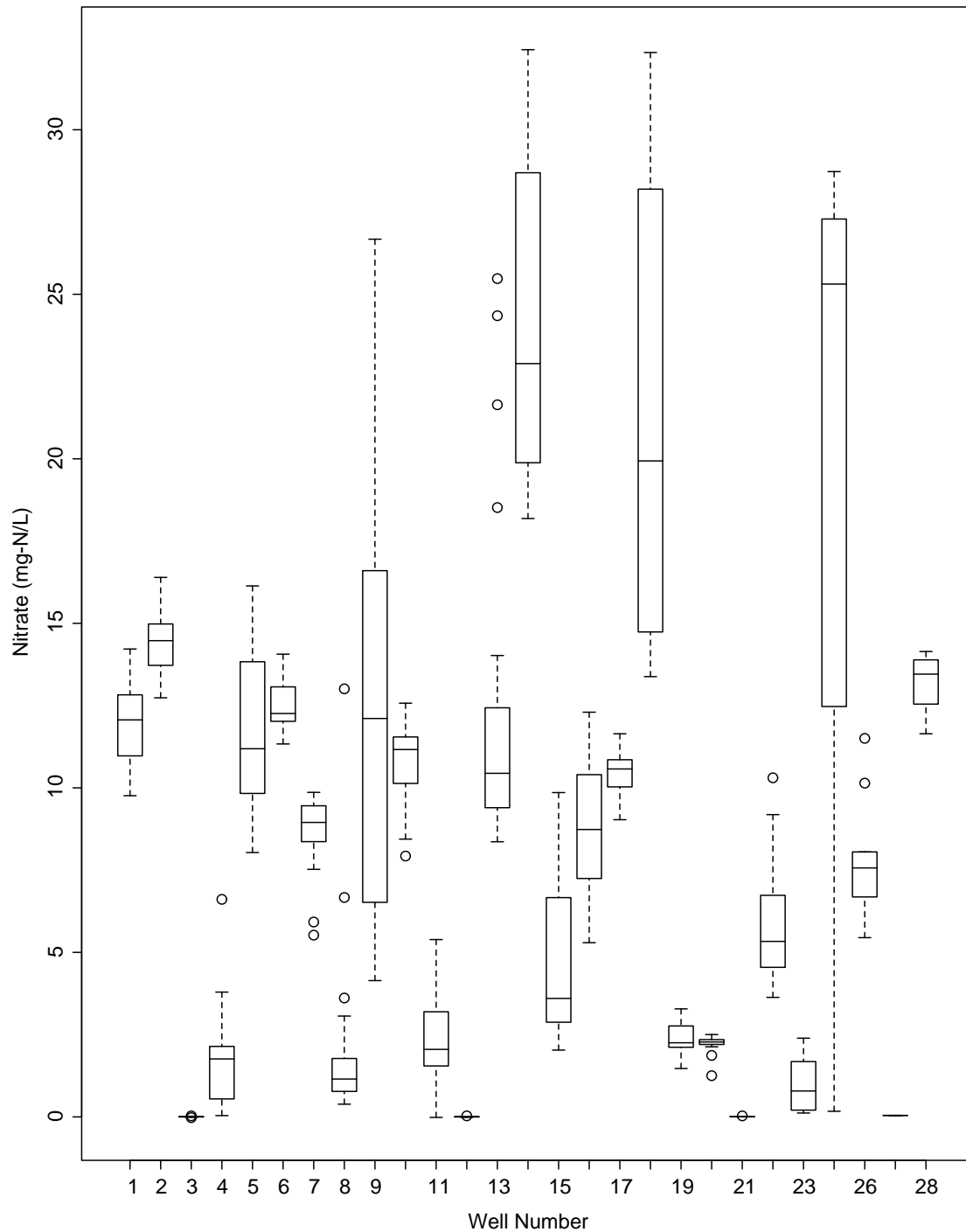


Figure 12: Boxplot of nitrate concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

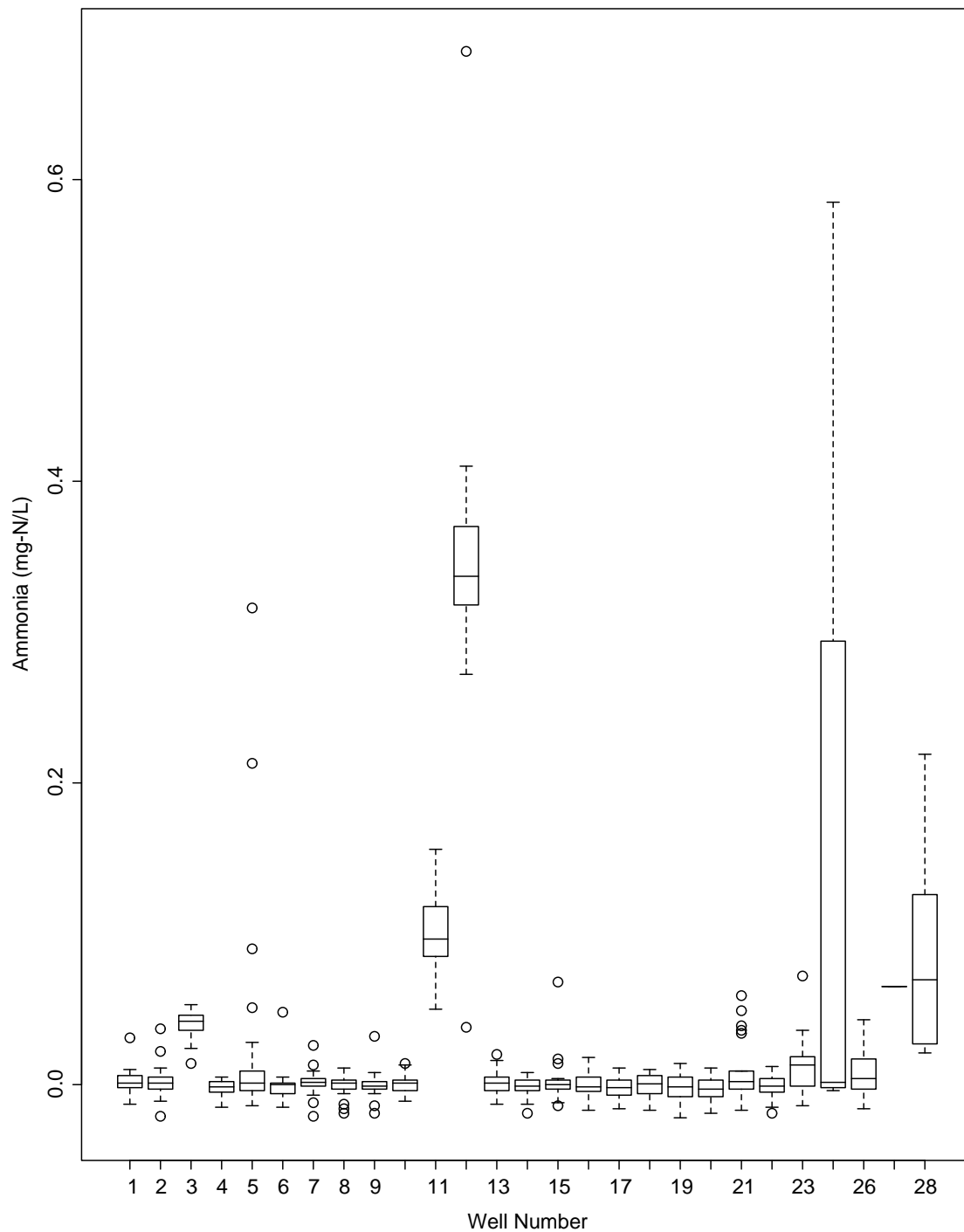


Figure 13: Boxplot of ammonia concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

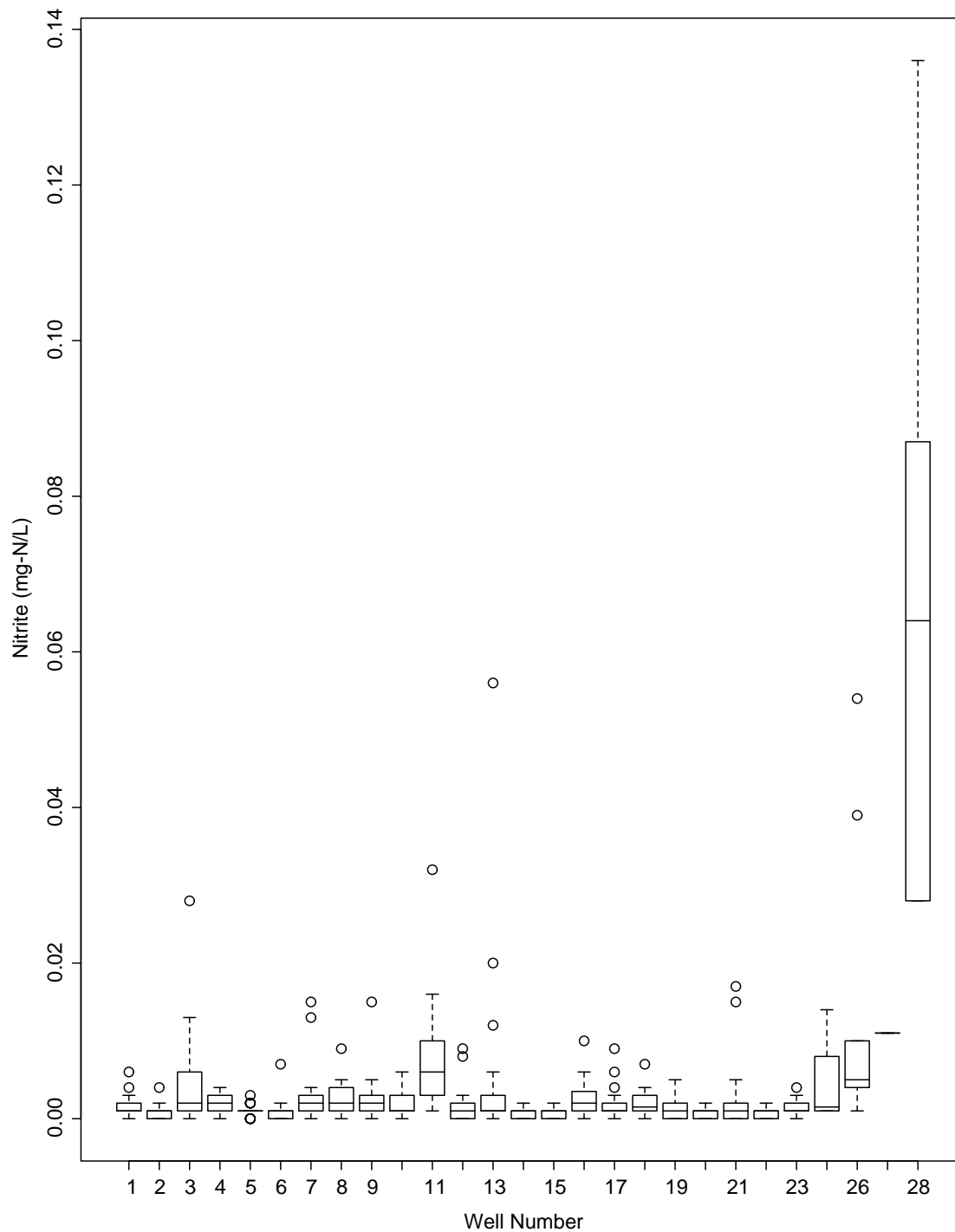


Figure 14: Boxplot of nitrite concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

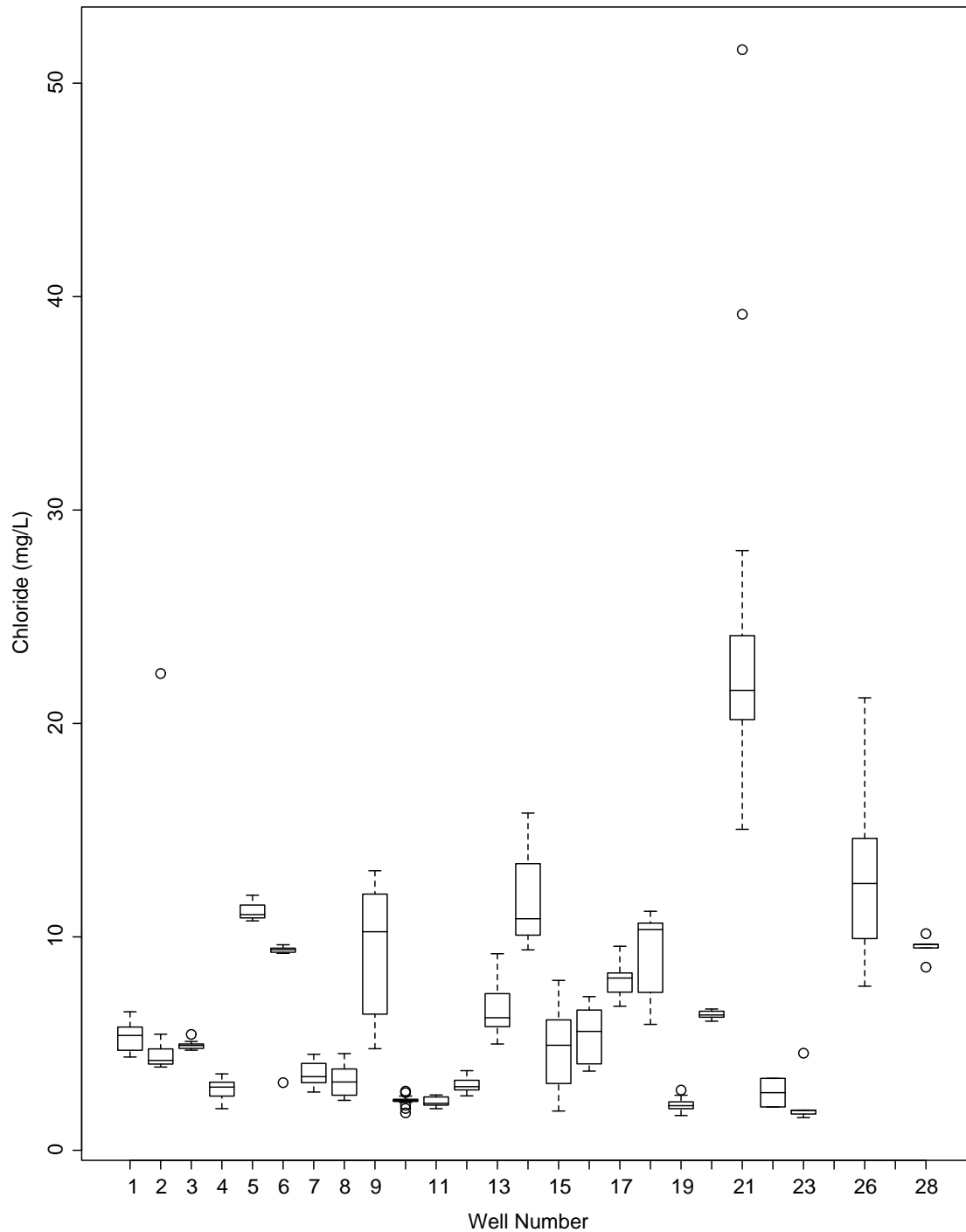


Figure 15: Boxplot of chloride concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

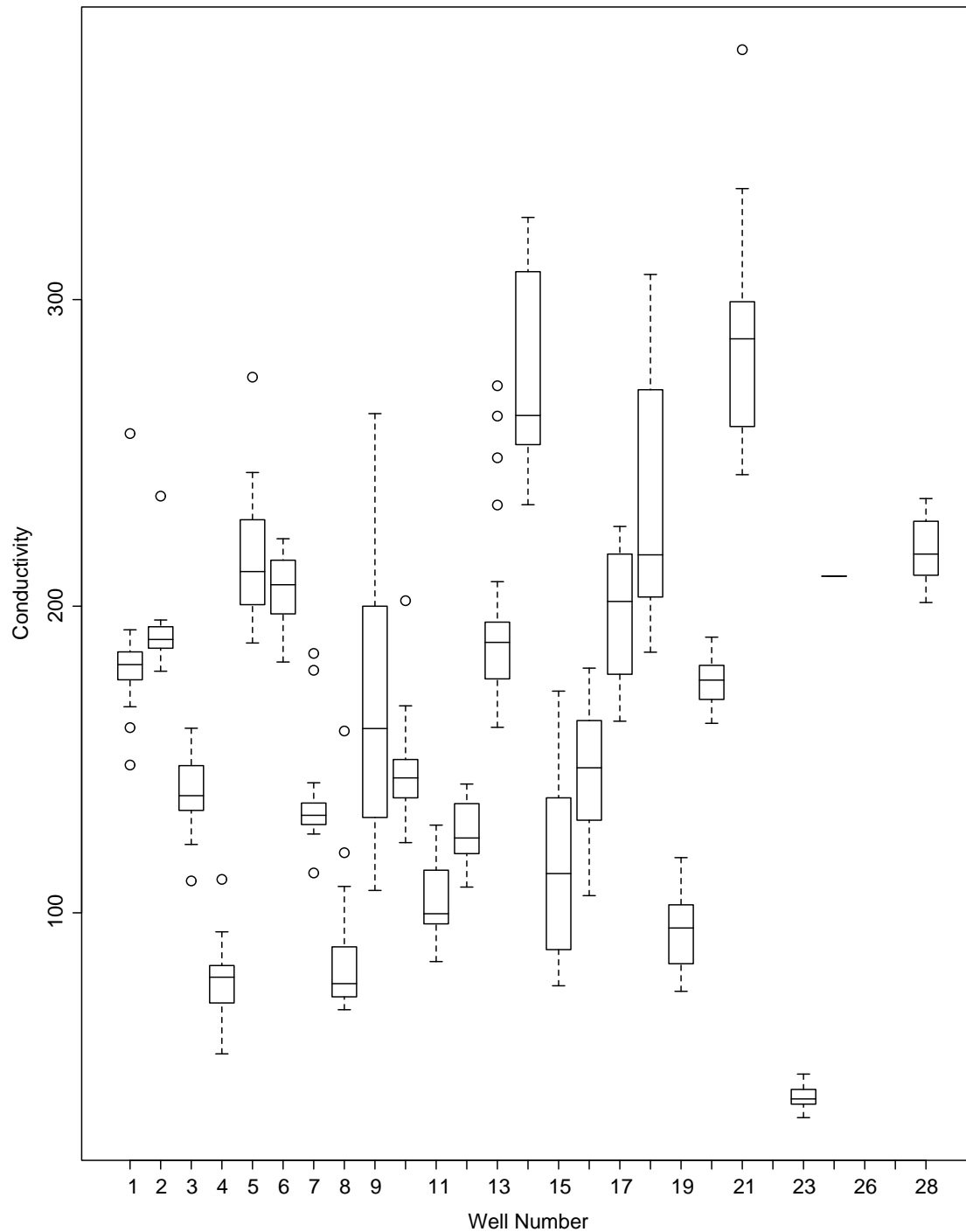


Figure 16: Boxplot of conductivity values. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

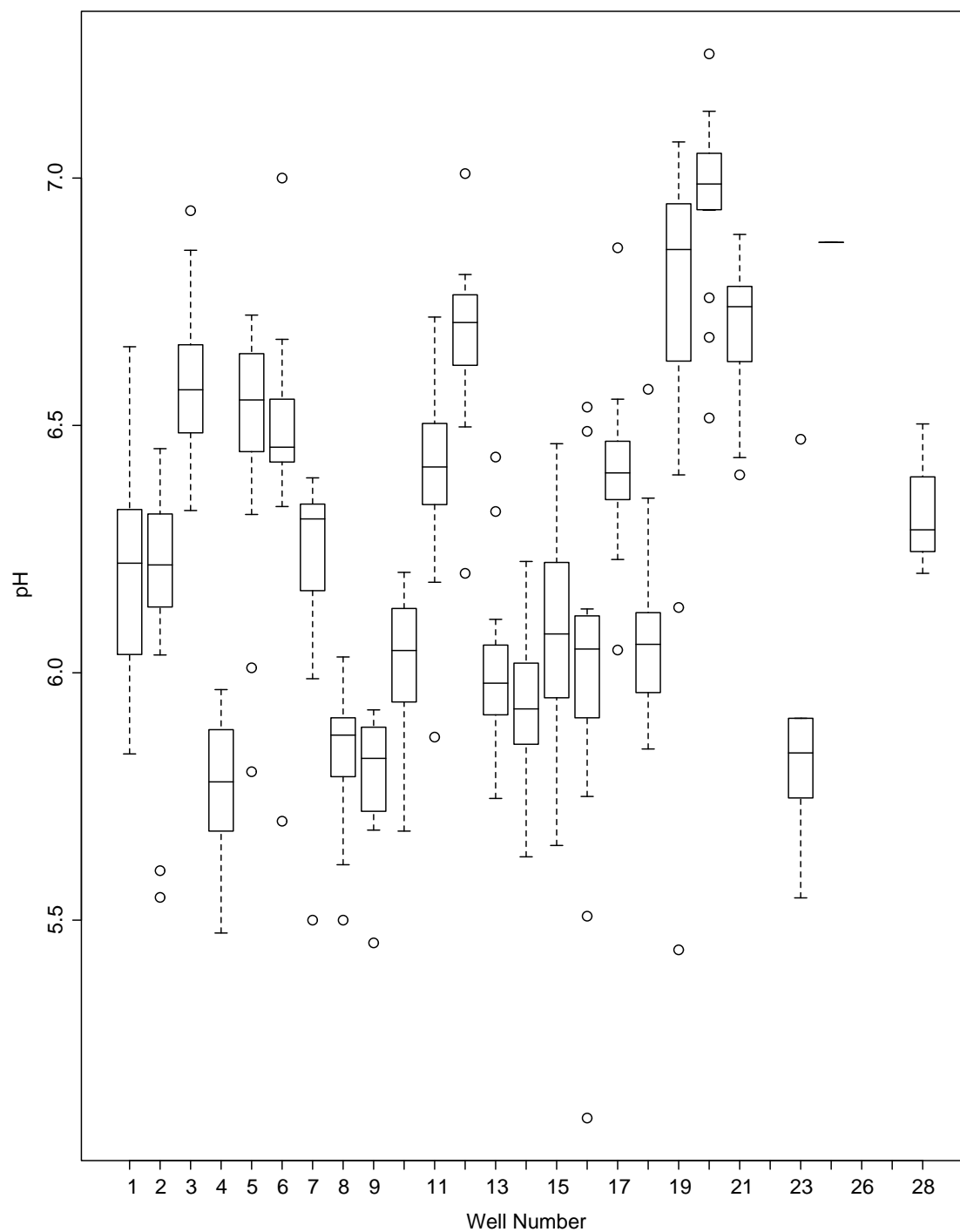


Figure 17: Boxplot of pH values. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

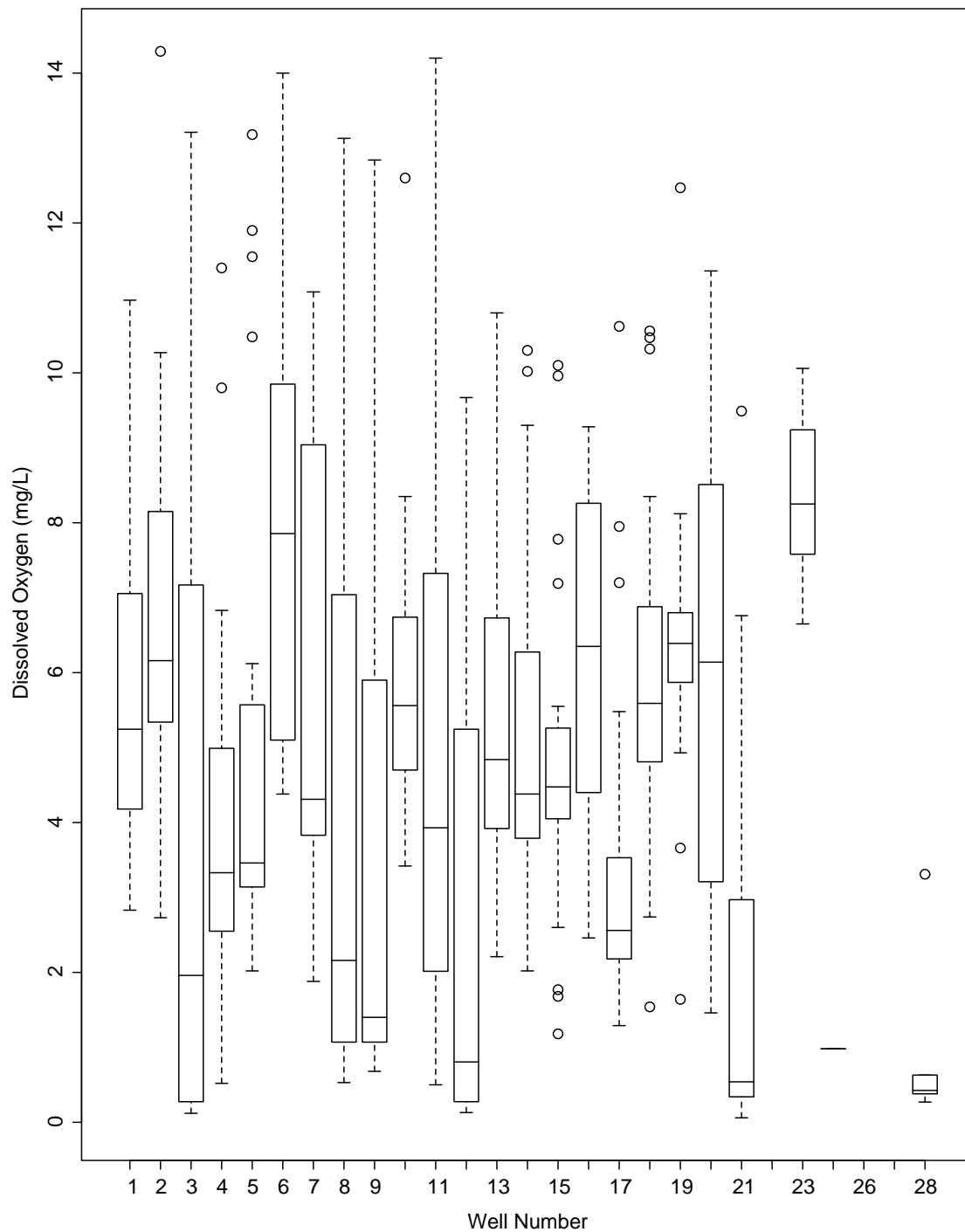


Figure 18: Boxplot of dissolved oxygen concentrations. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

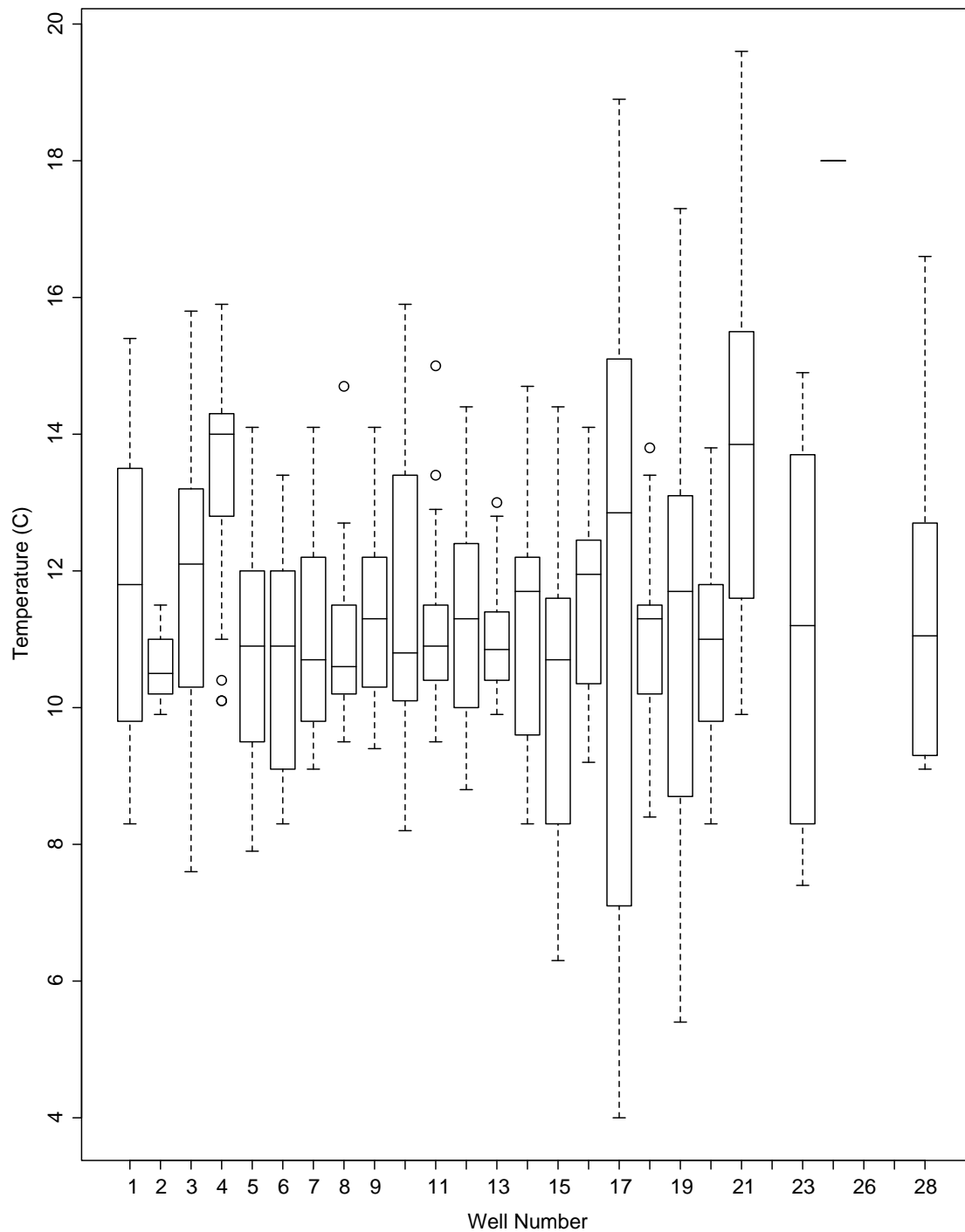


Figure 19: Boxplot of ground water temperatures. Boxes indicate the median and upper/lower 25% quartiles; whiskers show upper/lower 50% quartiles; outliers are $\geq 1.5 \times$ interquartile range. Wells 25 and 27 are not plotted (see text for discussion).

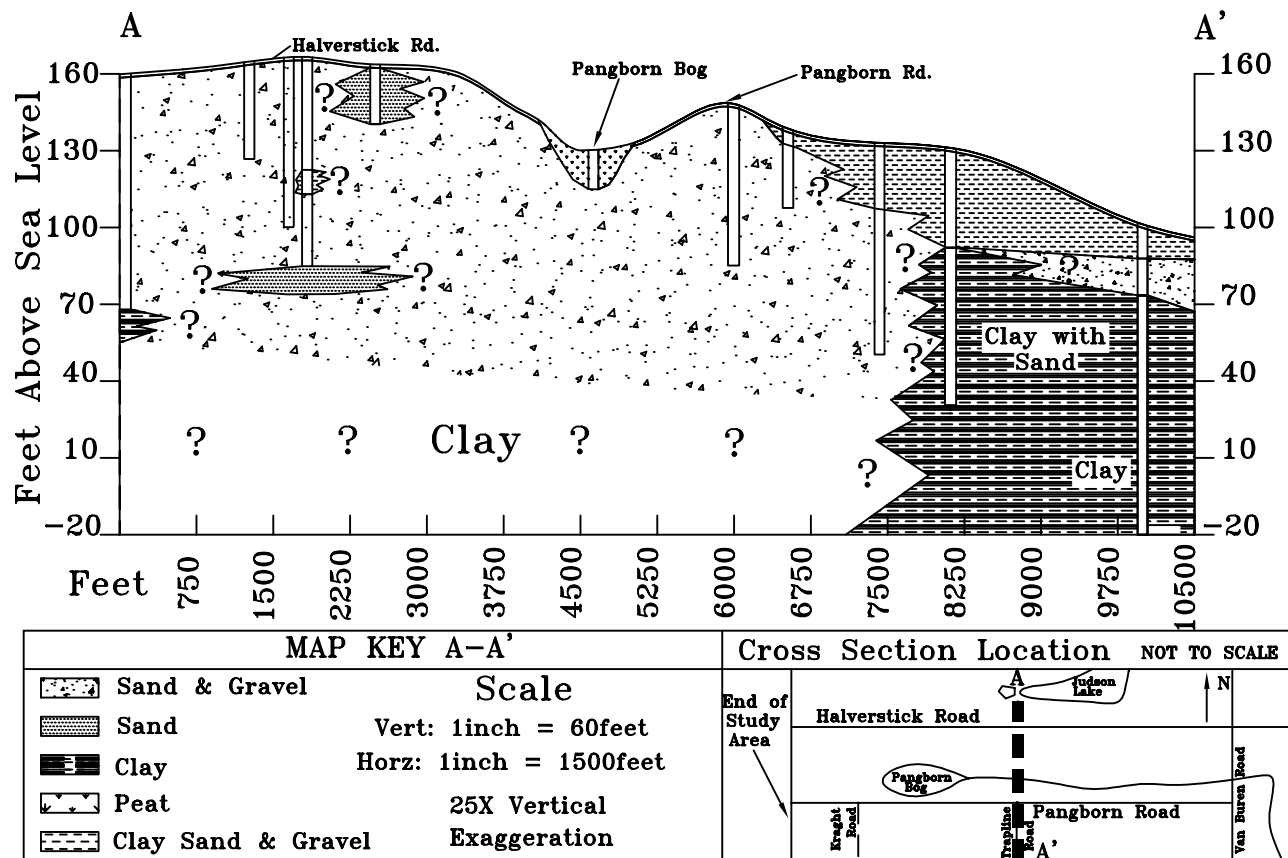


Figure 20: Geologic cross section A-A'.

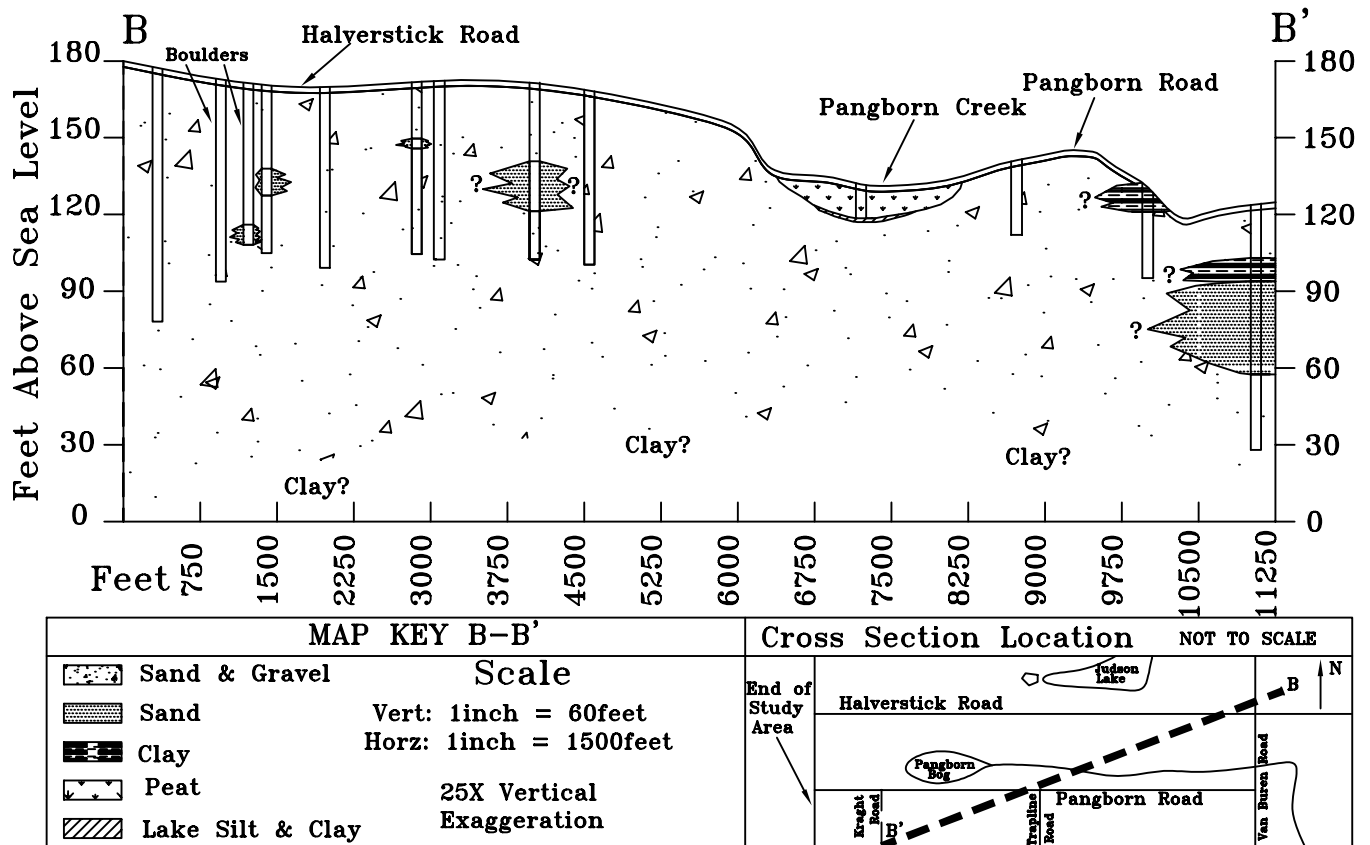


Figure 21: Geologic cross section B-B'.

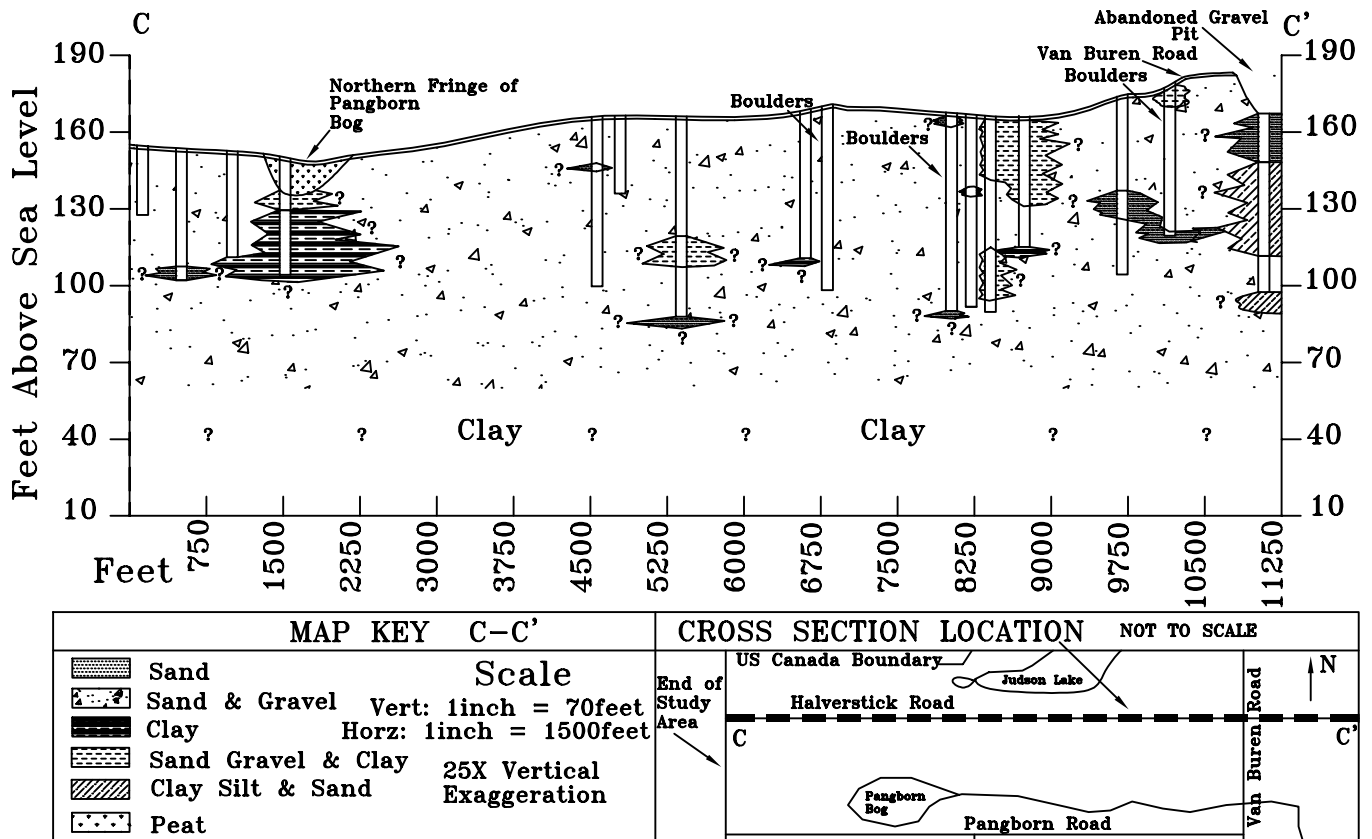


Figure 22: Geologic cross section C-C'.

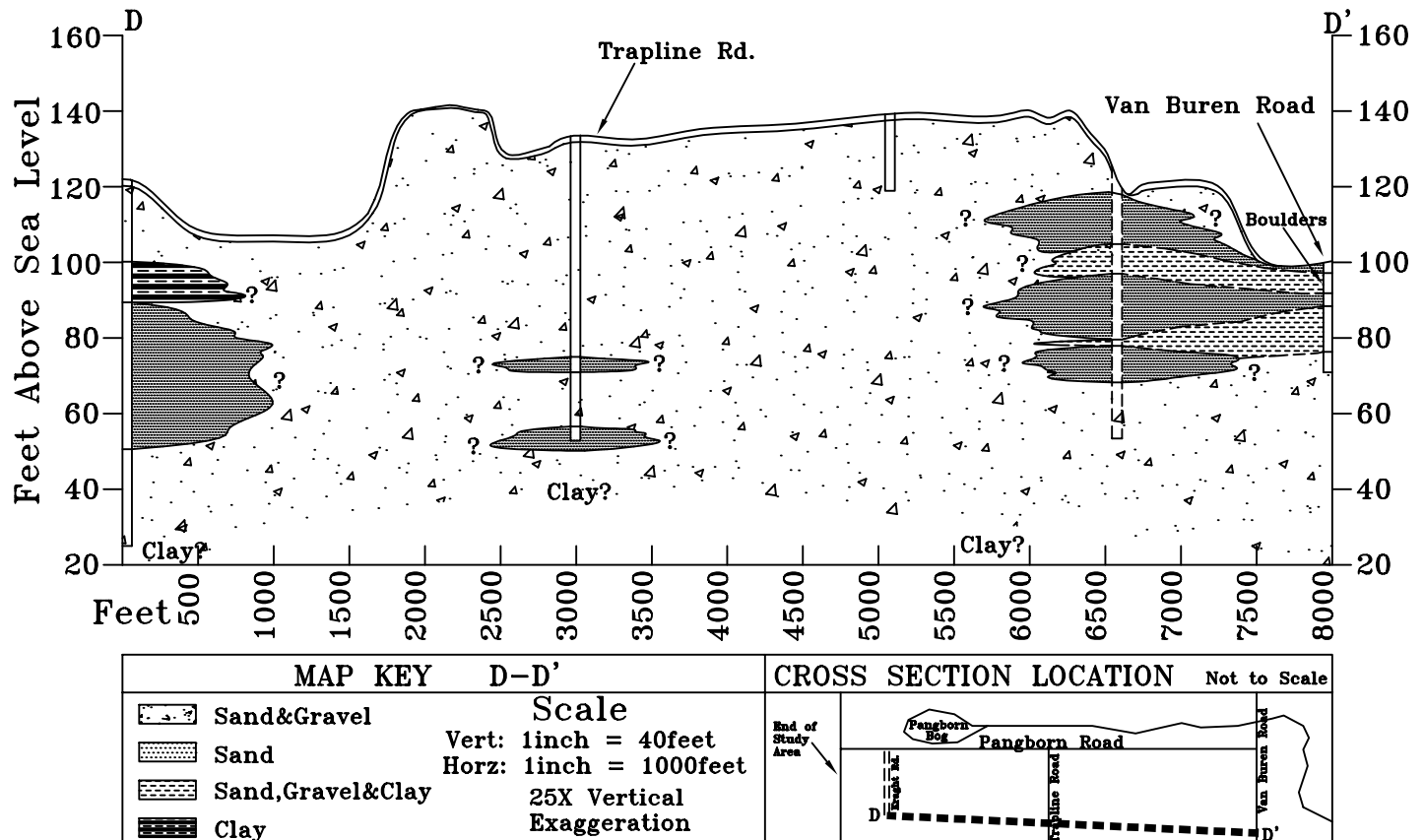


Figure 23: Geologic cross section D-D'.

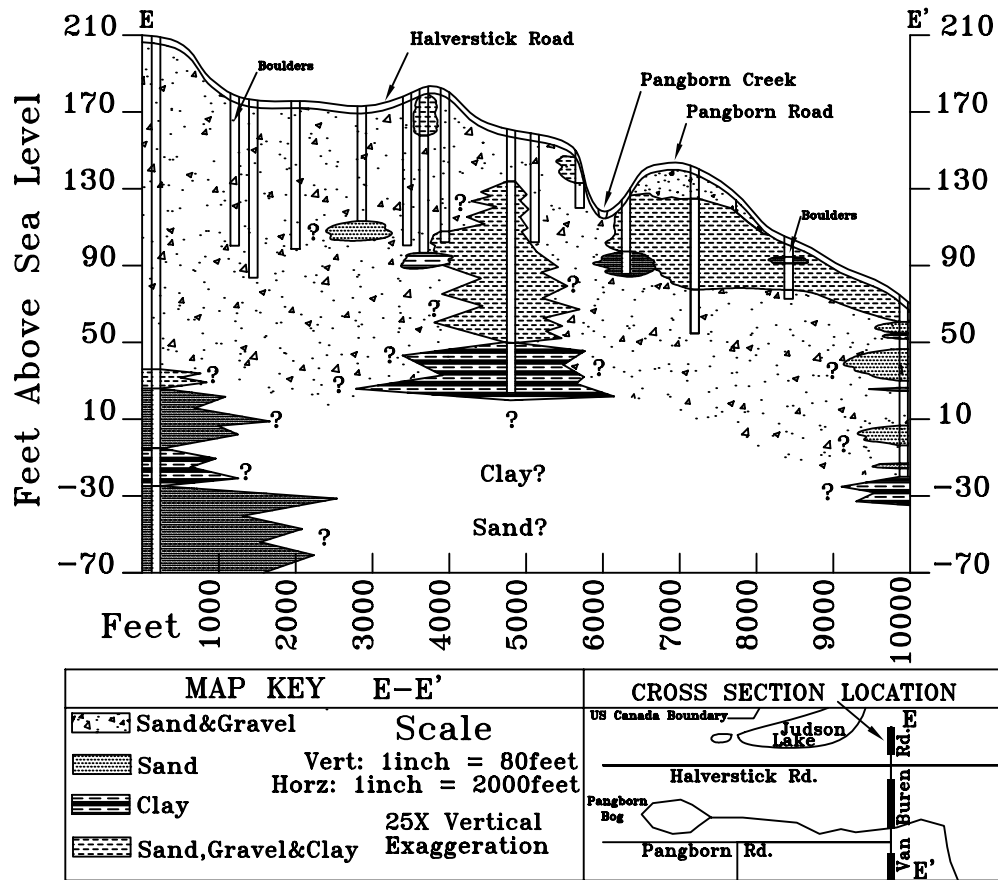


Figure 24: Geologic cross section E-E'.

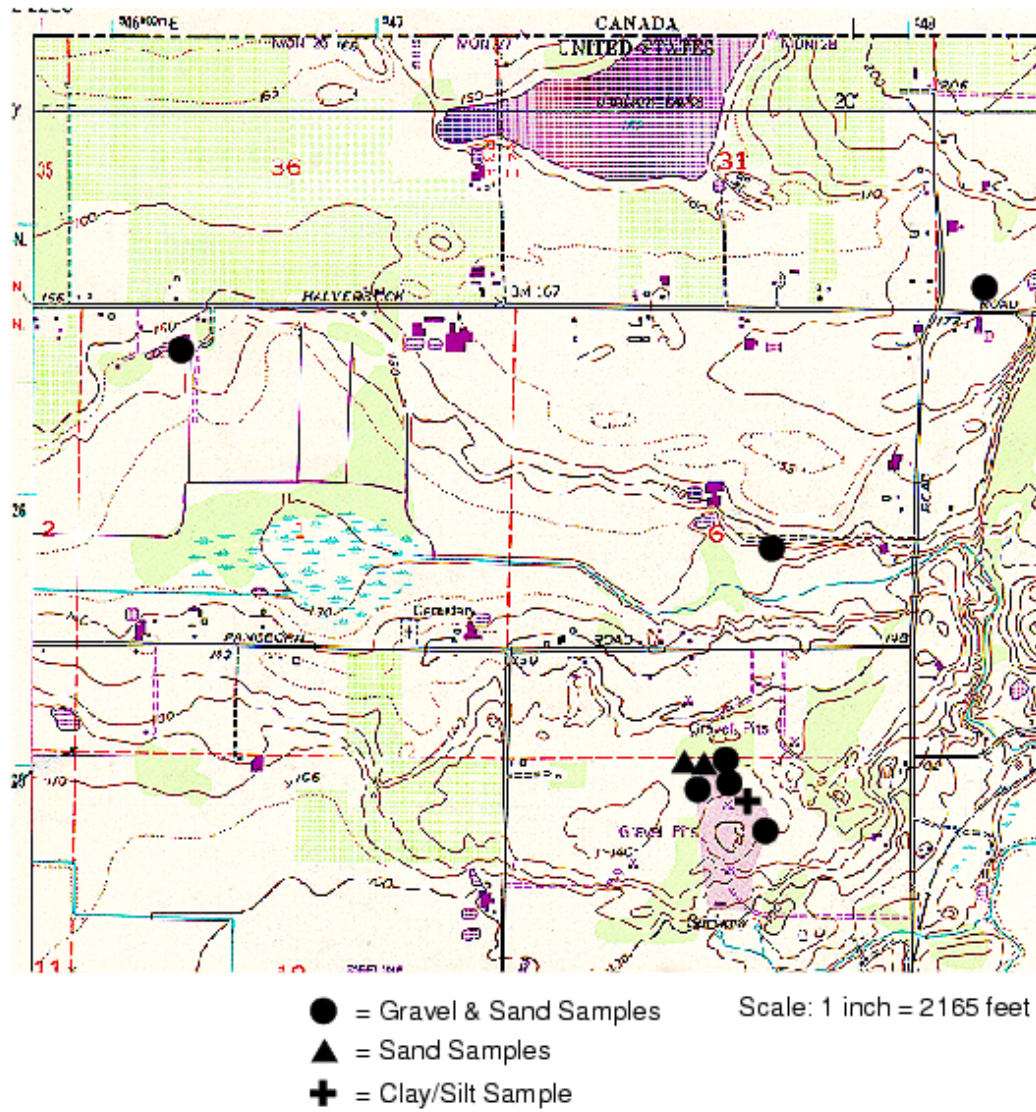


Figure 25: Sumas outwash soil sampling sites.

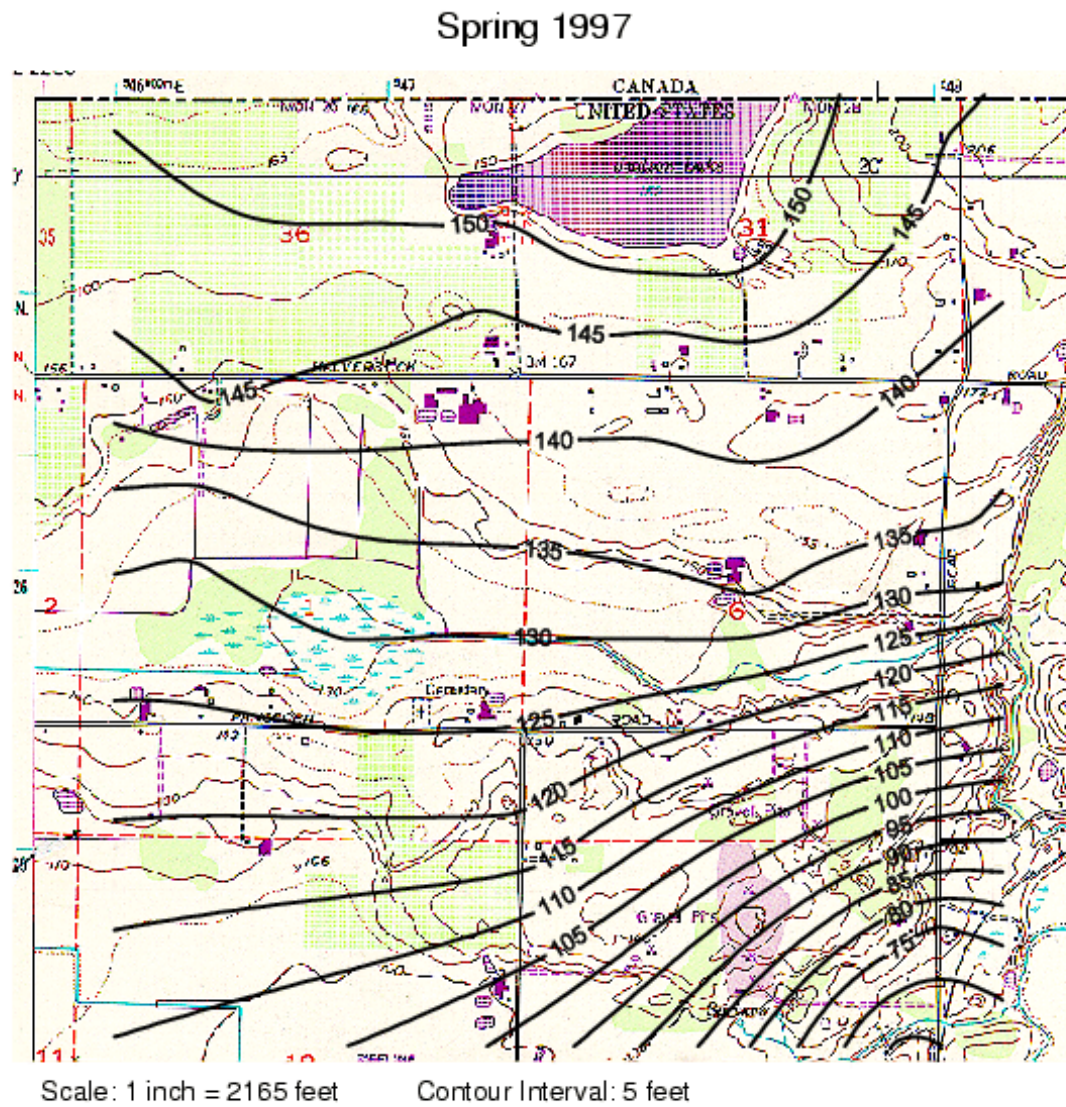


Figure 26: Water table contours, spring 1997.

Summer 1997

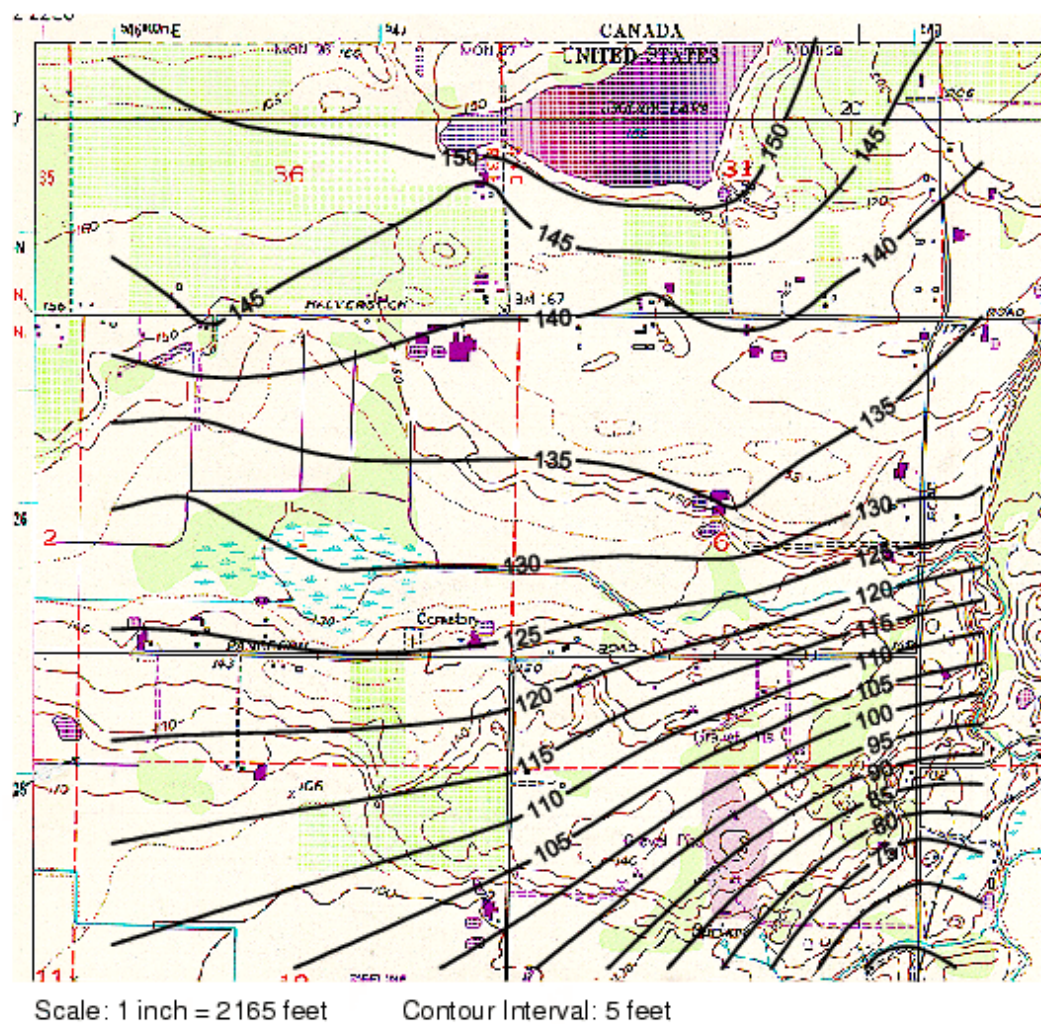


Figure 27: Water table contours, summer 1997.

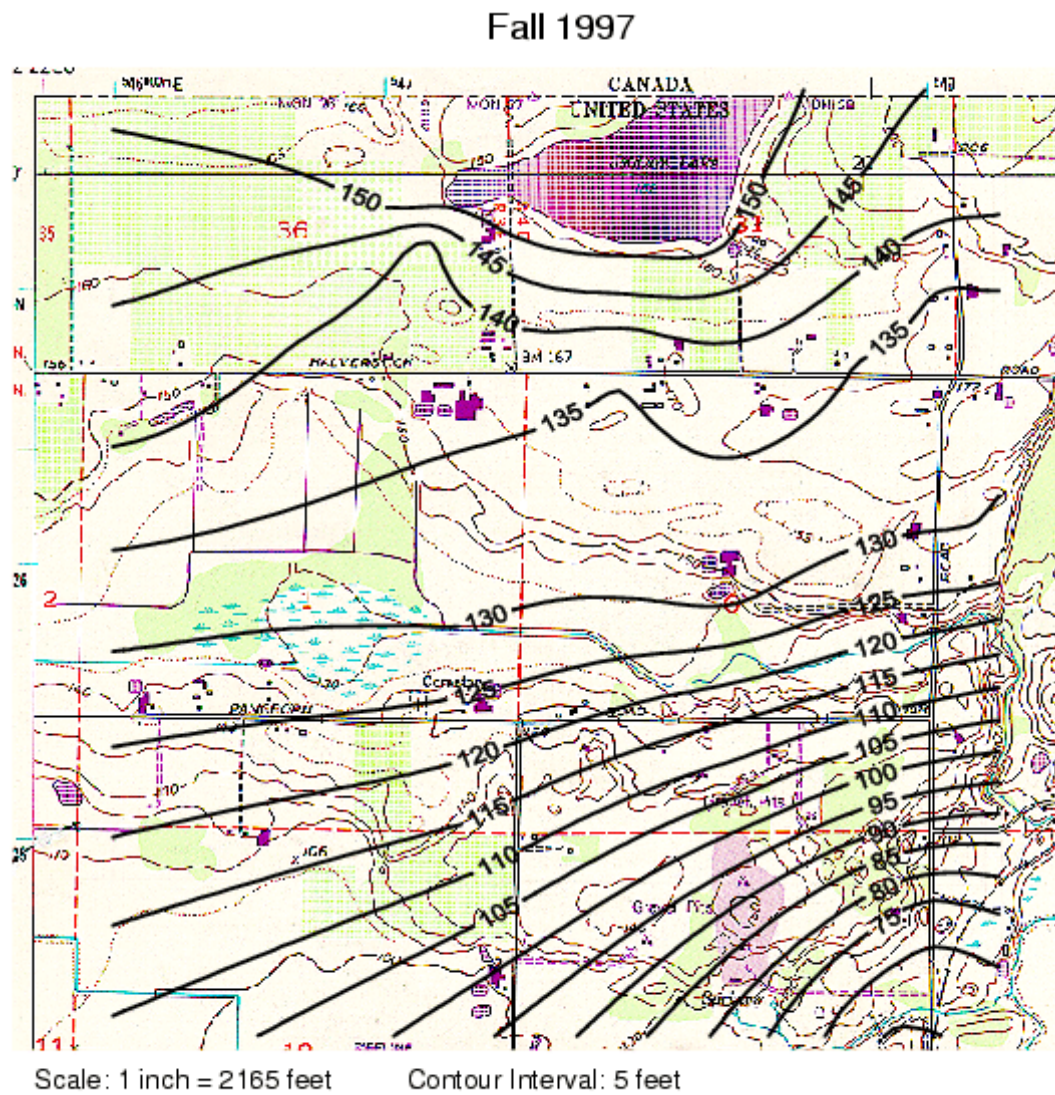
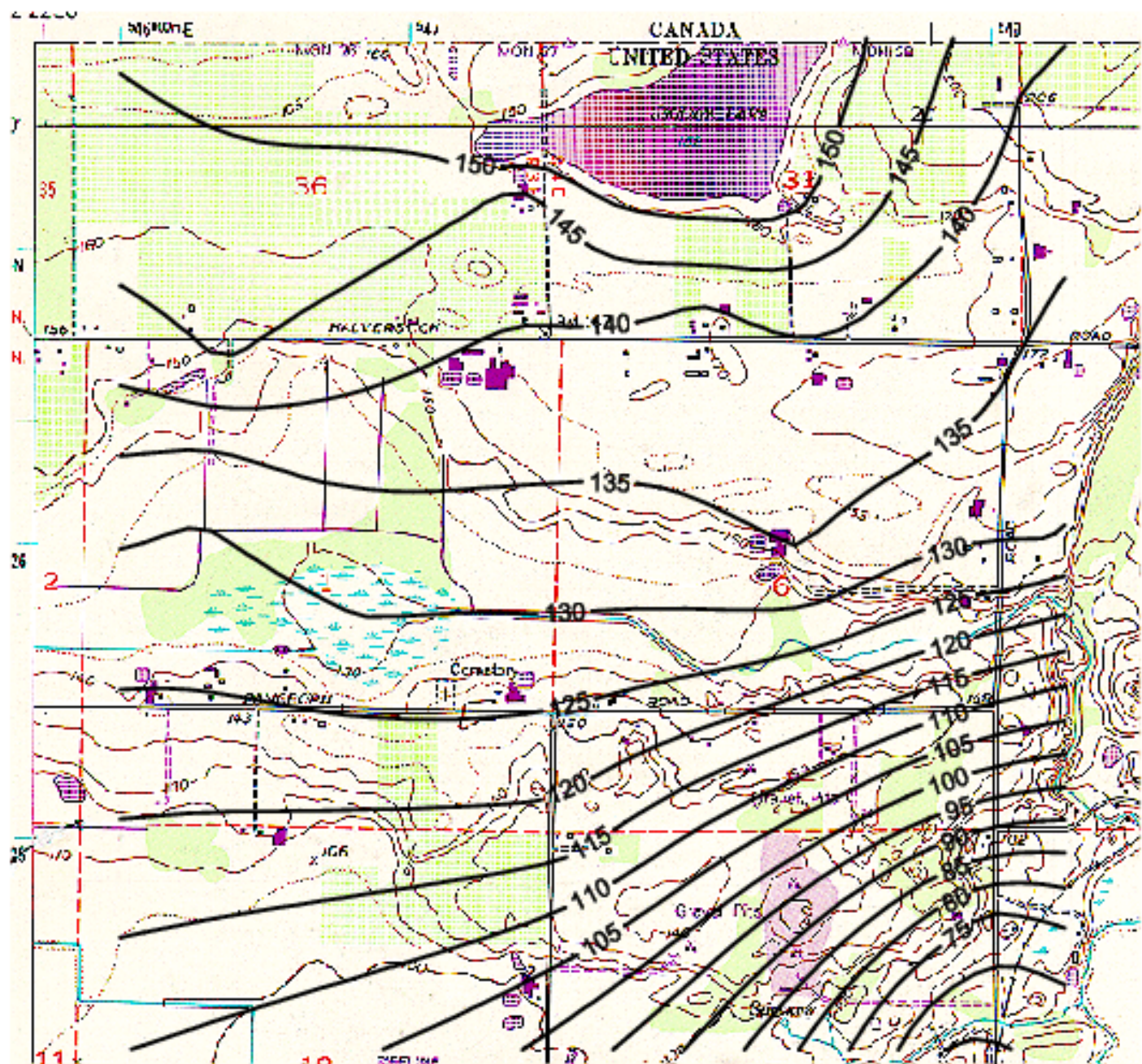


Figure 28: Water table contours, fall 1997.

Winter 1998



Scale: 1 inch = 2165 feet

Contour Interval: 5 feet

Figure 29: Water table contours, winter 1997.

Spring 1998

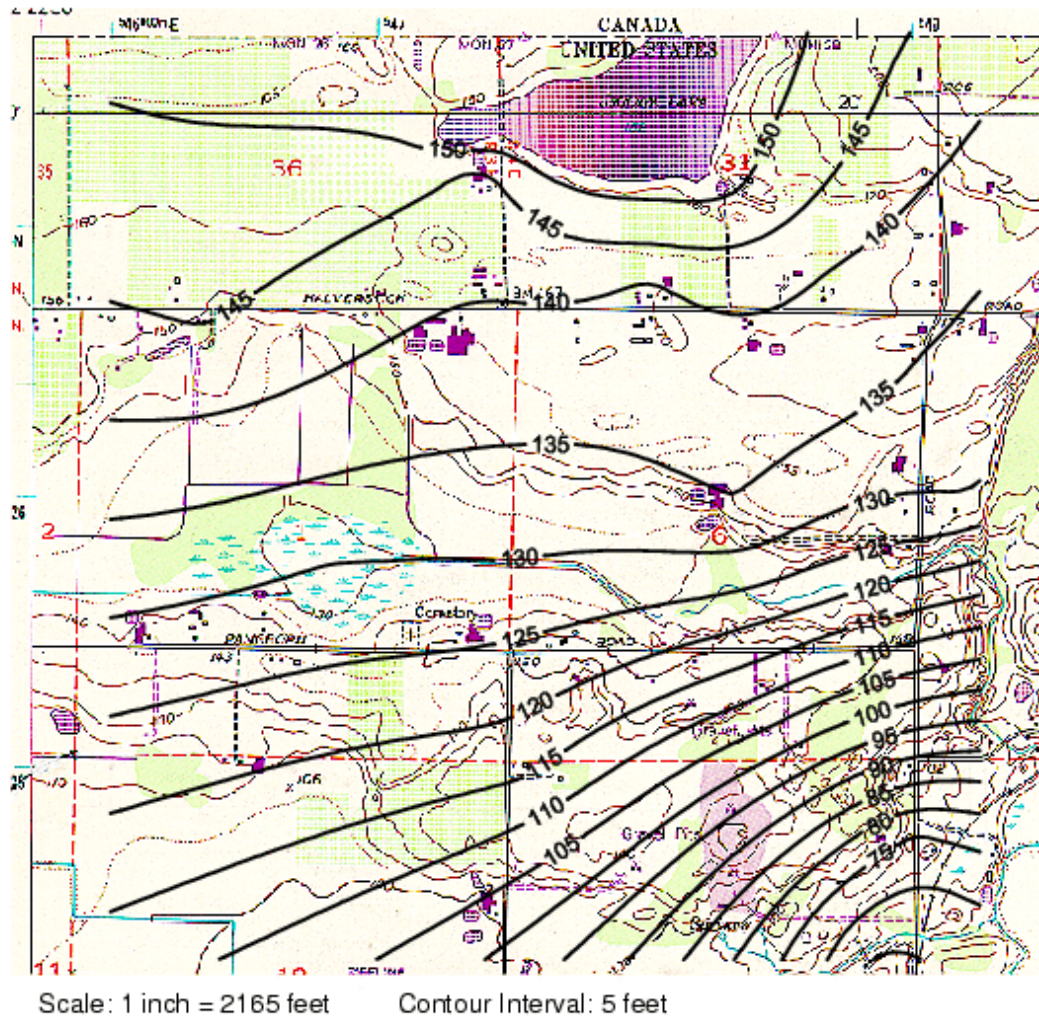


Figure 30: Water table contours, spring 1998.

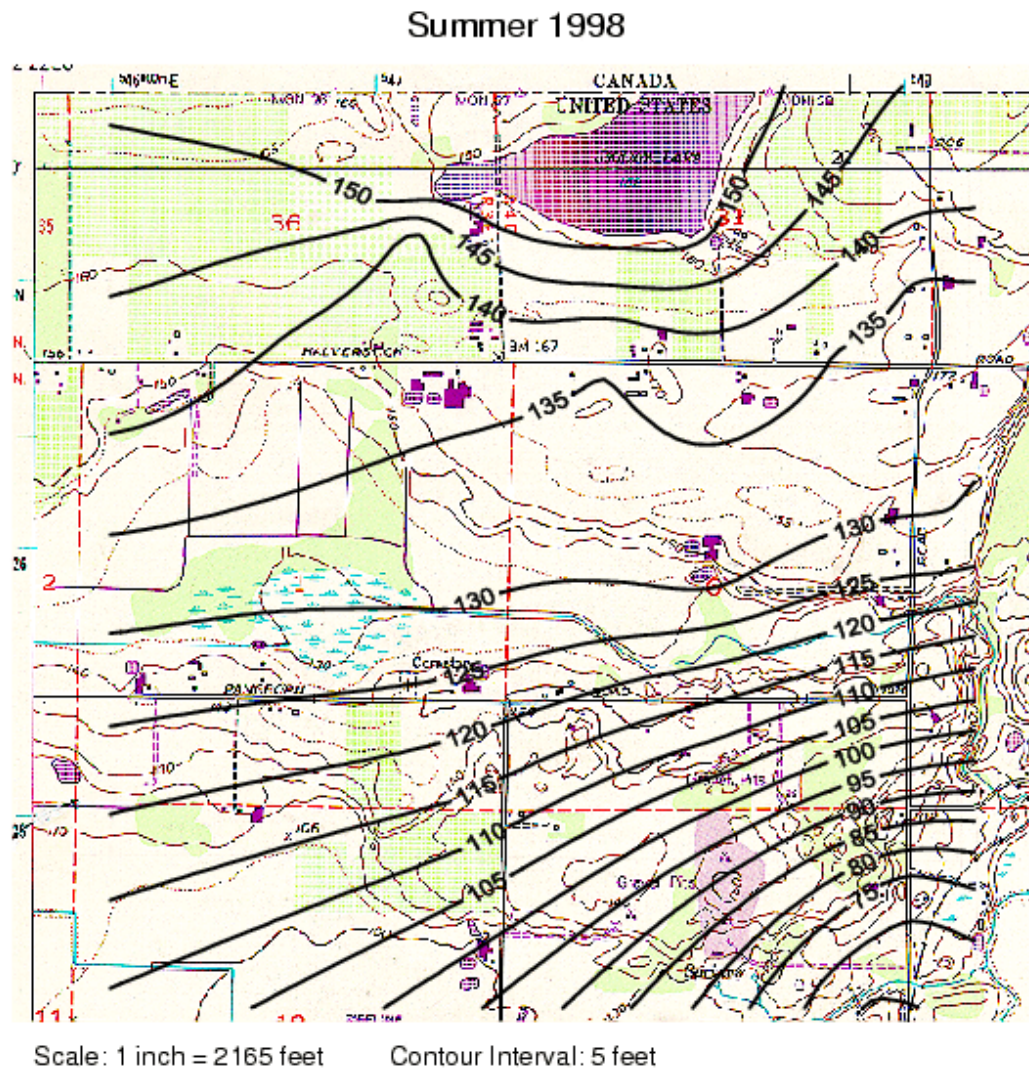


Figure 31: Water table contours, summer 1998.

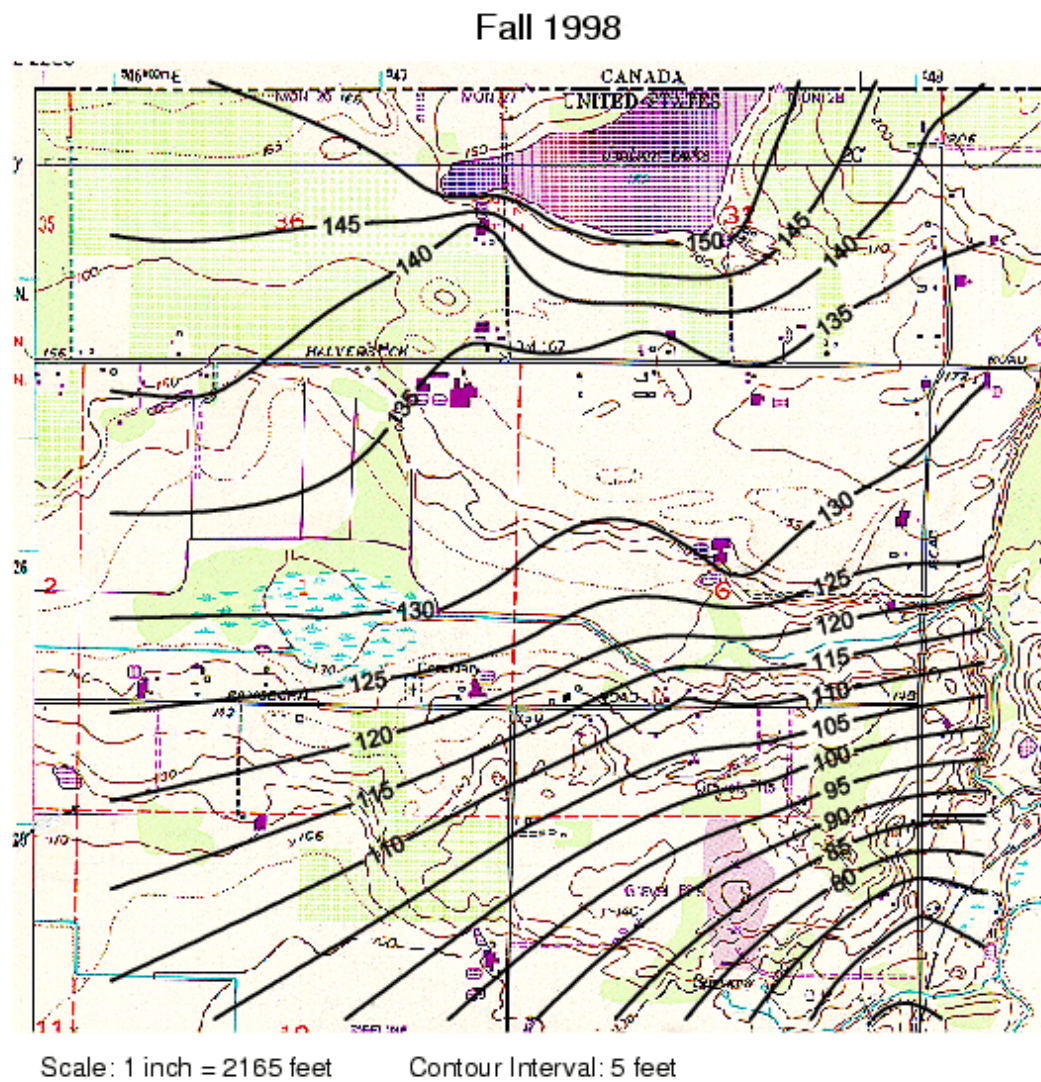
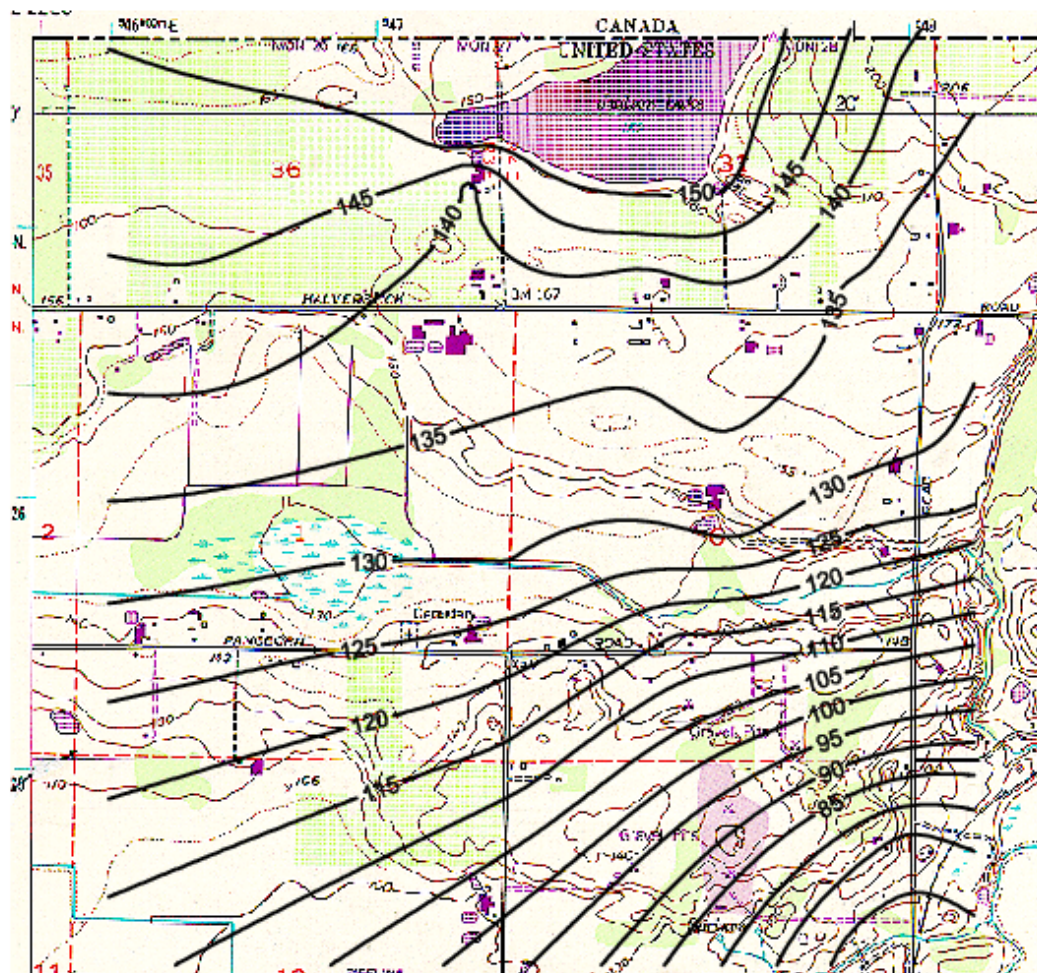


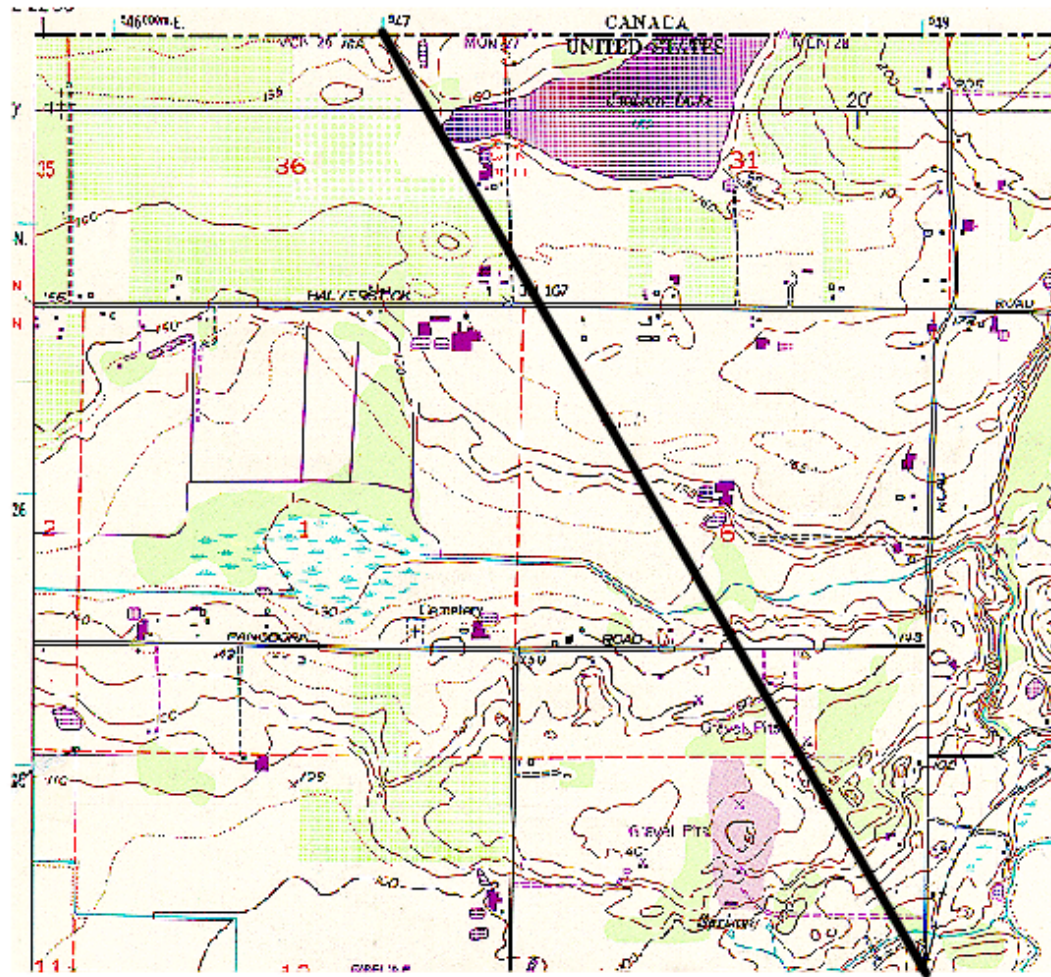
Figure 32: Water table contours, fall 1998.

Winter 1999



Scale: 1 inch = 2165 feet Contour Interval: 5 feet

Figure 33: Water table contours, winter 1998.



Scale: 1 inch = 2165 feet

Figure 34: Northwest-southeast transect used to generate water table profiles.

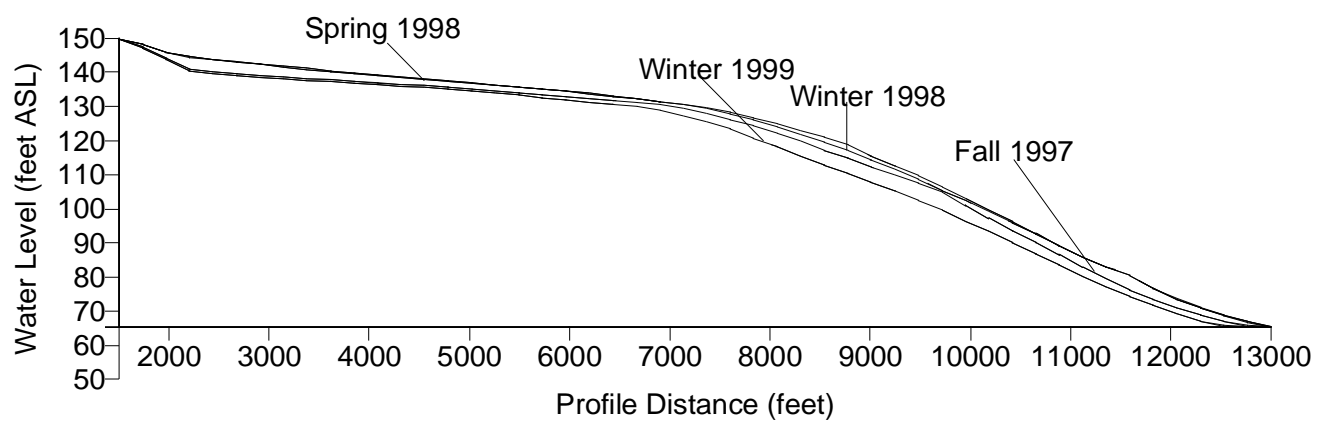


Figure 35: Water table profiles showing seasonal extremes.

Spring 1997

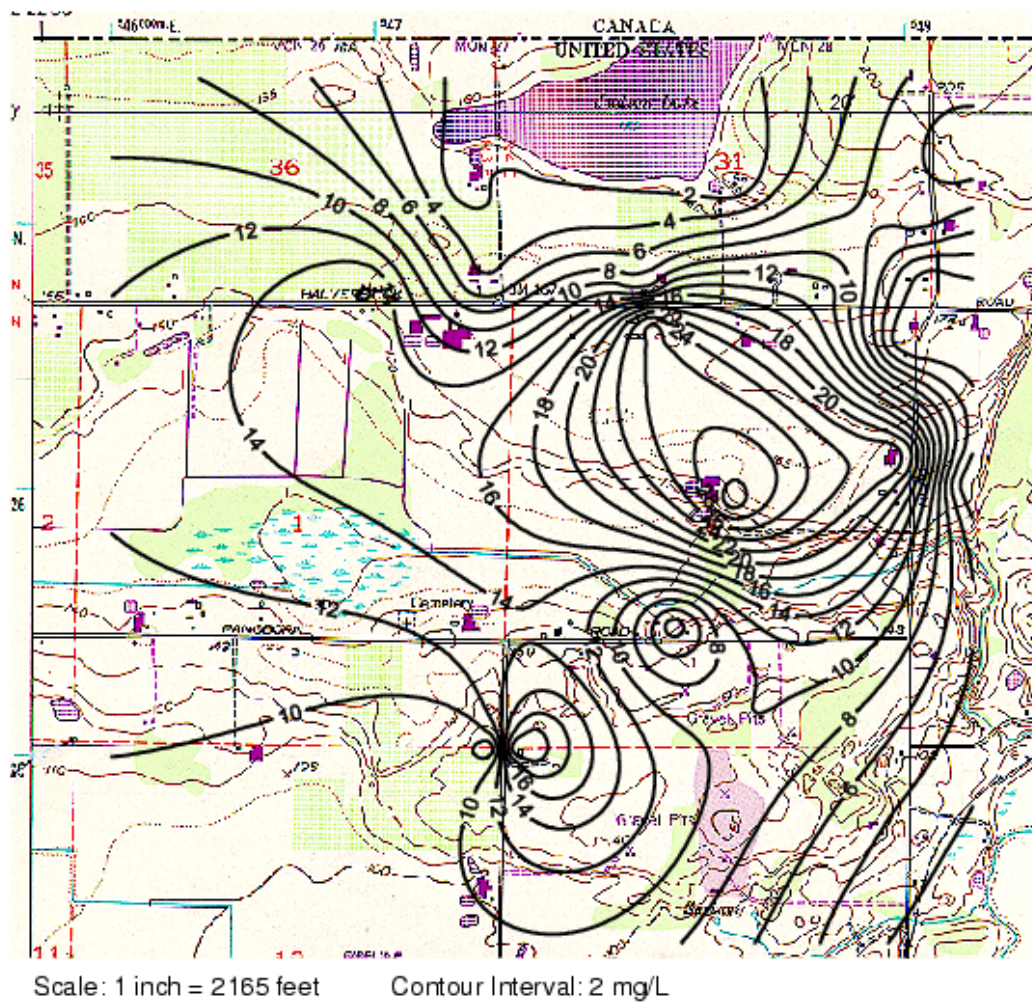


Figure 36: Nitrate contour map, spring 1997.

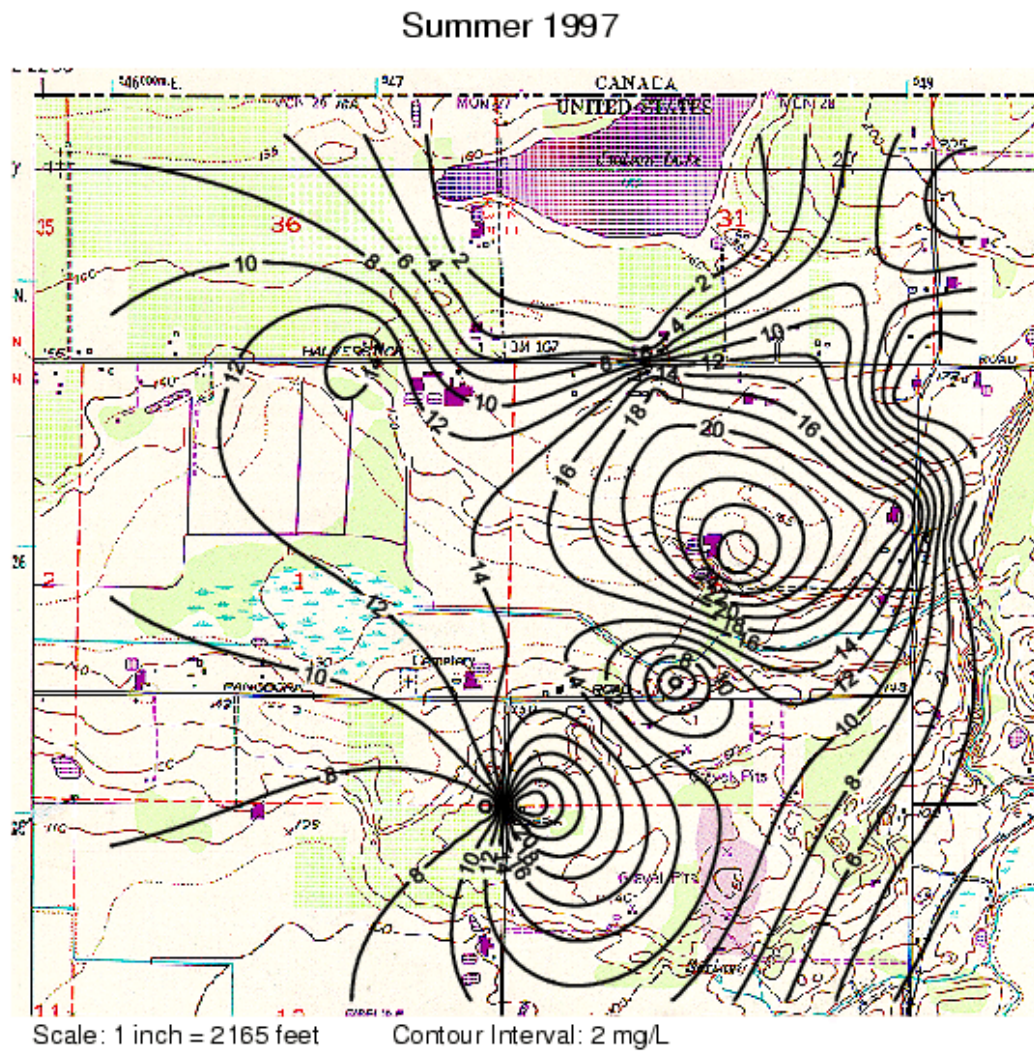


Figure 37: Nitrate contour map, summer 1997.

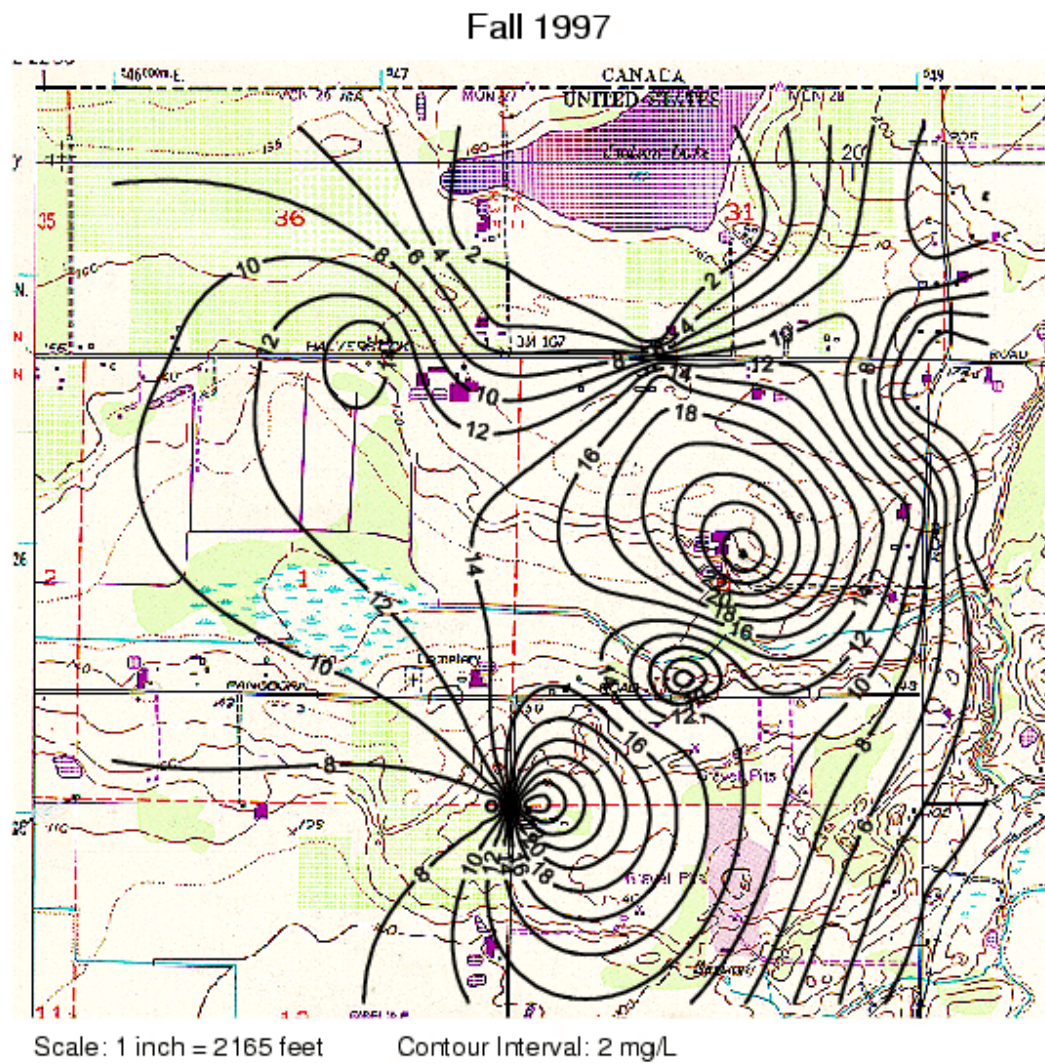


Figure 38: Nitrate contour map, fall 1997.

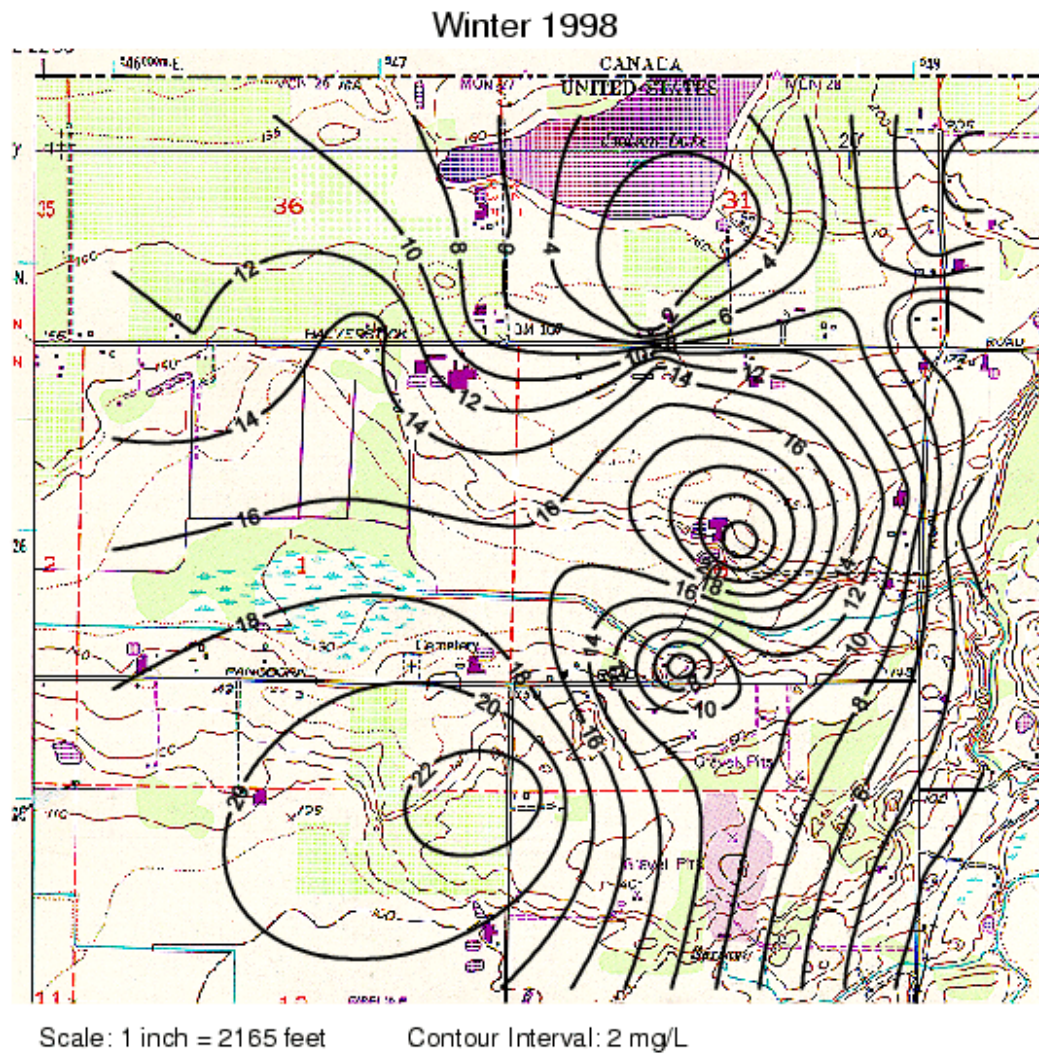


Figure 39: Nitrate contour map, winter 1997.

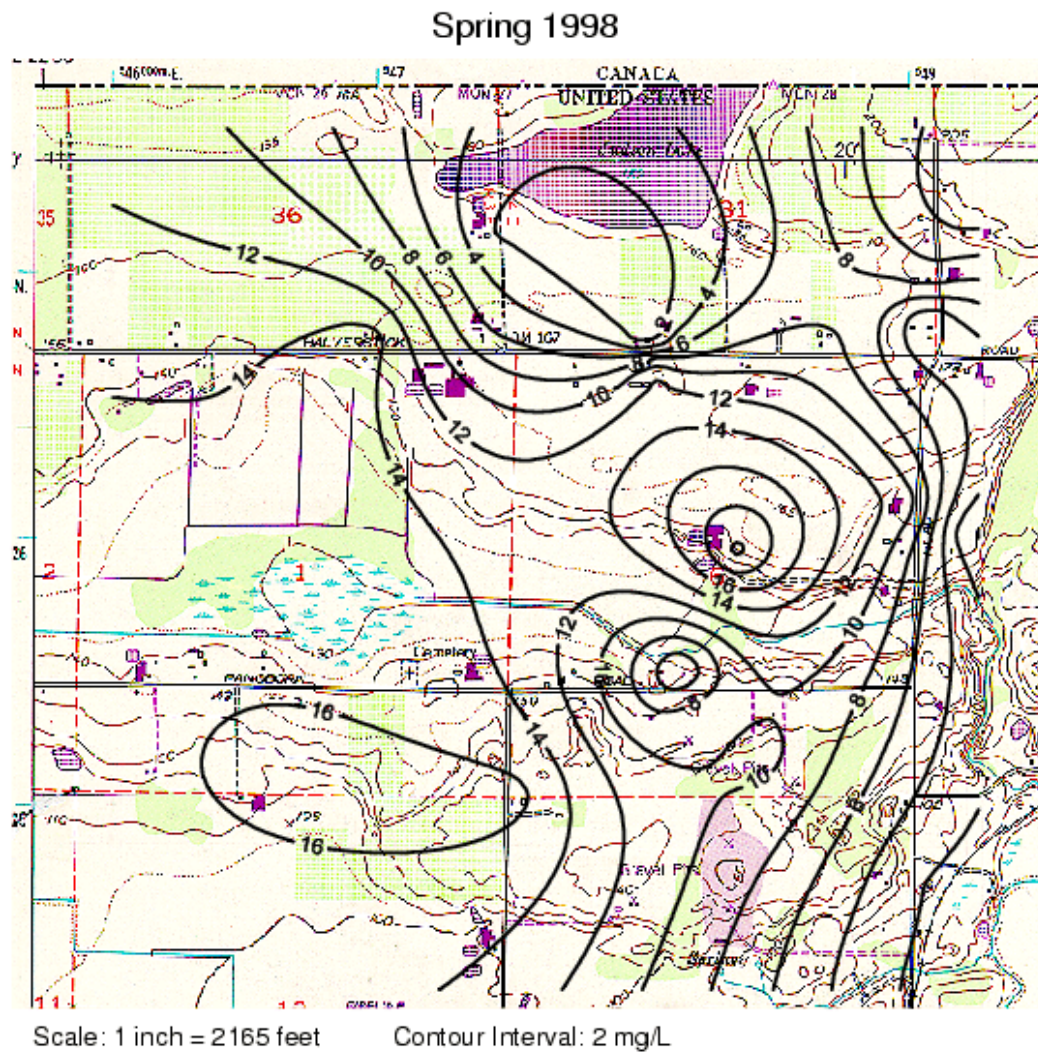


Figure 40: Nitrate contour map, spring 1998.

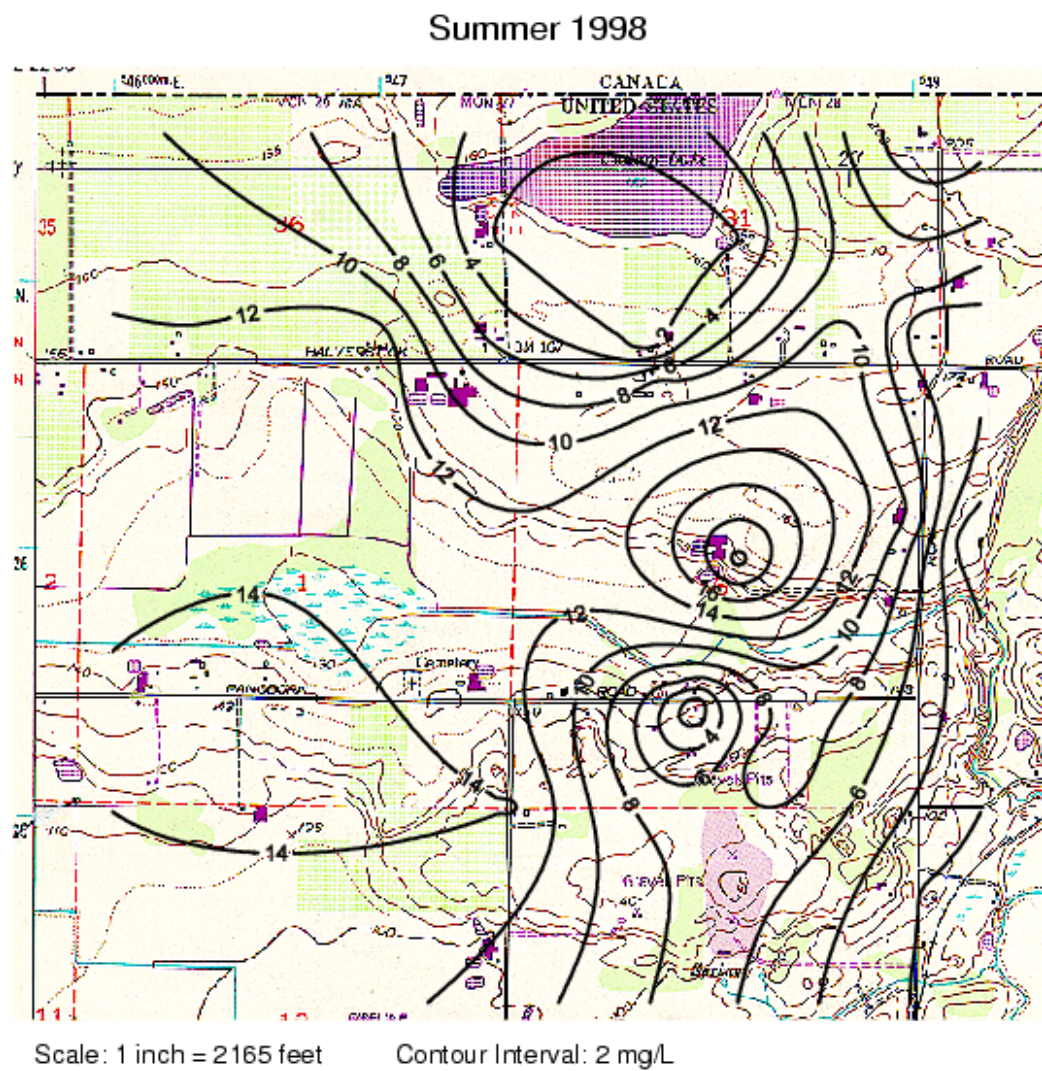


Figure 41: Nitrate contour map, summer 1998.

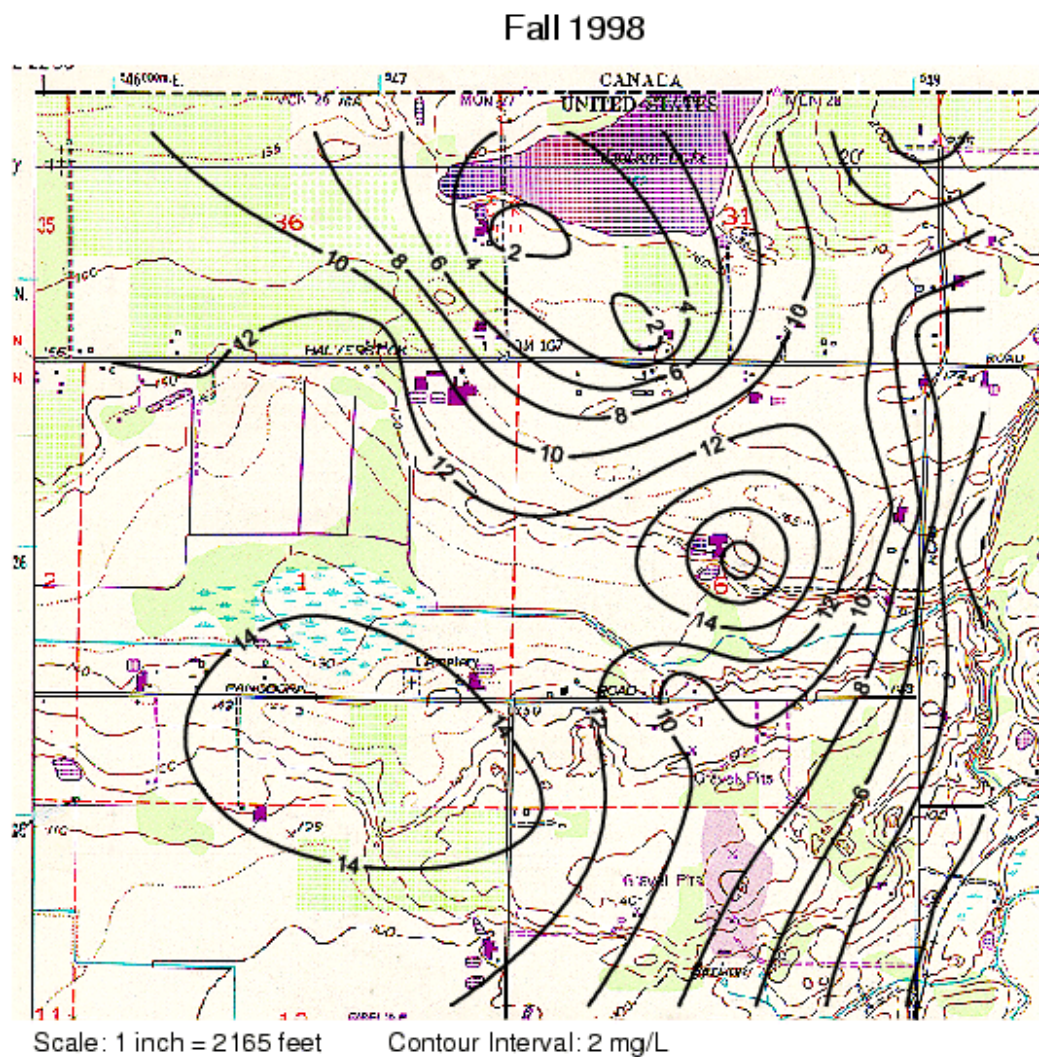


Figure 42: Nitrate contour map, fall 1998.

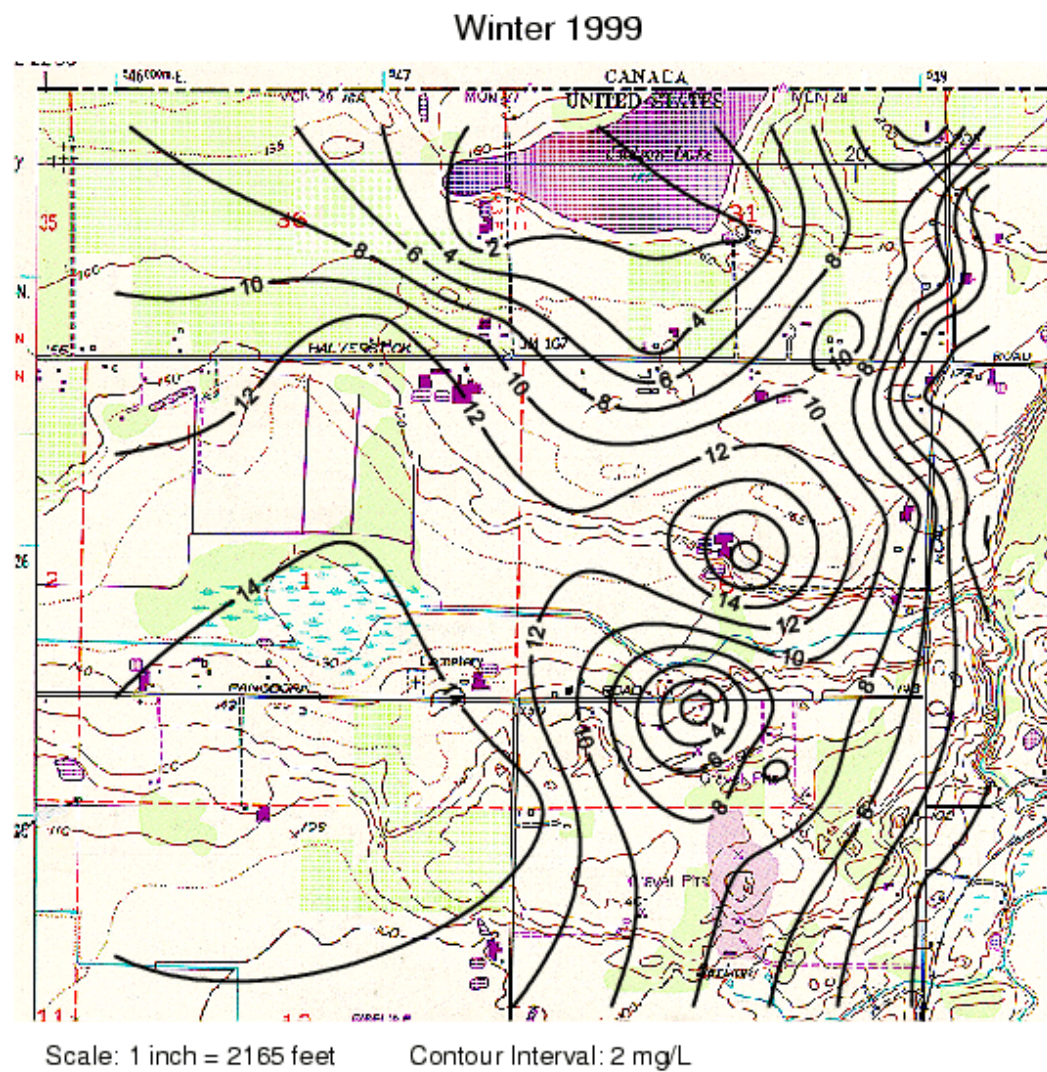


Figure 43: Nitrate contour map, winter 1998.

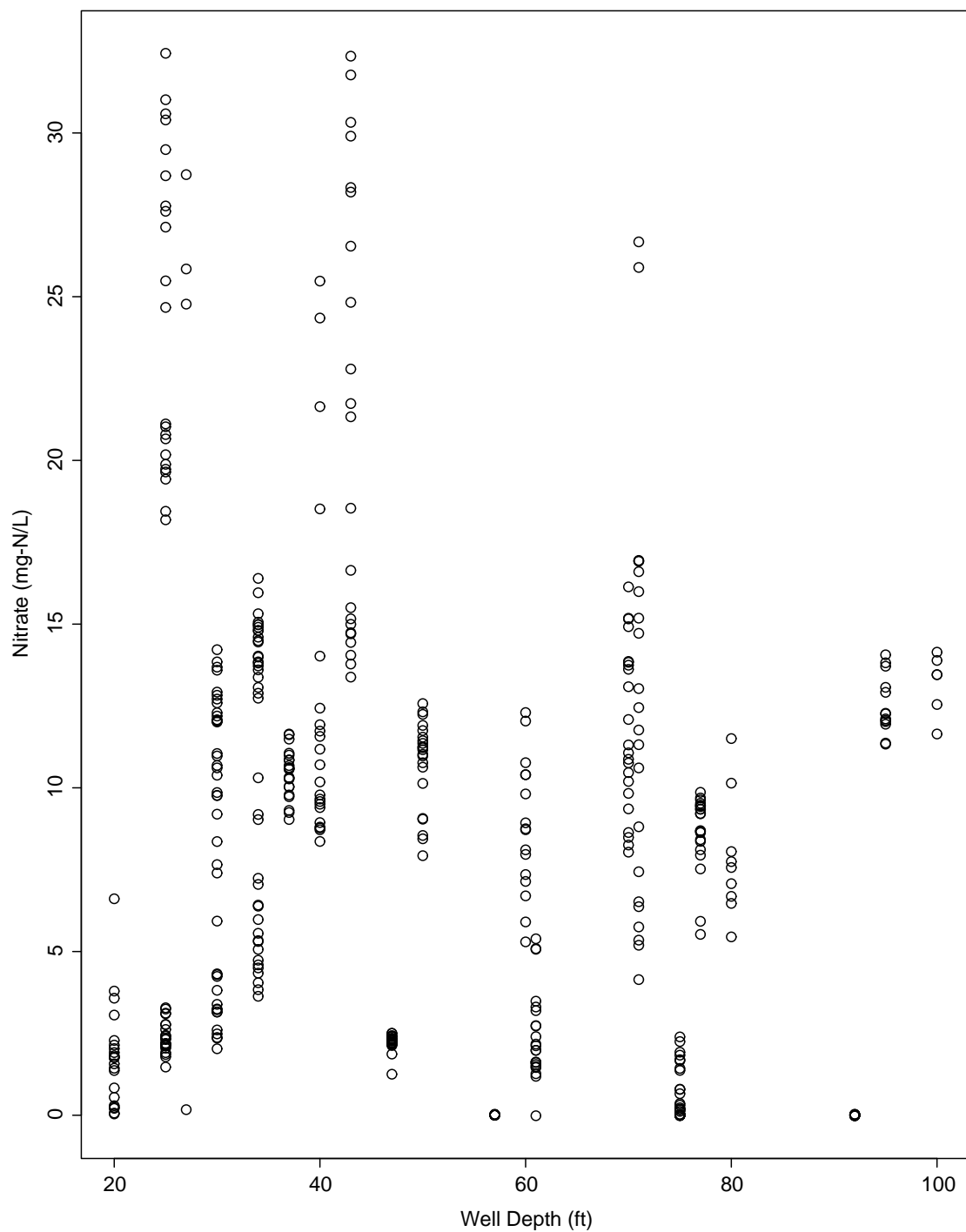


Figure 44: Scatterplot of well depth vs. nitrate concentrations.

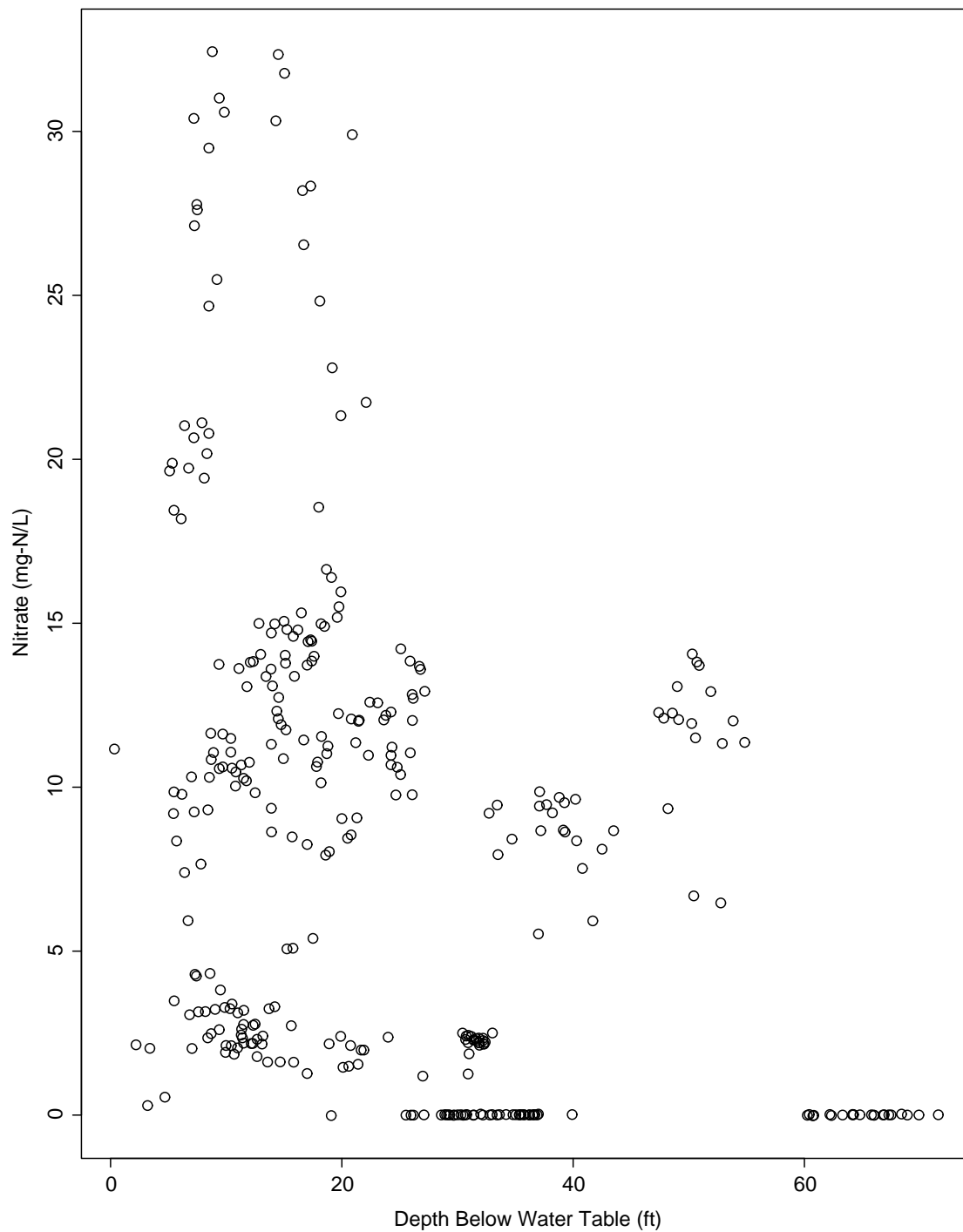


Figure 45: Scatterplot of depth of well below water table vs. nitrate concentrations.

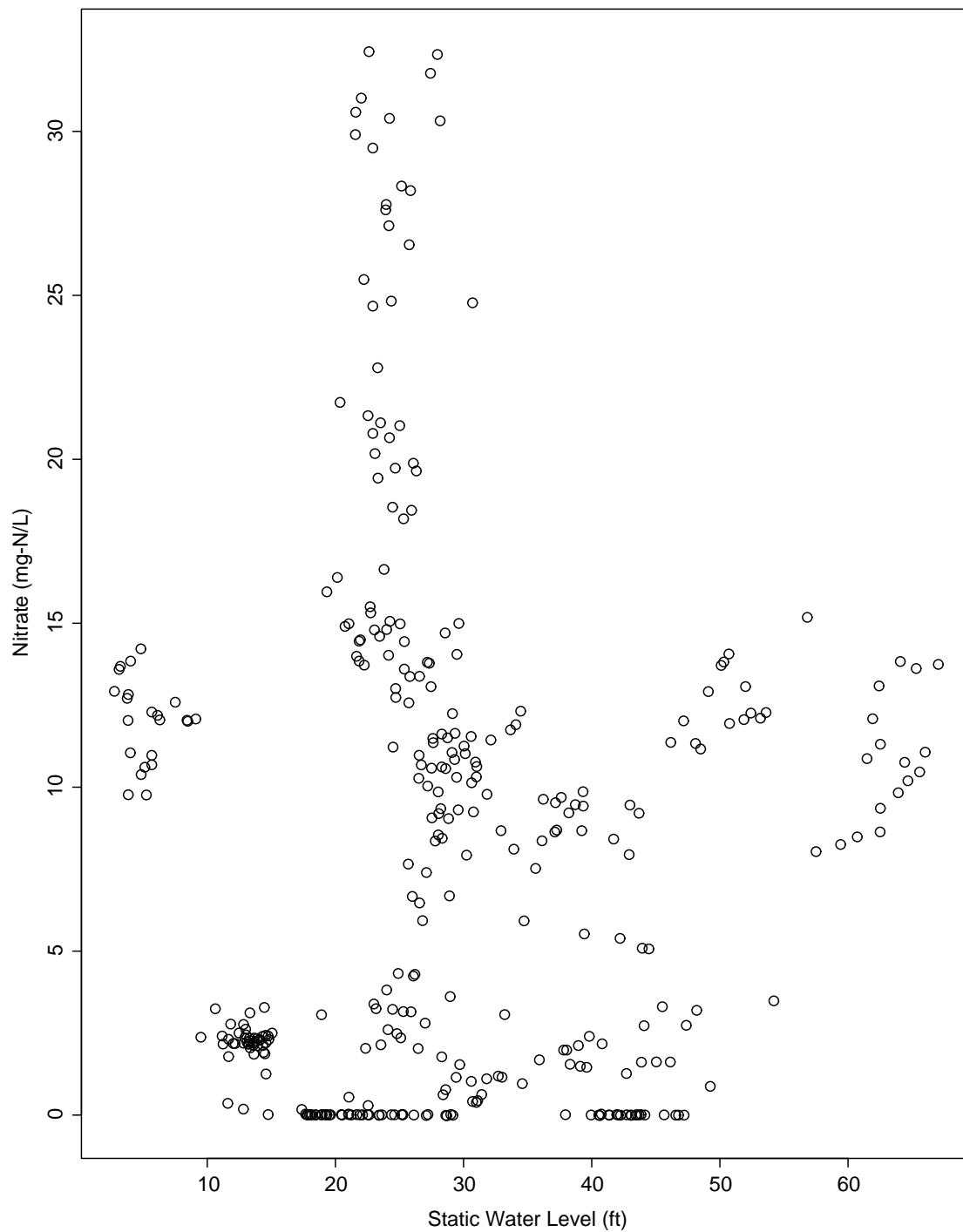


Figure 46: Scatterplot of static water level vs. nitrate concentrations.

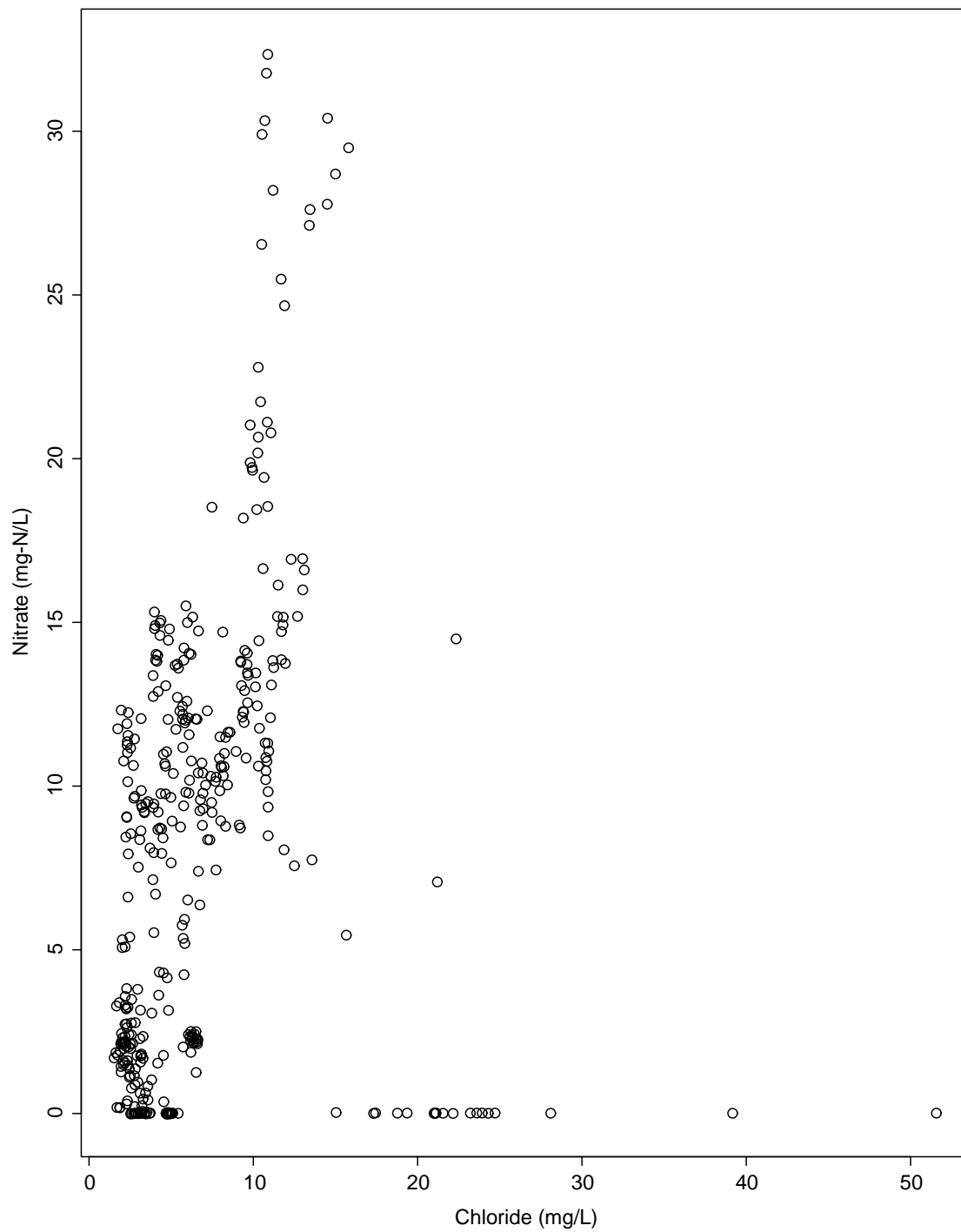


Figure 47: Scatterplot of chloride concentrations vs. nitrate concentrations.

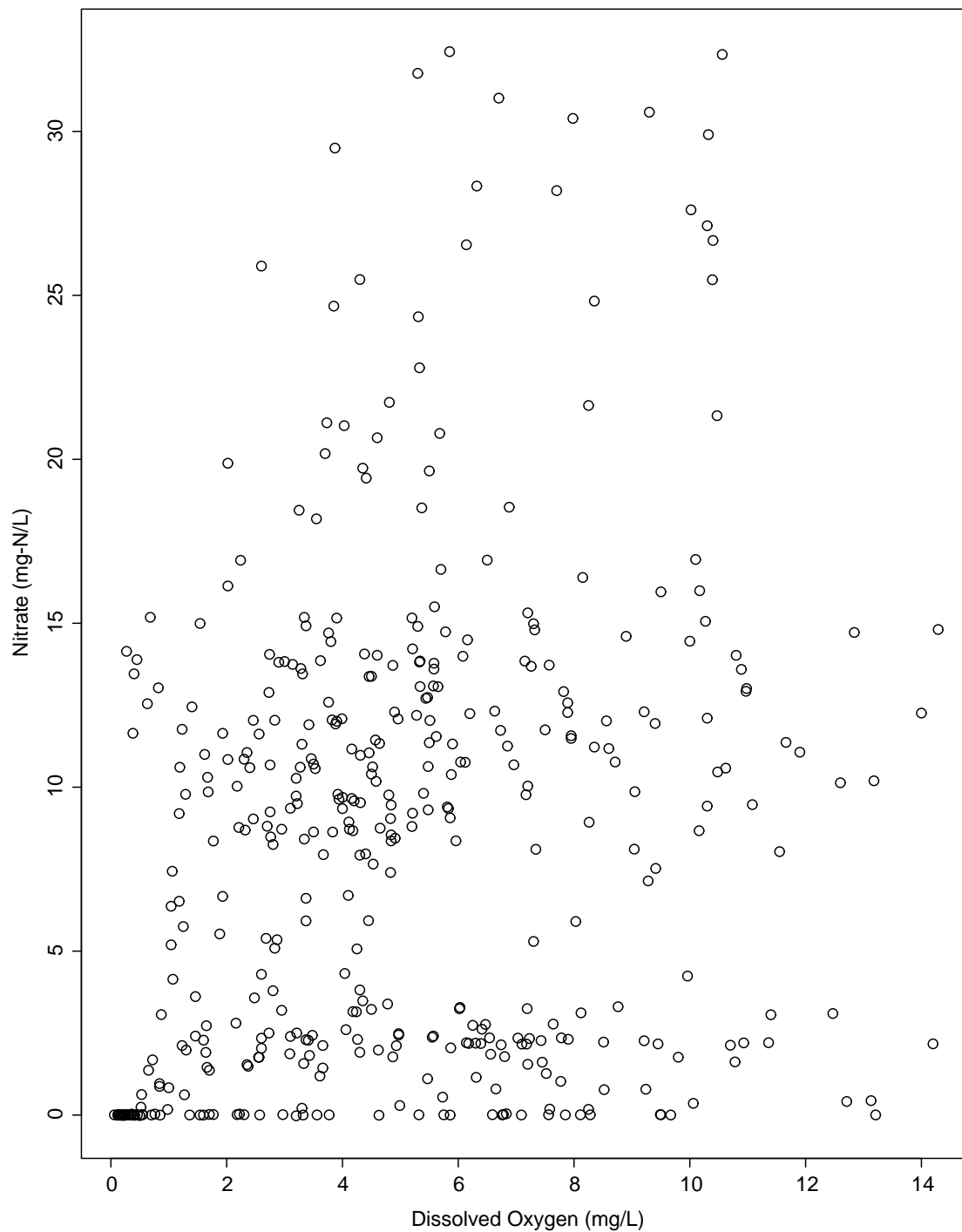


Figure 48: Scatterplot of dissolved oxygen concentrations vs. nitrate concentrations.

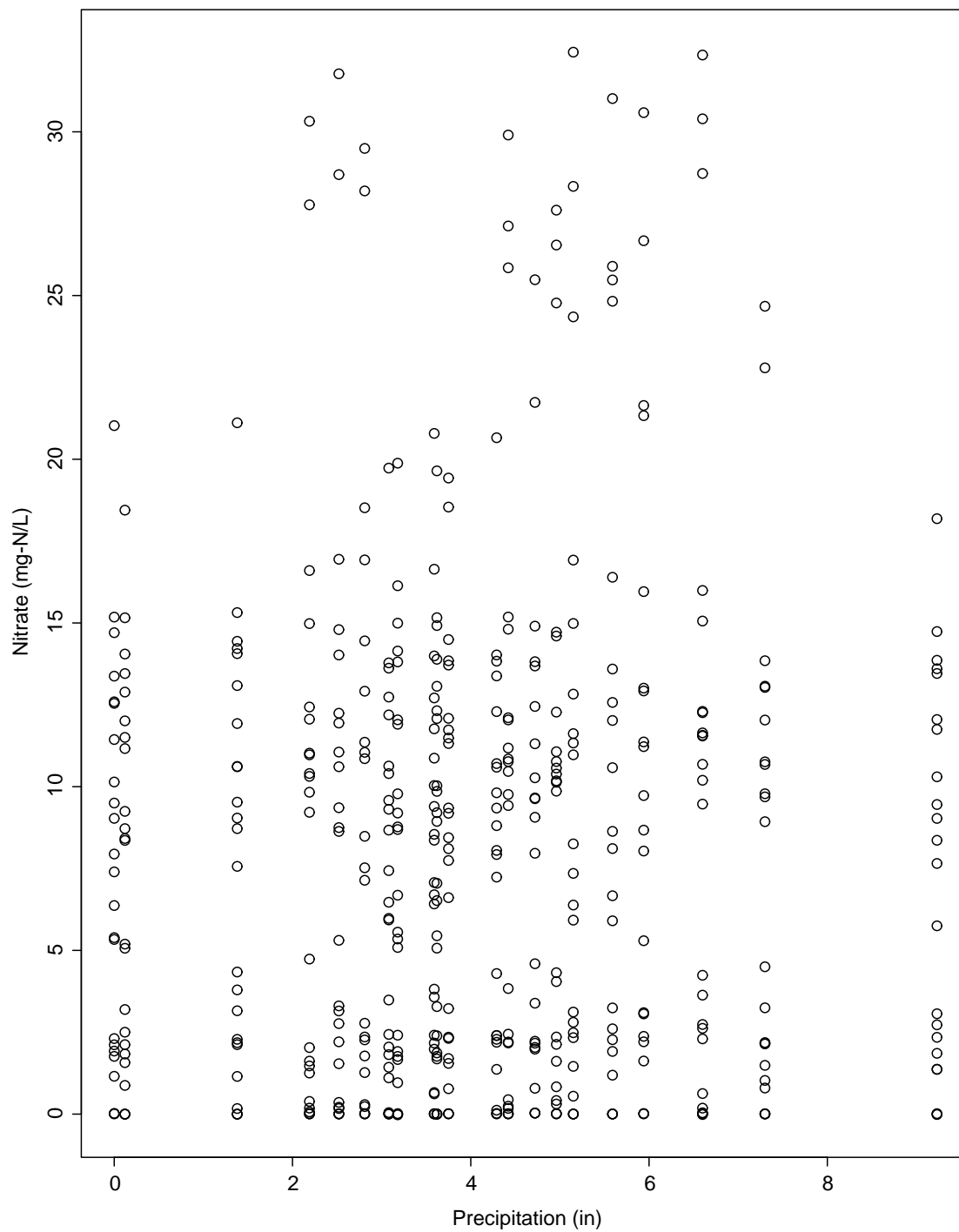


Figure 49: Scatterplot of cumulative precipitation 30 days prior to sampling vs. nitrate concentrations.

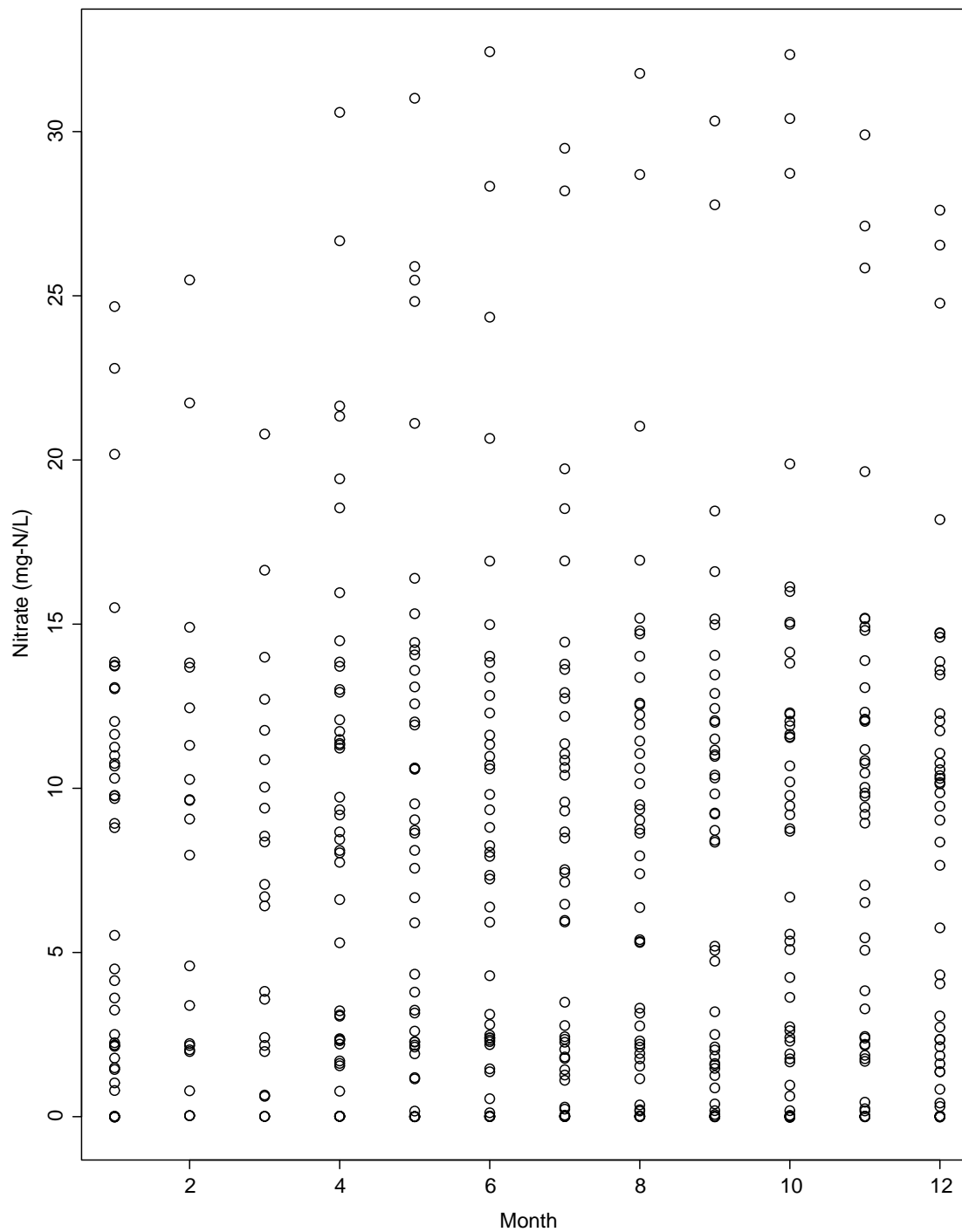


Figure 50: Scatterplot of the month of the year vs. nitrate concentrations.

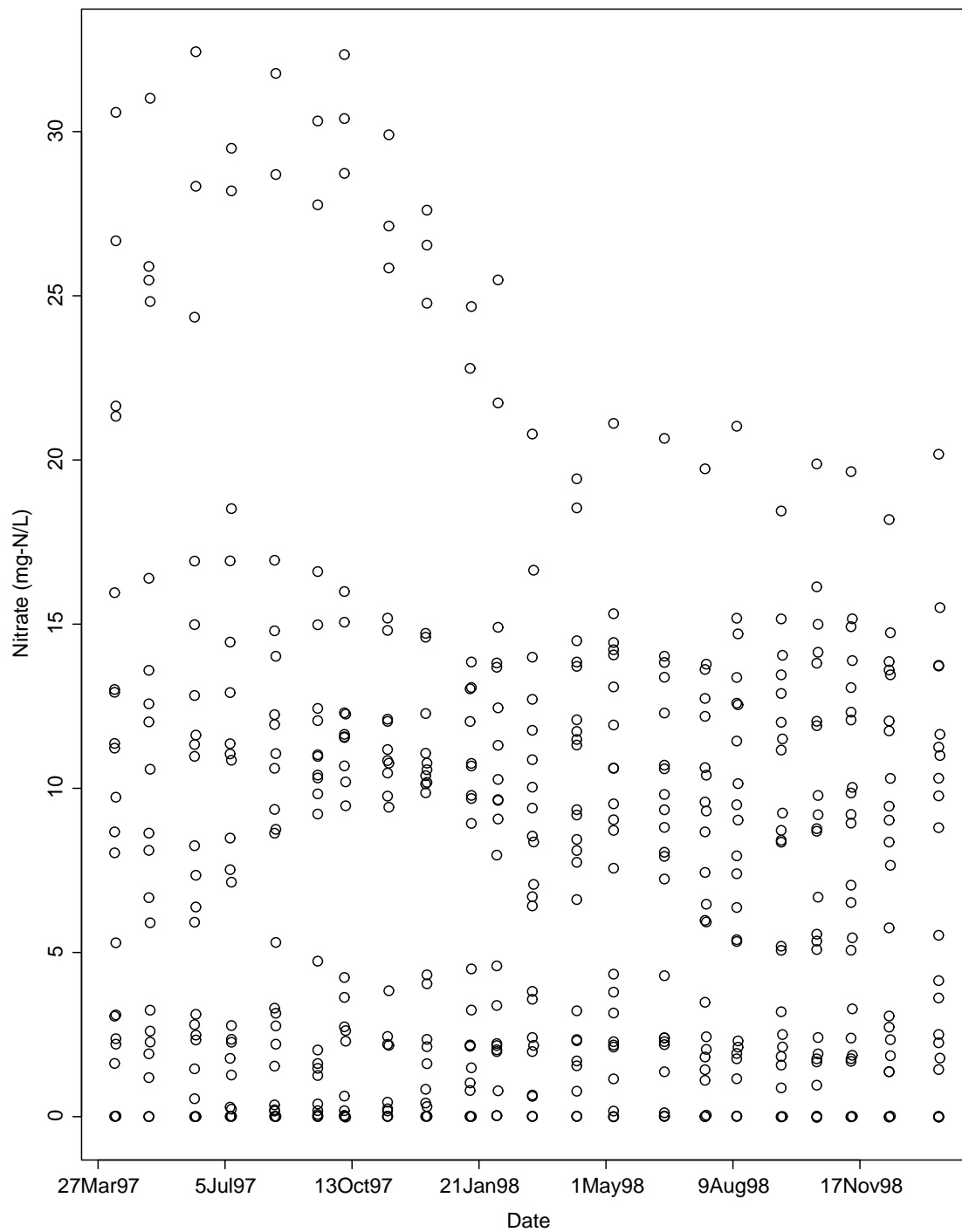


Figure 51: Scatterplot of nitrate concentrations over time.

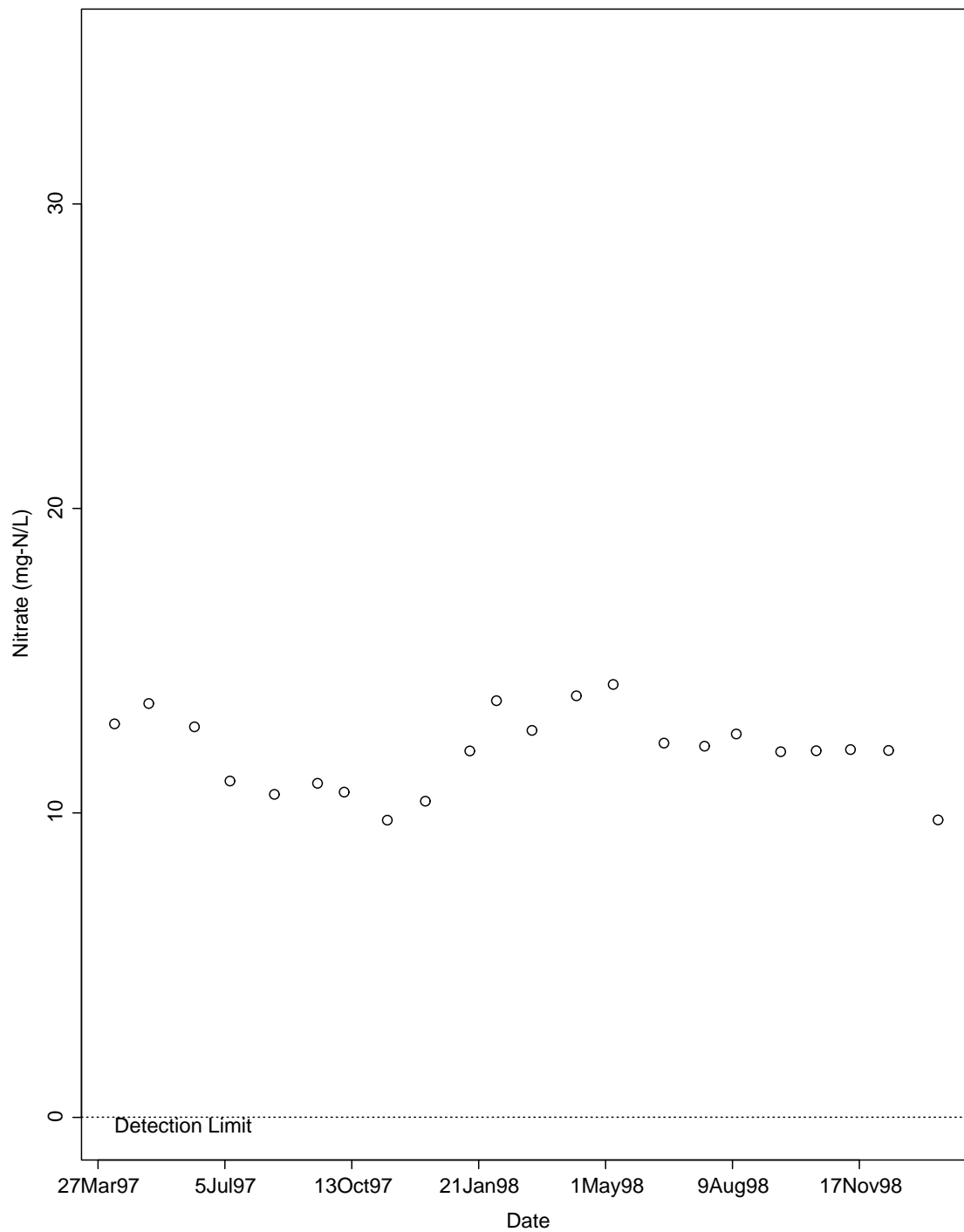


Figure 52: Scatterplot of nitrate concentrations over time for Well 1.

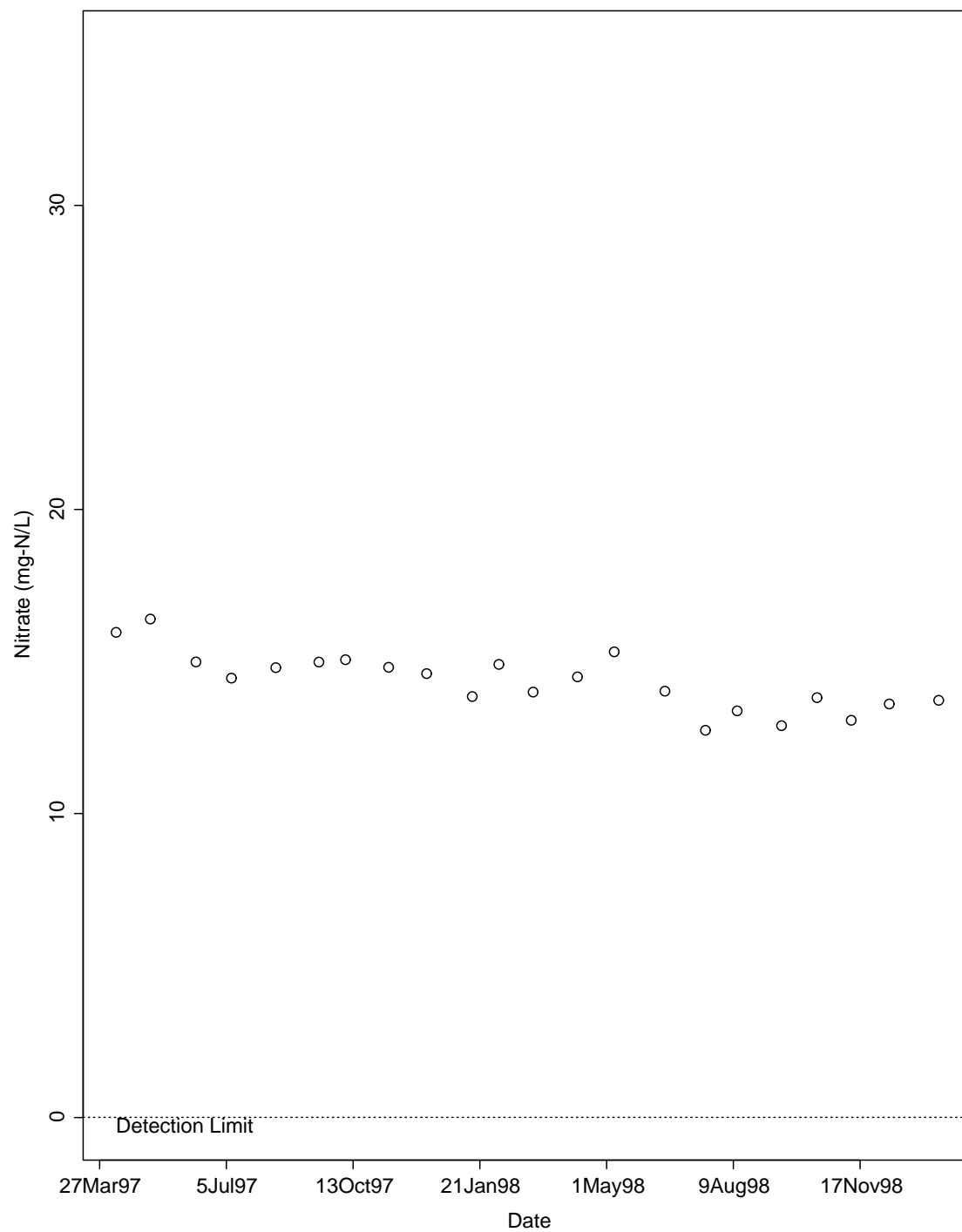


Figure 53: Scatterplot of nitrate concentrations over time for Well 2.

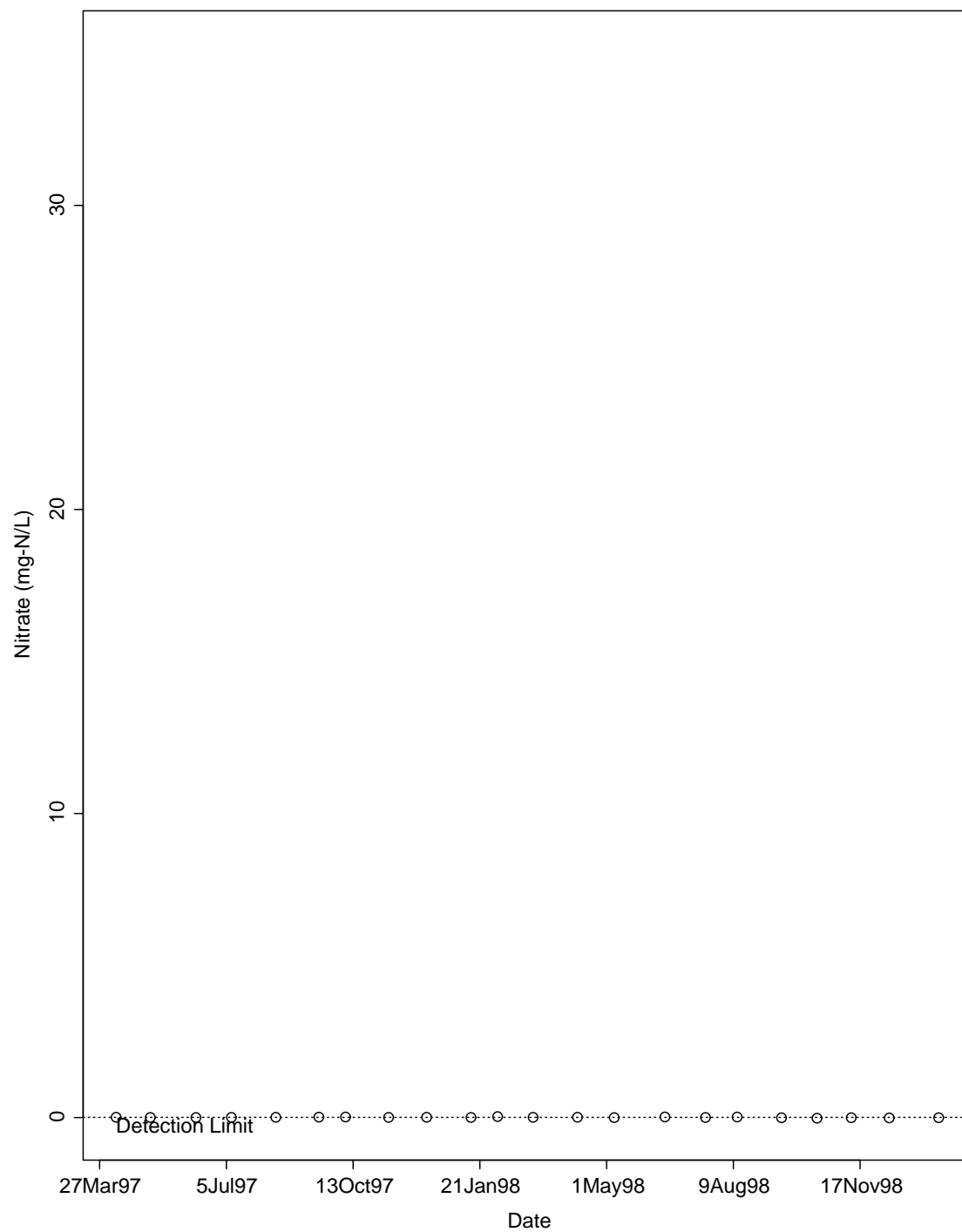


Figure 54: Scatterplot of nitrate concentrations over time for Well 3.

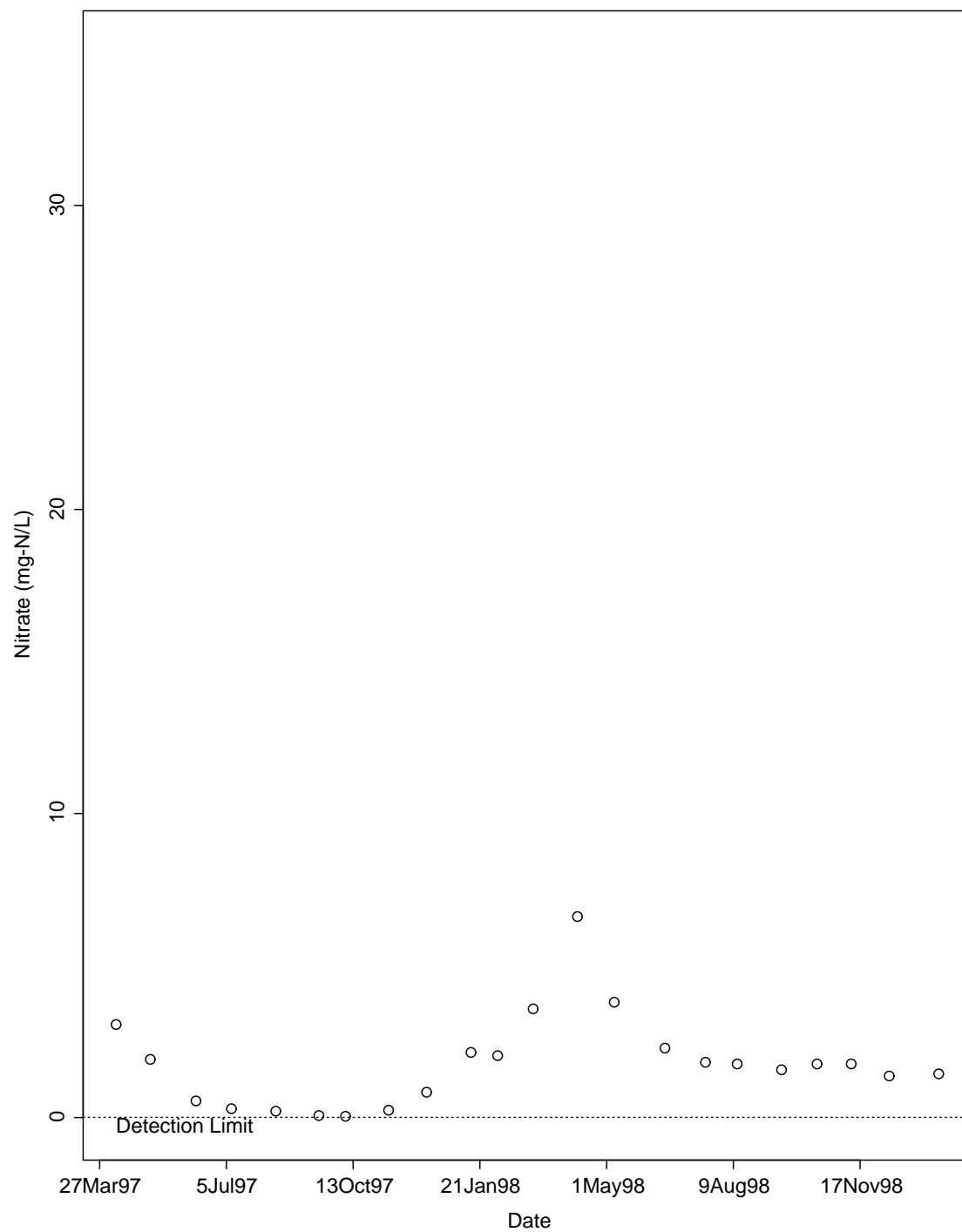


Figure 55: Scatterplot of nitrate concentrations over time for Well 4.

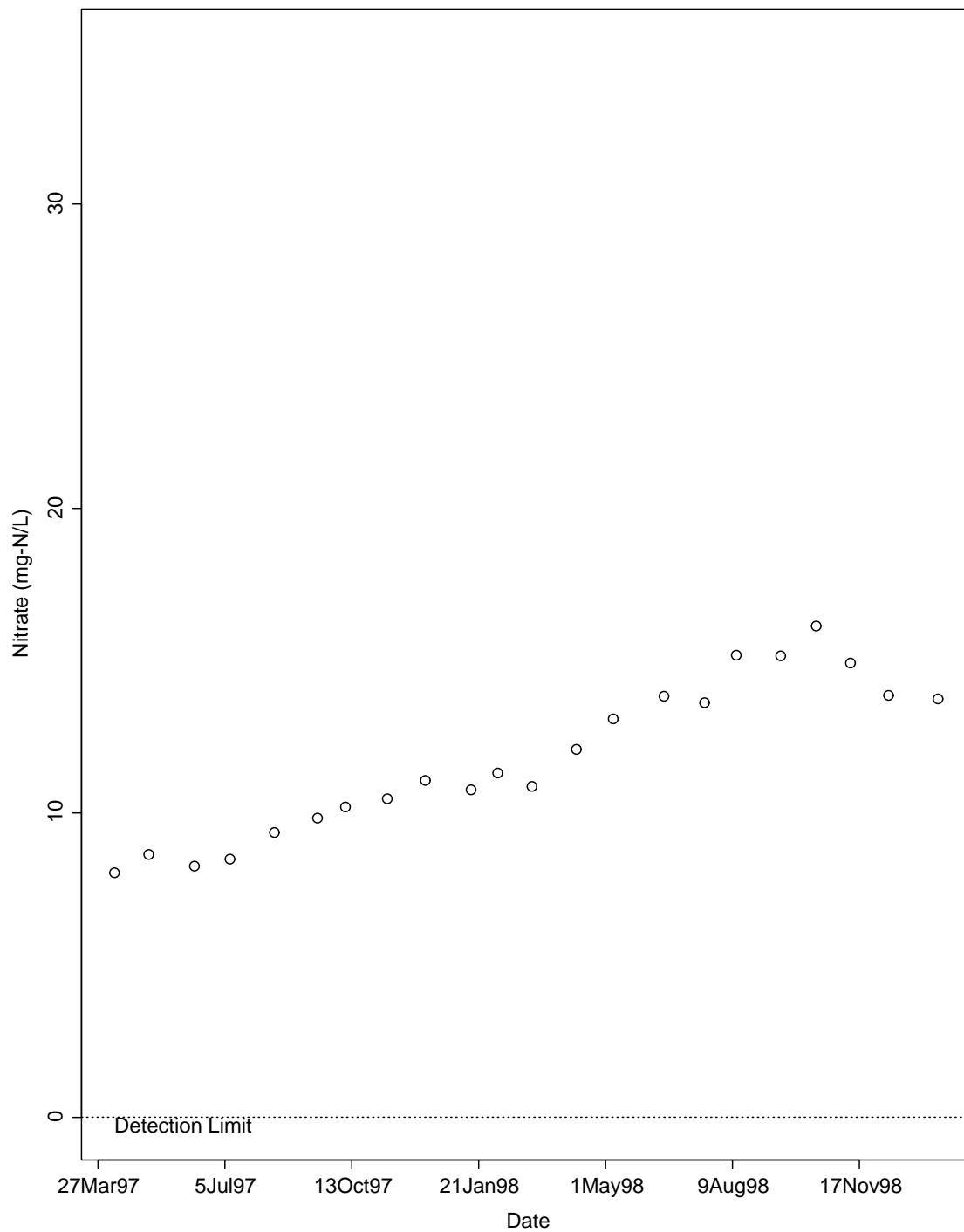


Figure 56: Scatterplot of nitrate concentrations over time for Well 5.

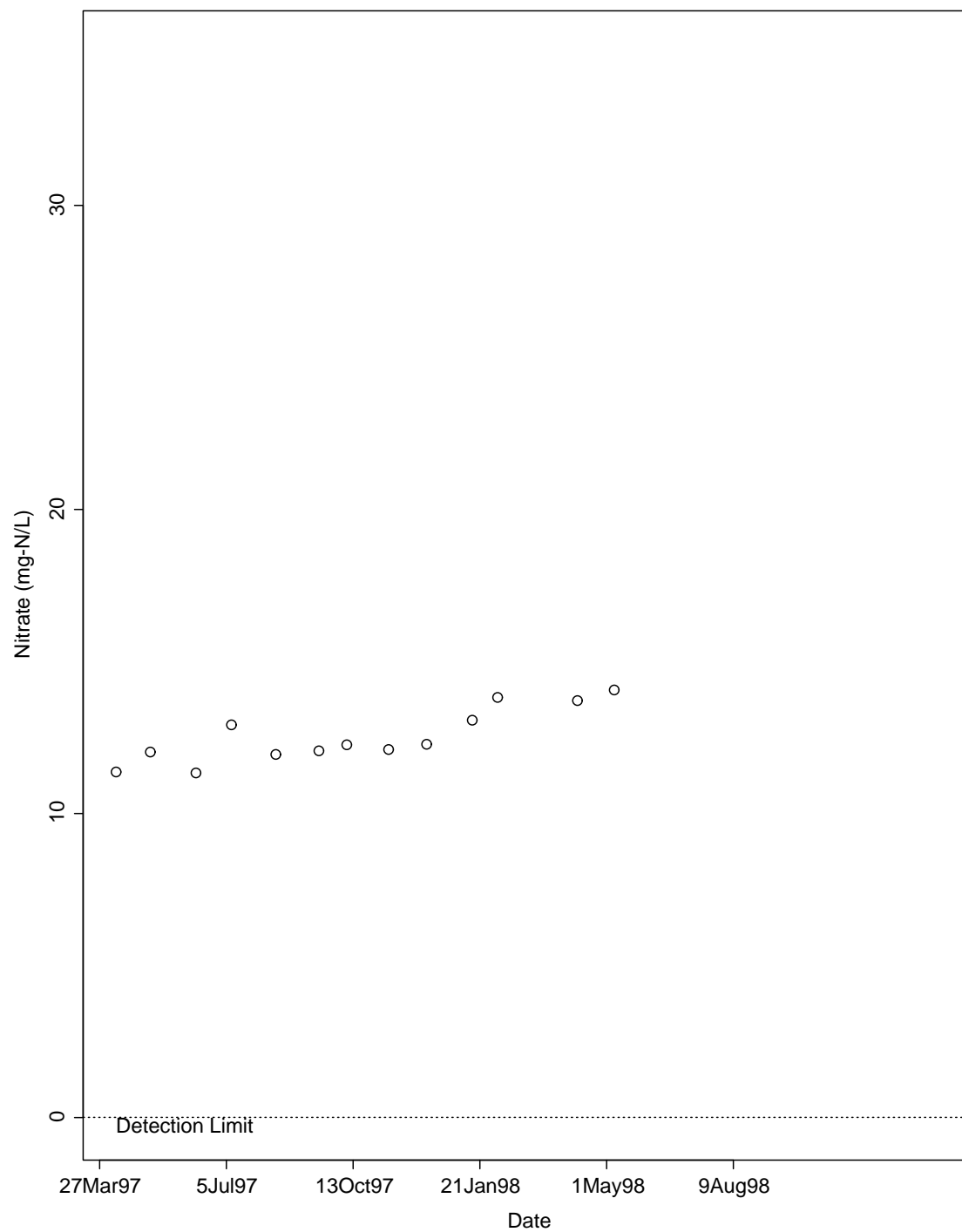


Figure 57: Scatterplot of nitrate concentrations over time for Well 6.

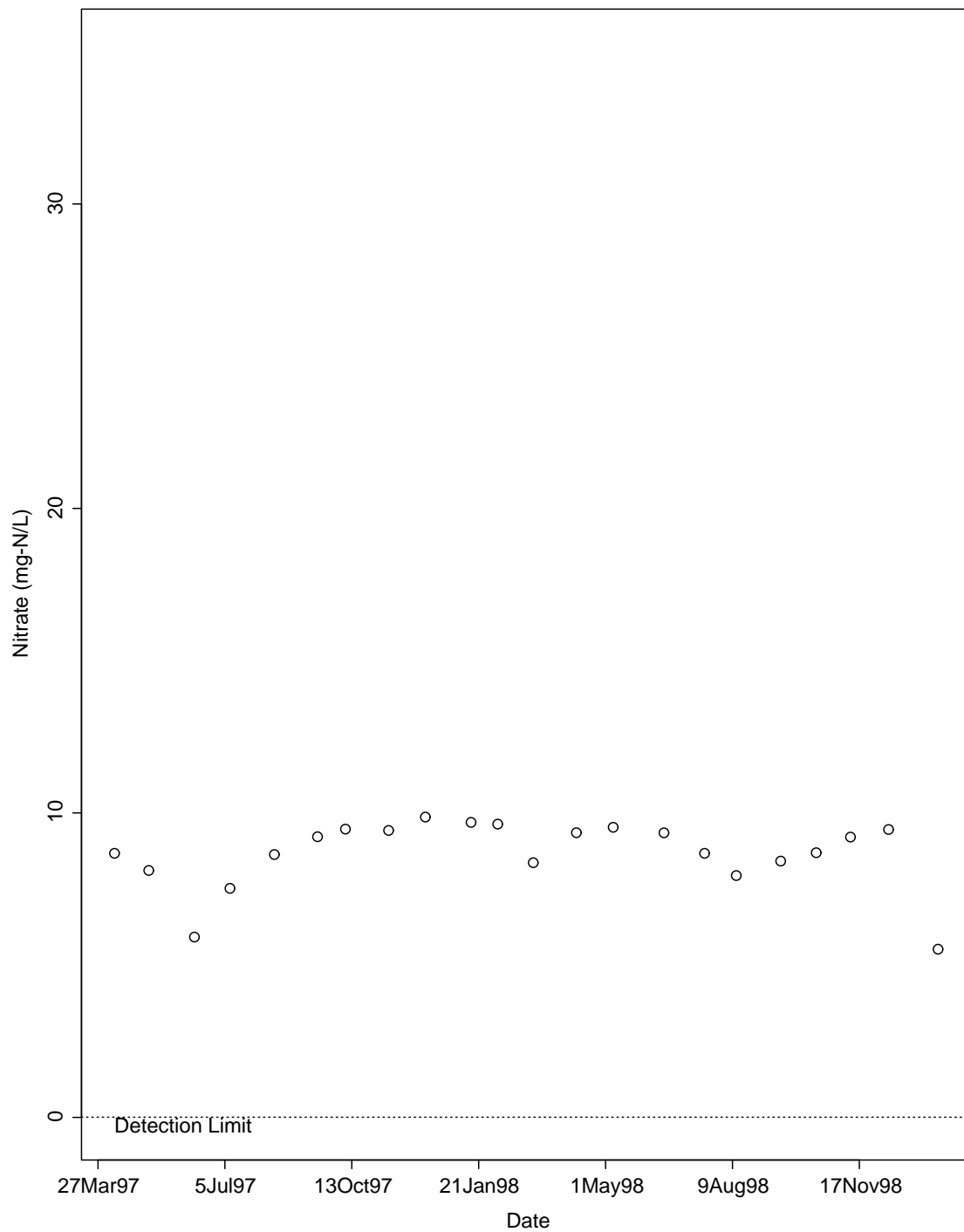


Figure 58: Scatterplot of nitrate concentrations over time for Well 7.

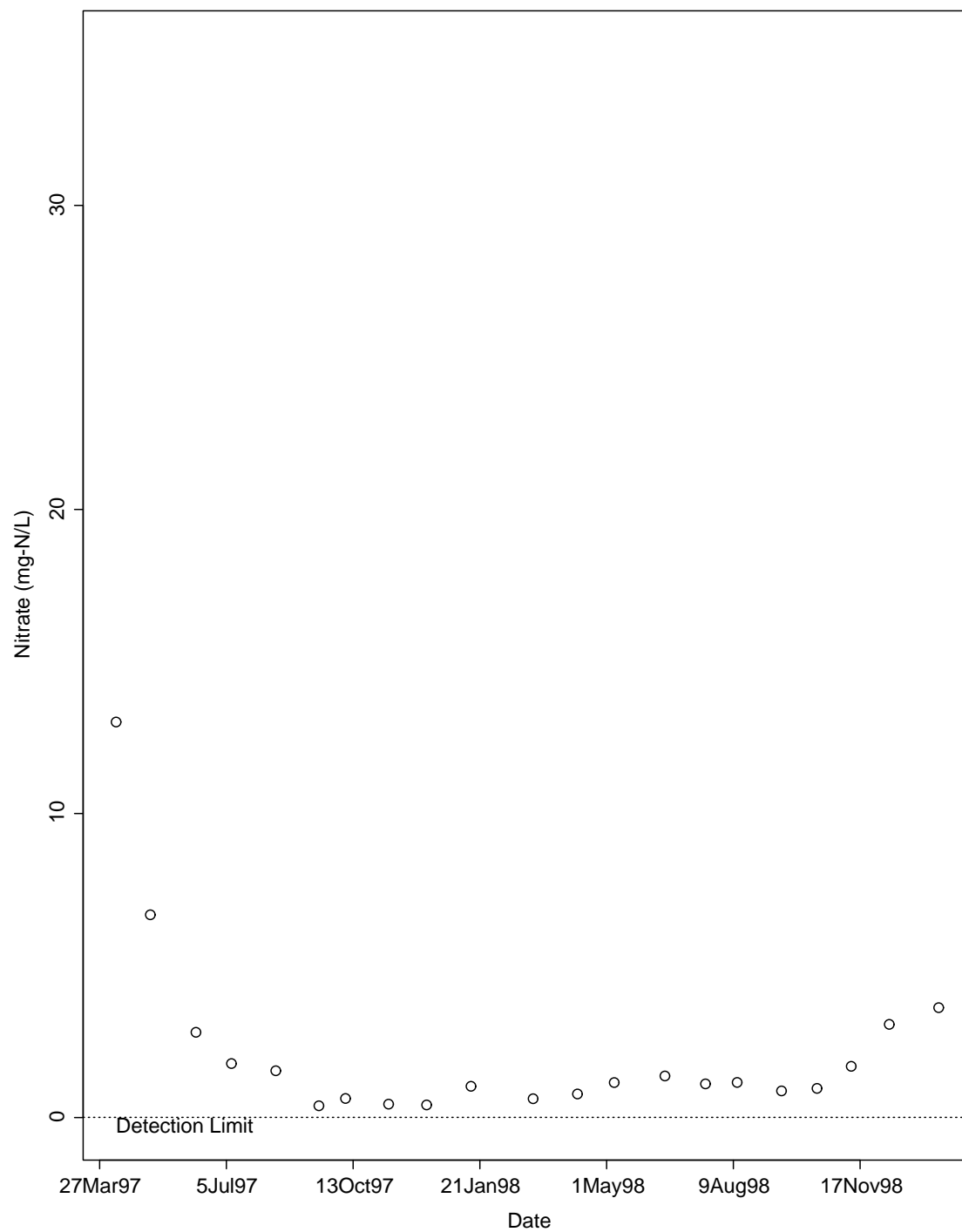


Figure 59: Scatterplot of nitrate concentrations over time for Well 8.

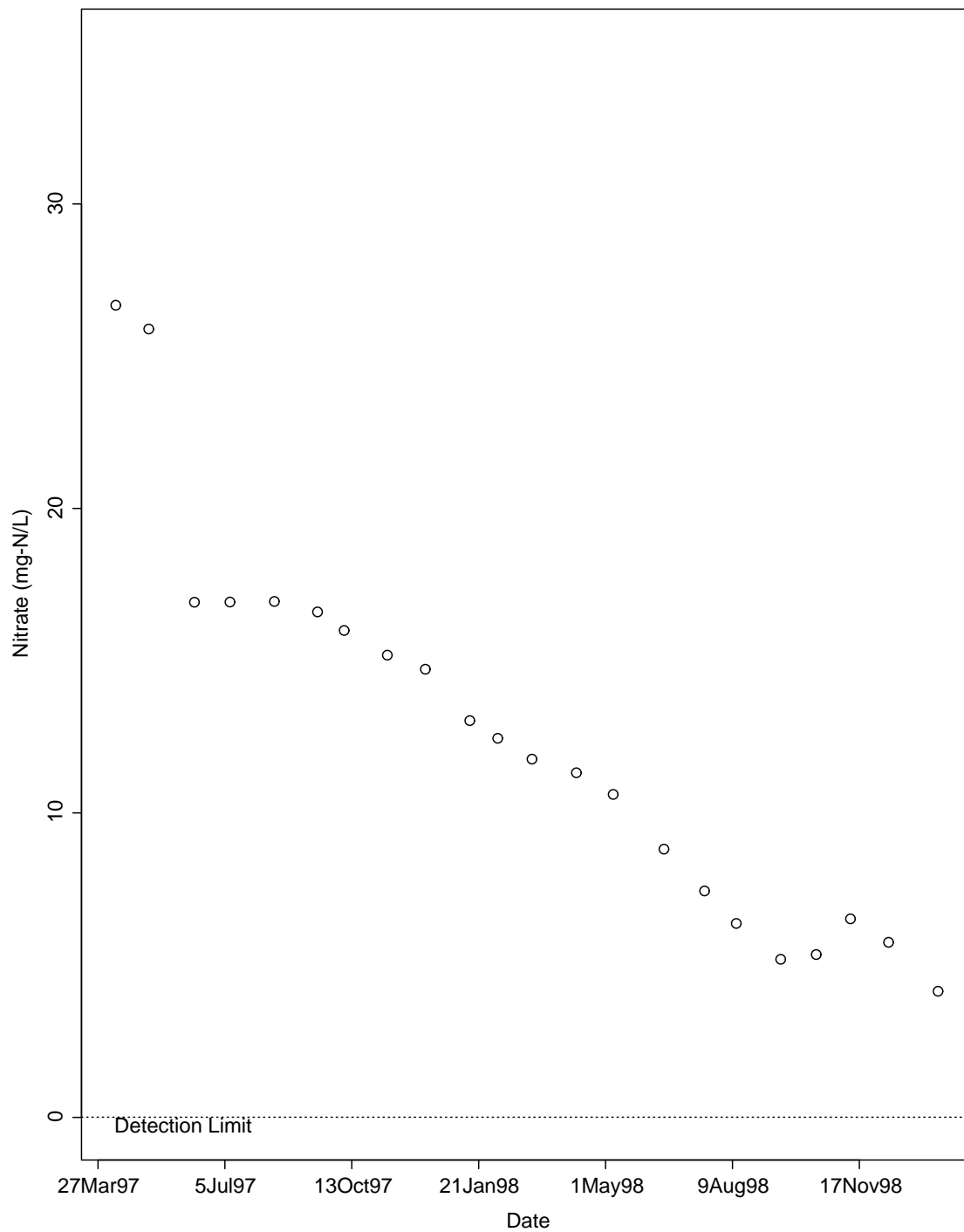


Figure 60: Scatterplot of nitrate concentrations over time for Well 9.

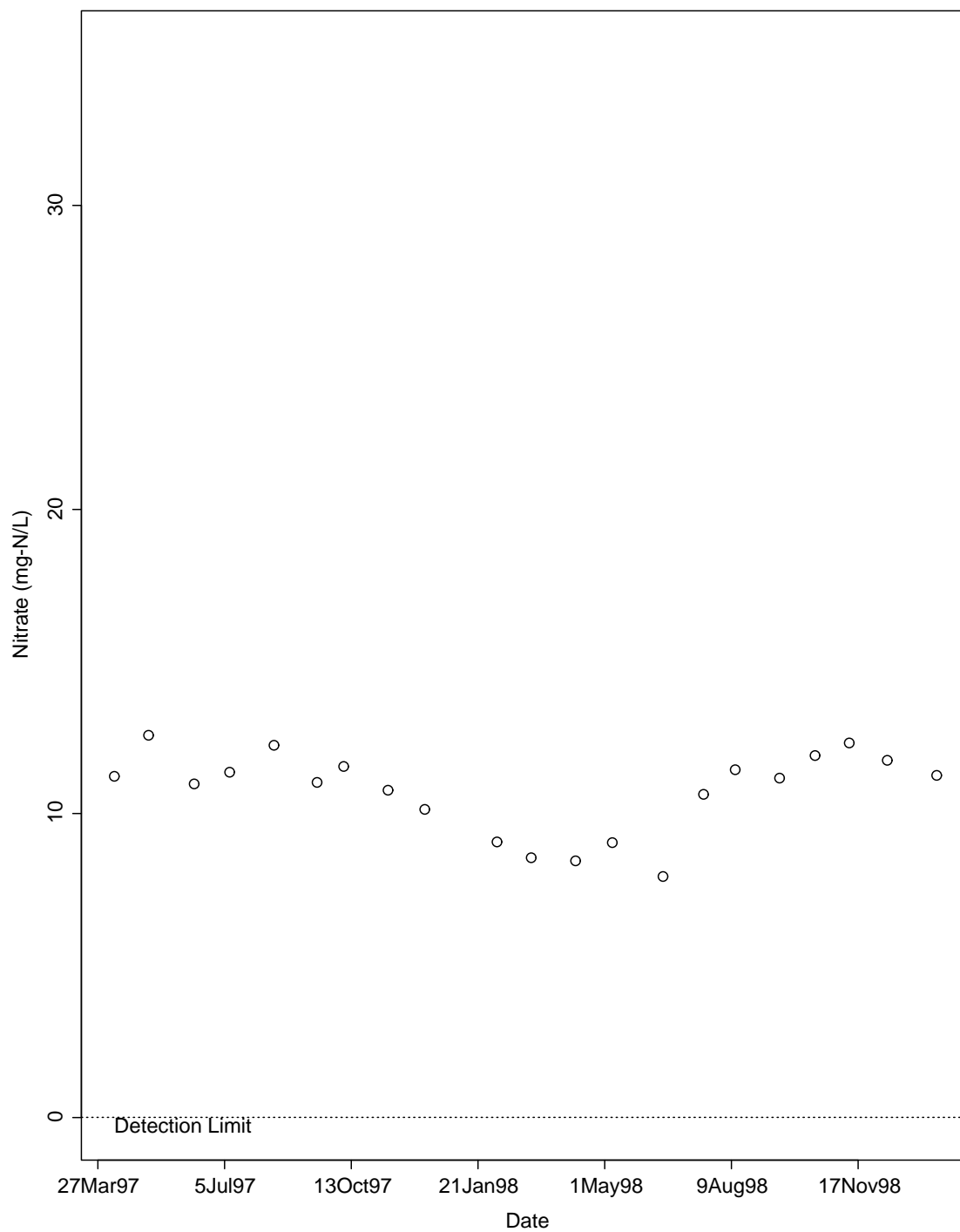


Figure 61: Scatterplot of nitrate concentrations over time for Well 10.

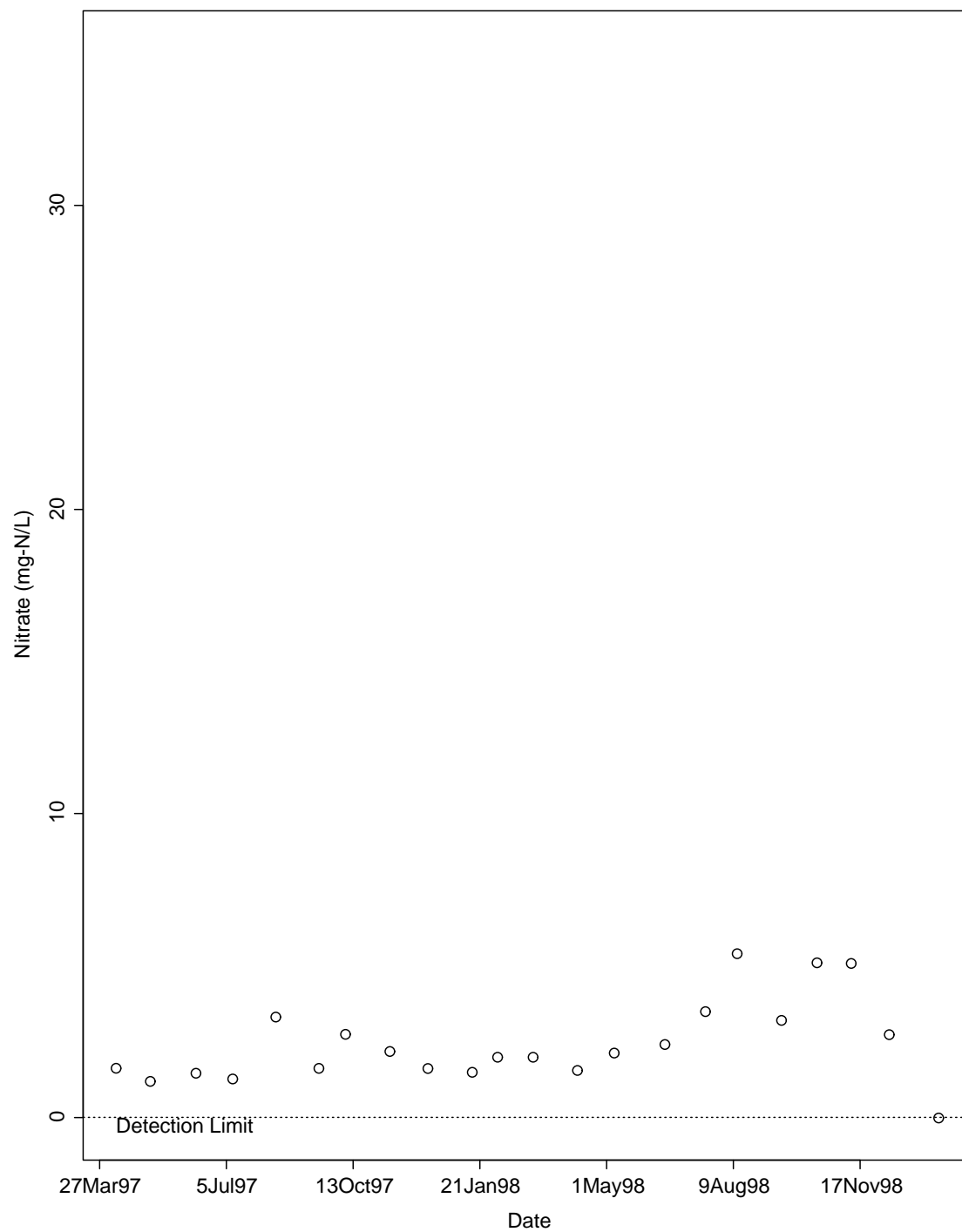


Figure 62: Scatterplot of nitrate concentrations over time for Well 11.

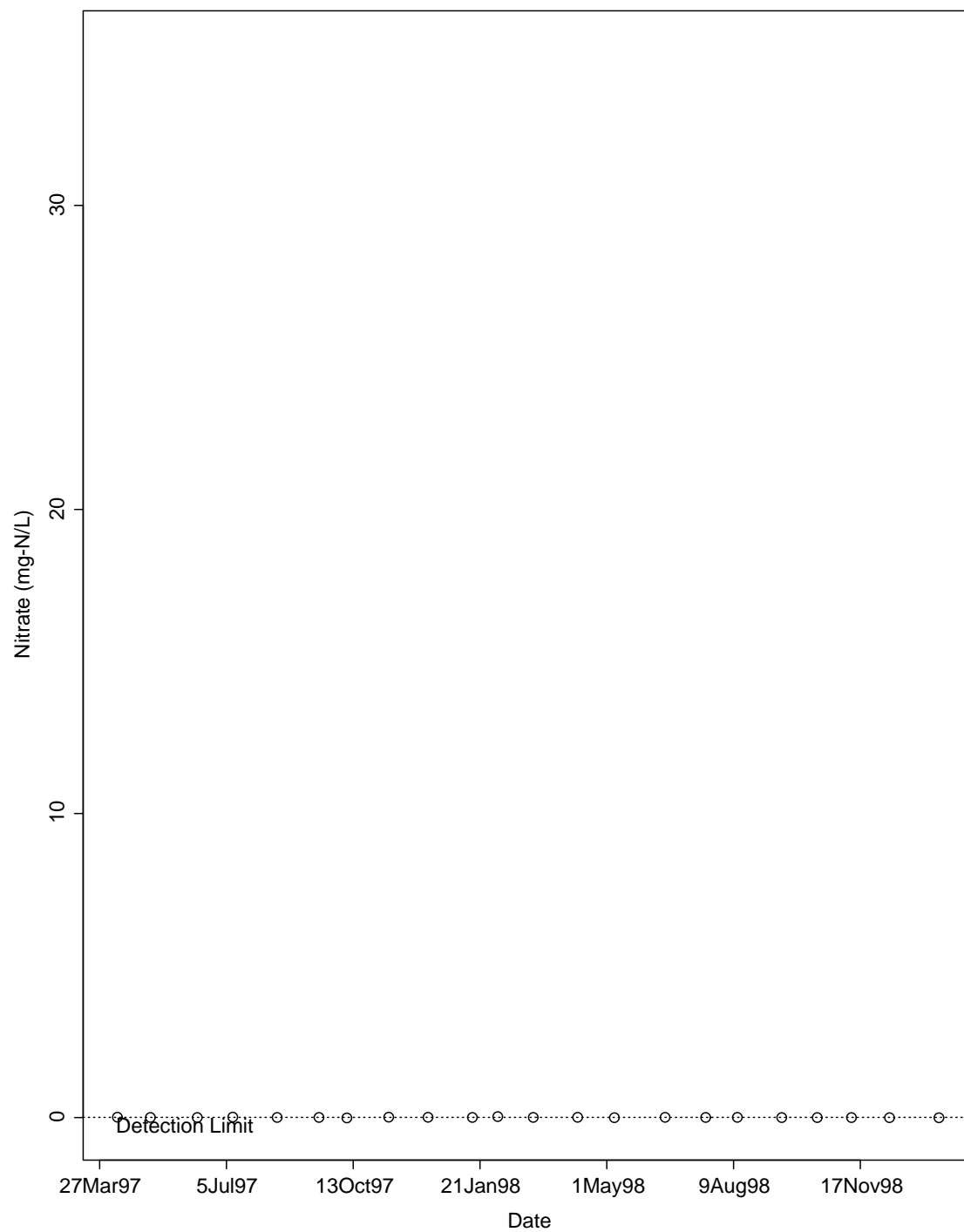


Figure 63: Scatterplot of nitrate concentrations over time for Well 12.

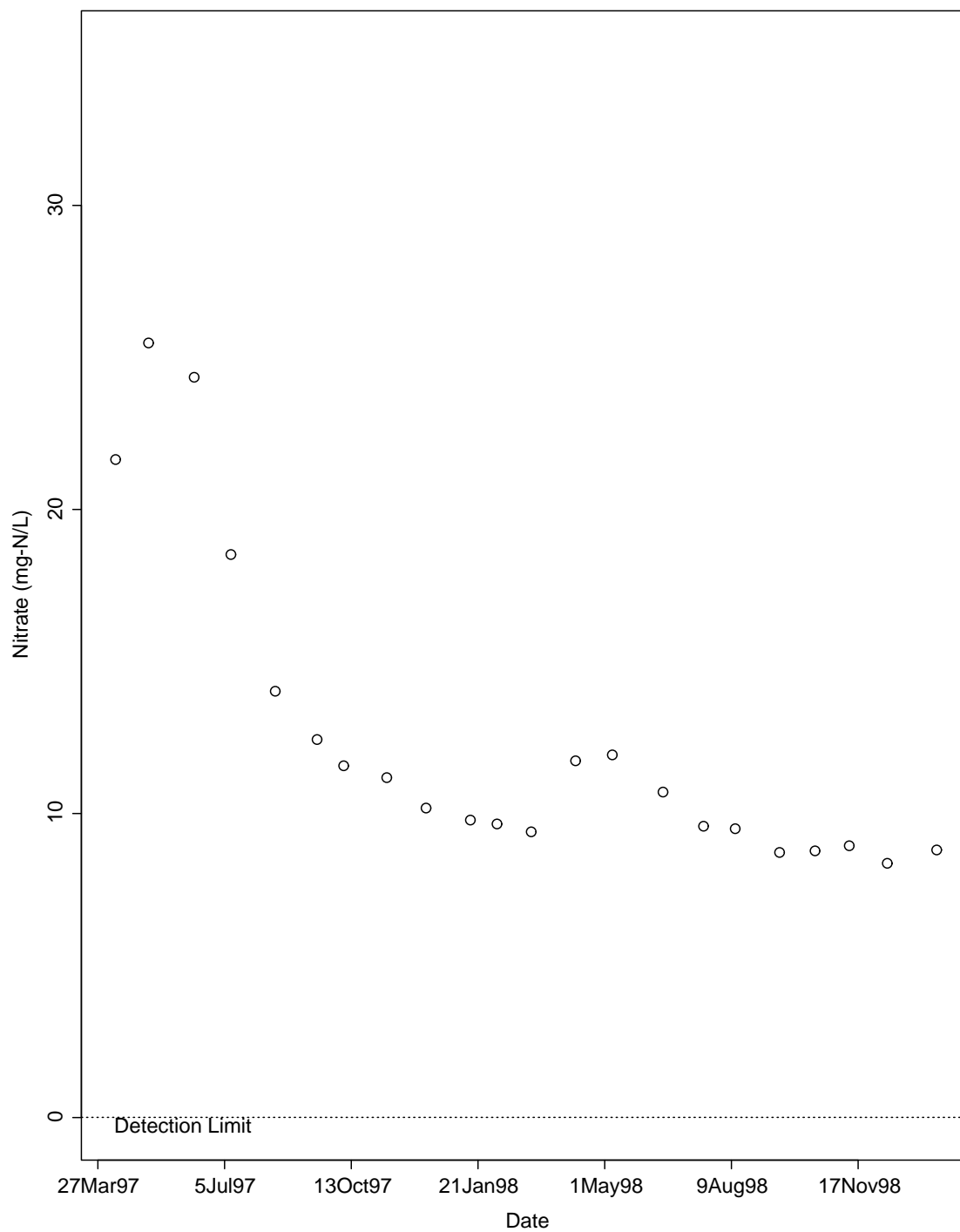


Figure 64: Scatterplot of nitrate concentrations over time for Well 13.

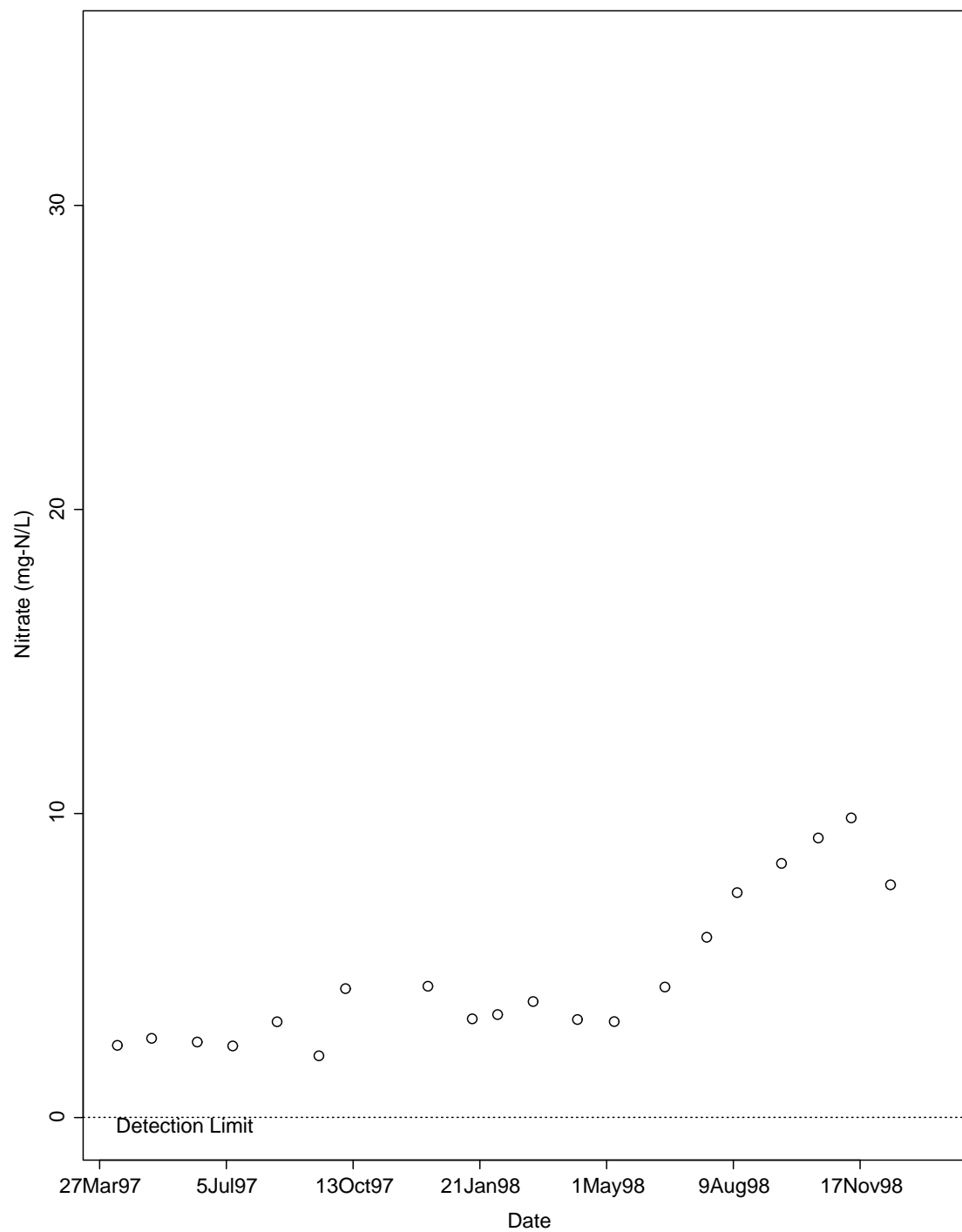


Figure 66: Scatterplot of nitrate concentrations over time for Well 15.

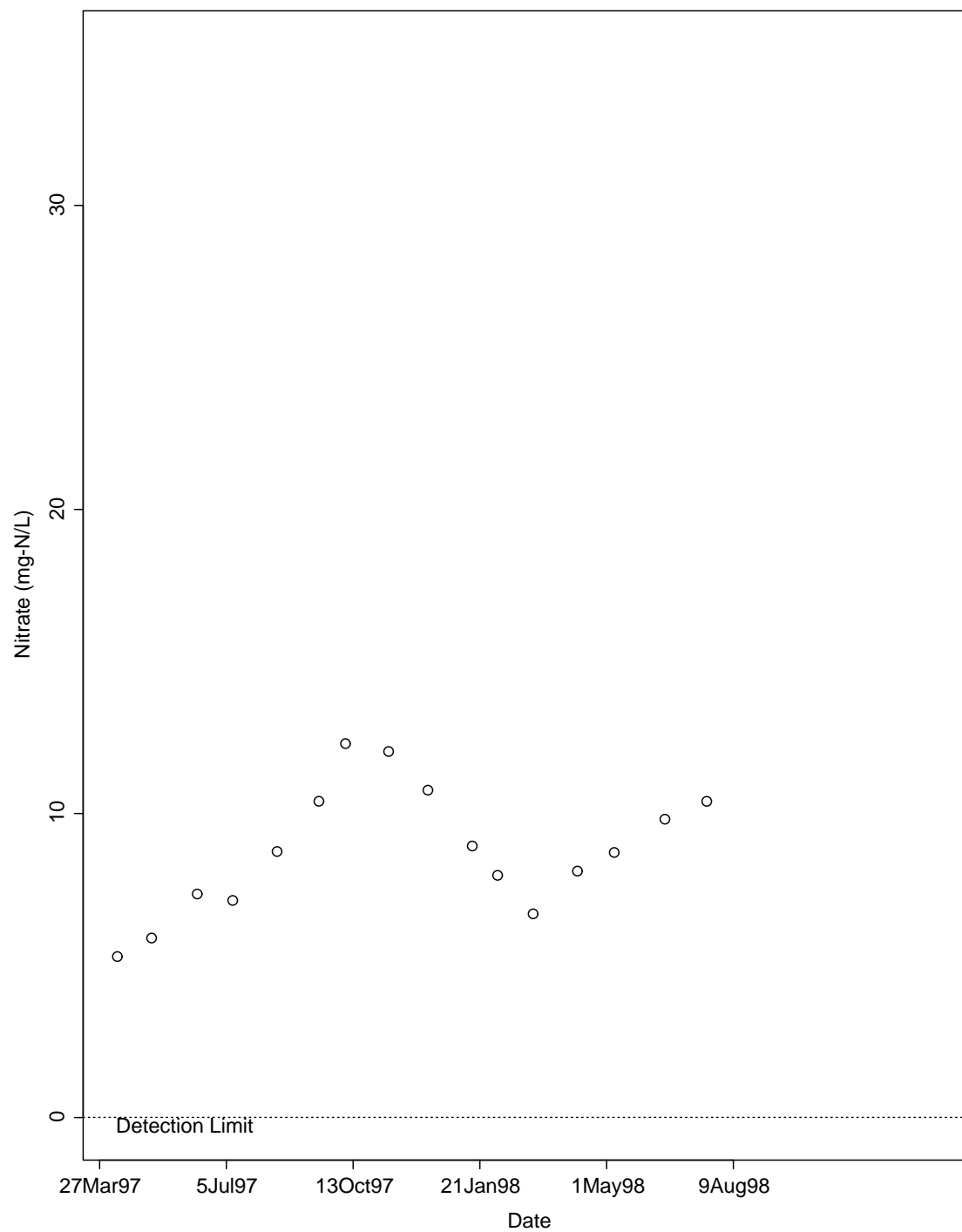


Figure 67: Scatterplot of nitrate concentrations over time for Well 16.

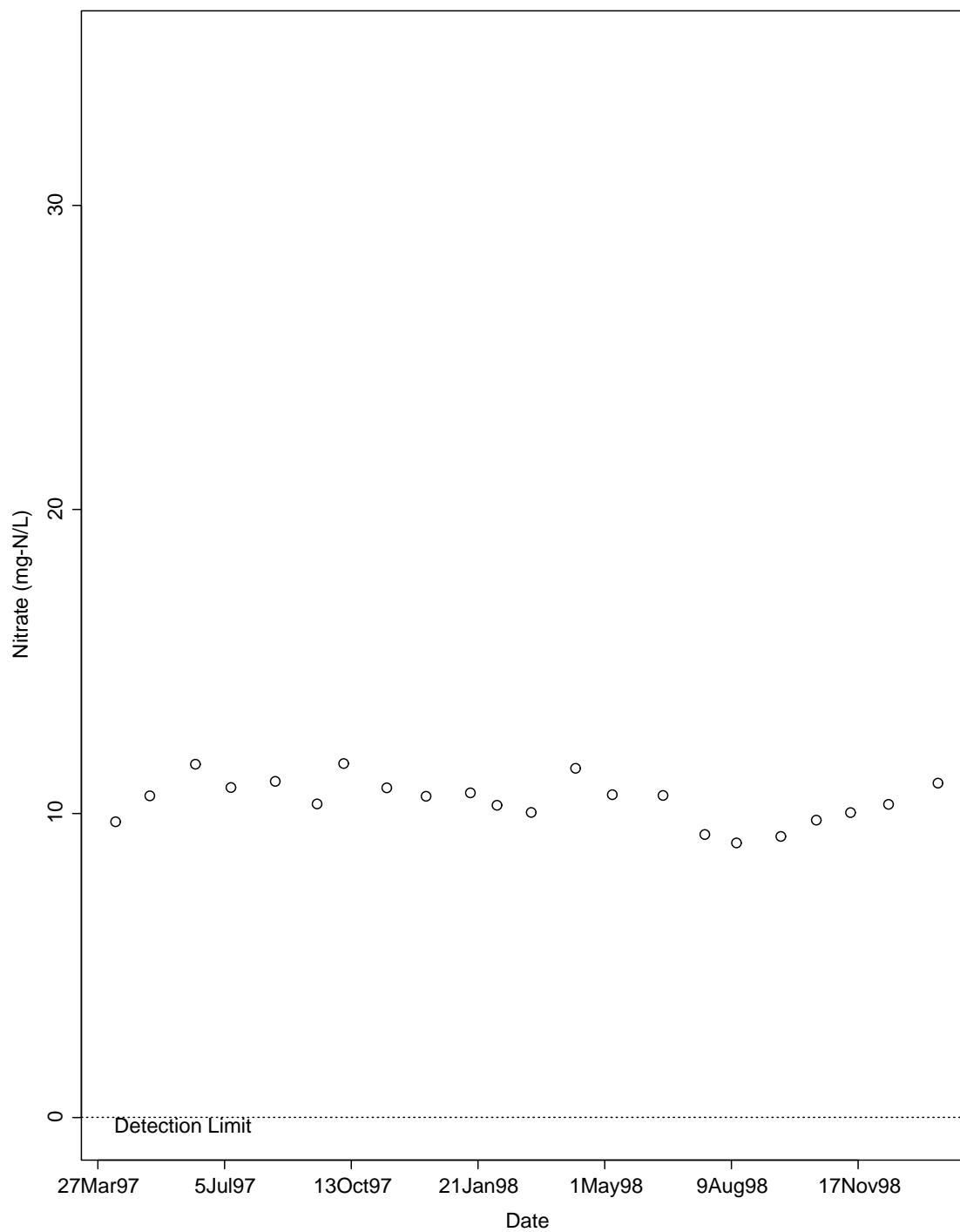


Figure 68: Scatterplot of nitrate concentrations over time for Well 17.

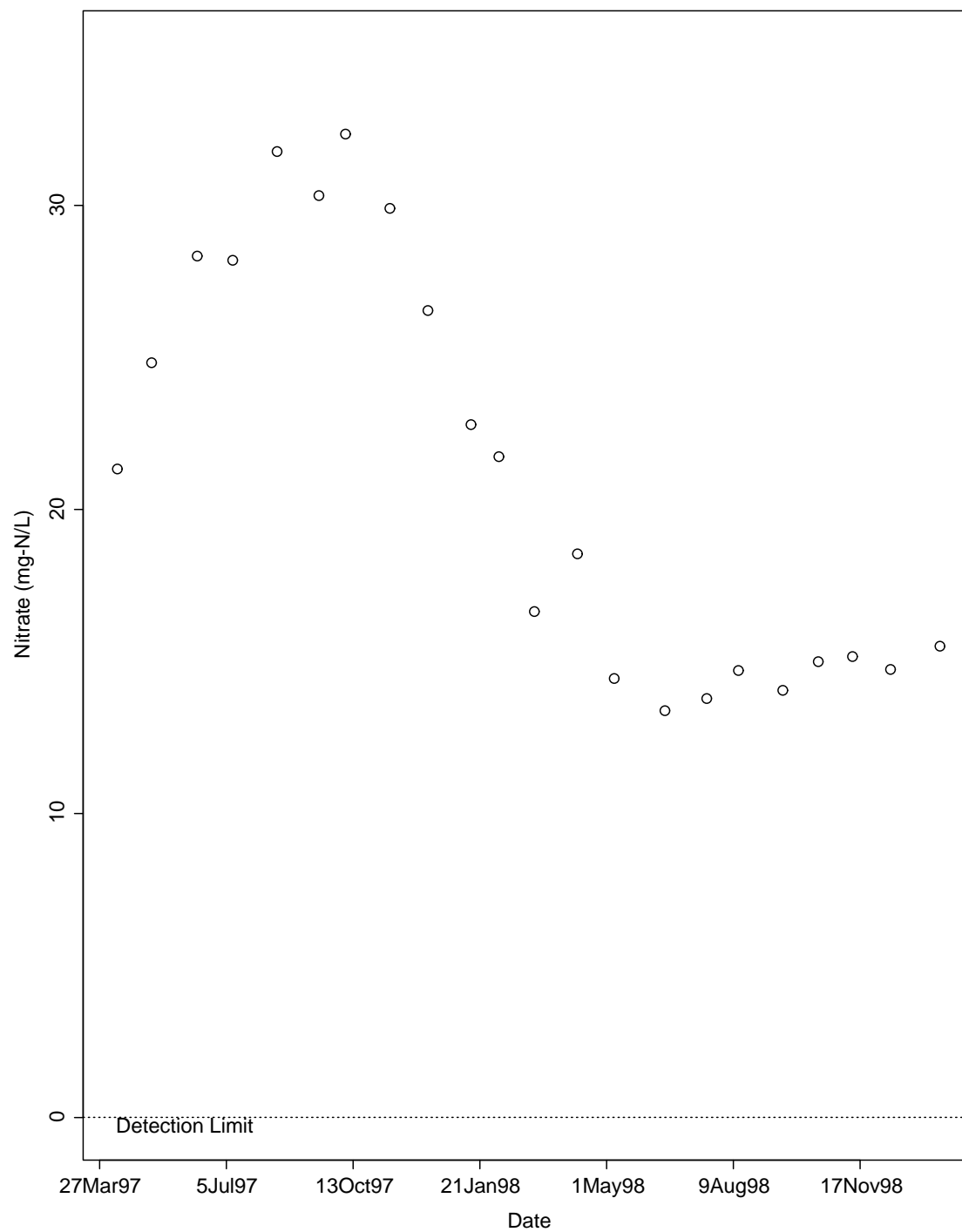


Figure 69: Scatterplot of nitrate concentrations over time for Well 18.

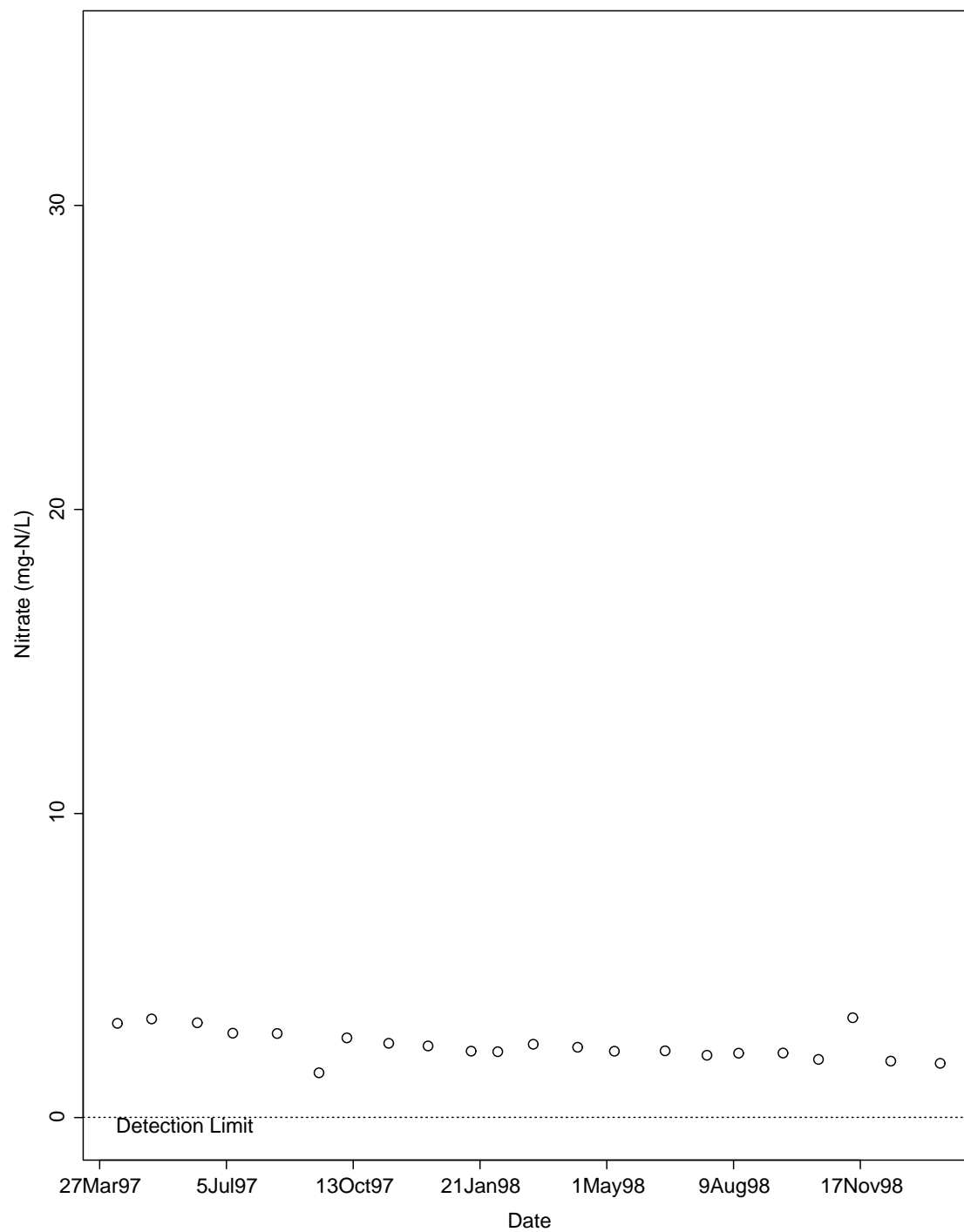


Figure 70: Scatterplot of nitrate concentrations over time for Well 19.

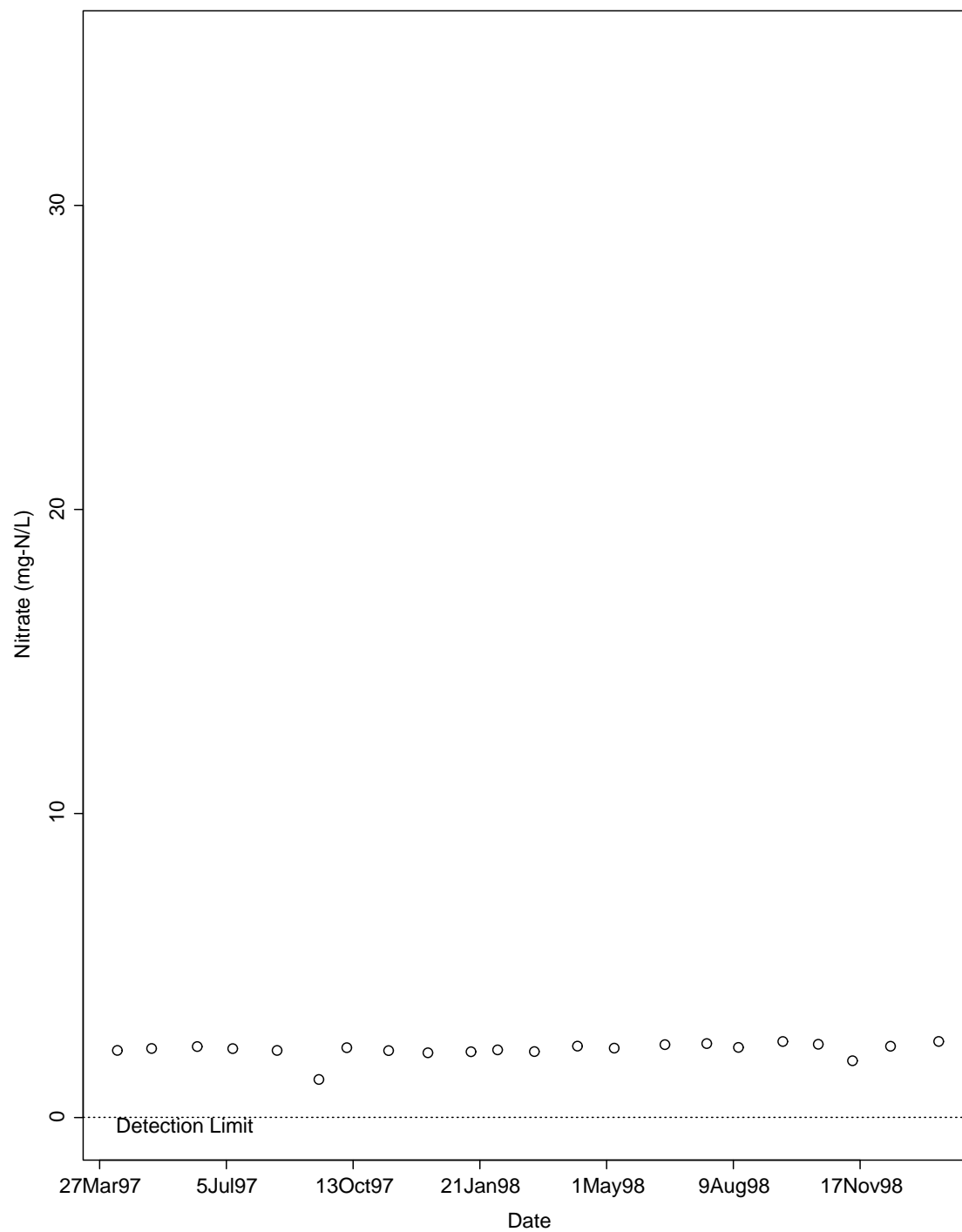


Figure 71: Scatterplot of nitrate concentrations over time for Well 20.

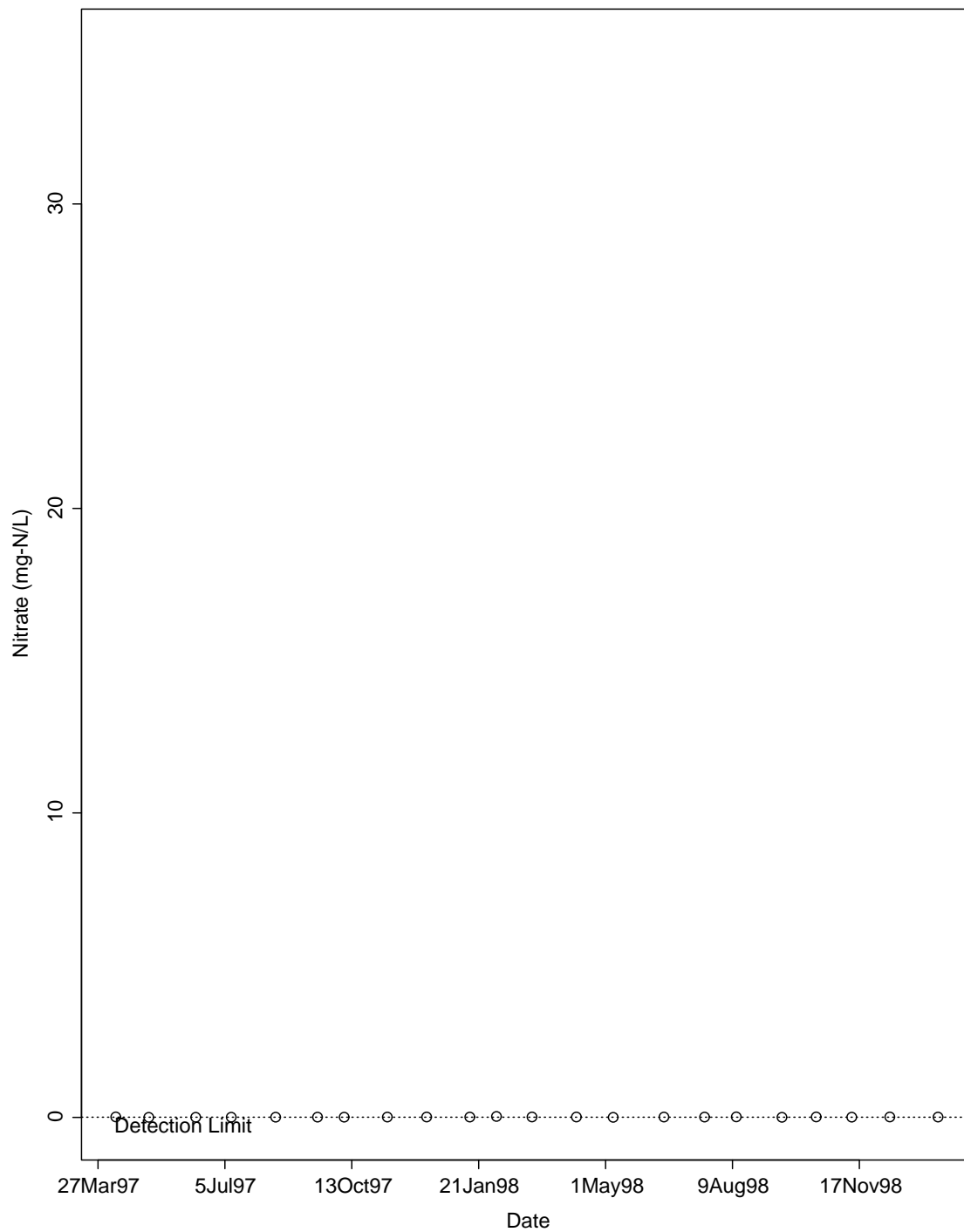


Figure 72: Scatterplot of nitrate concentrations over time for Well 21.

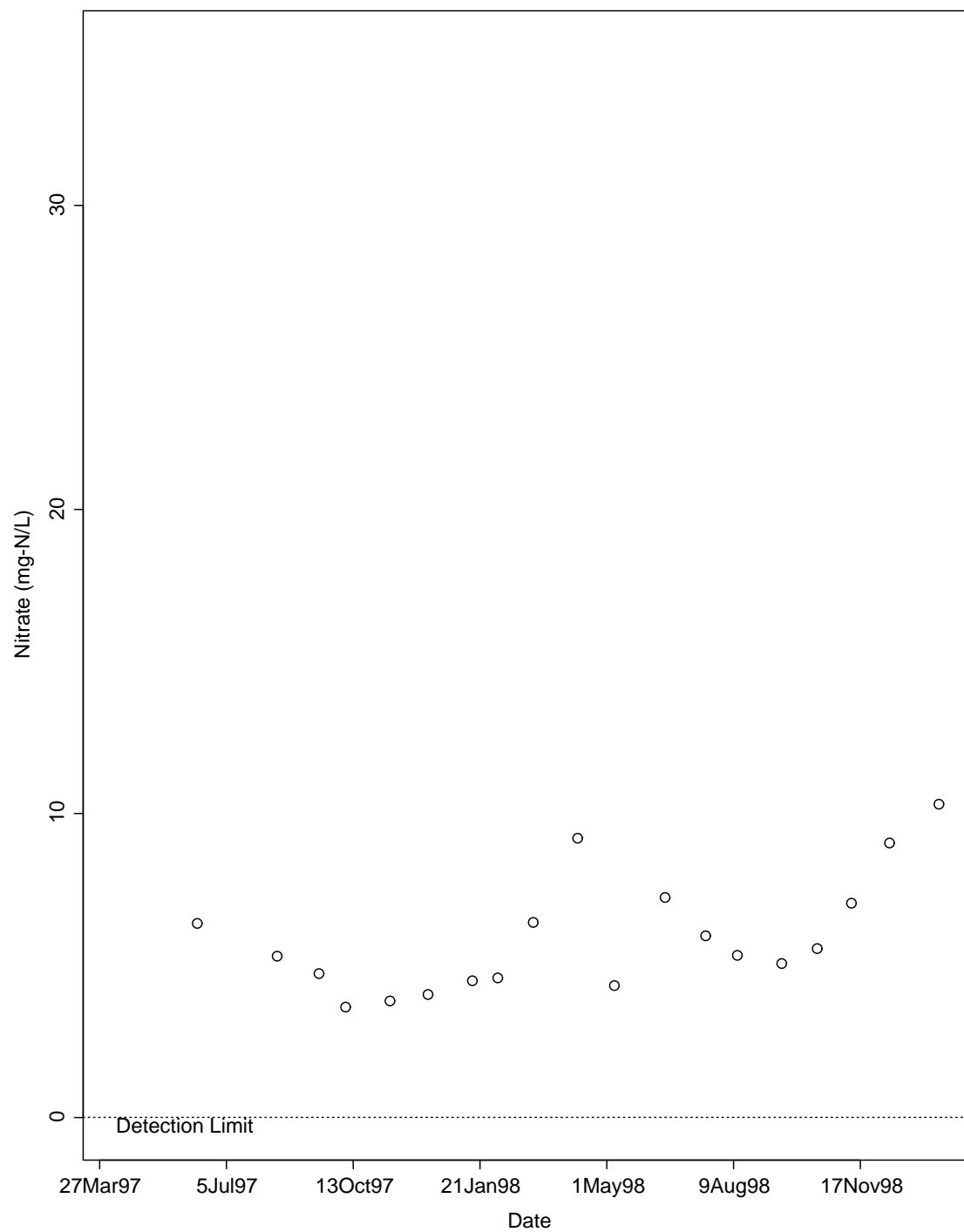


Figure 73: Scatterplot of nitrate concentrations over time for Well 22.

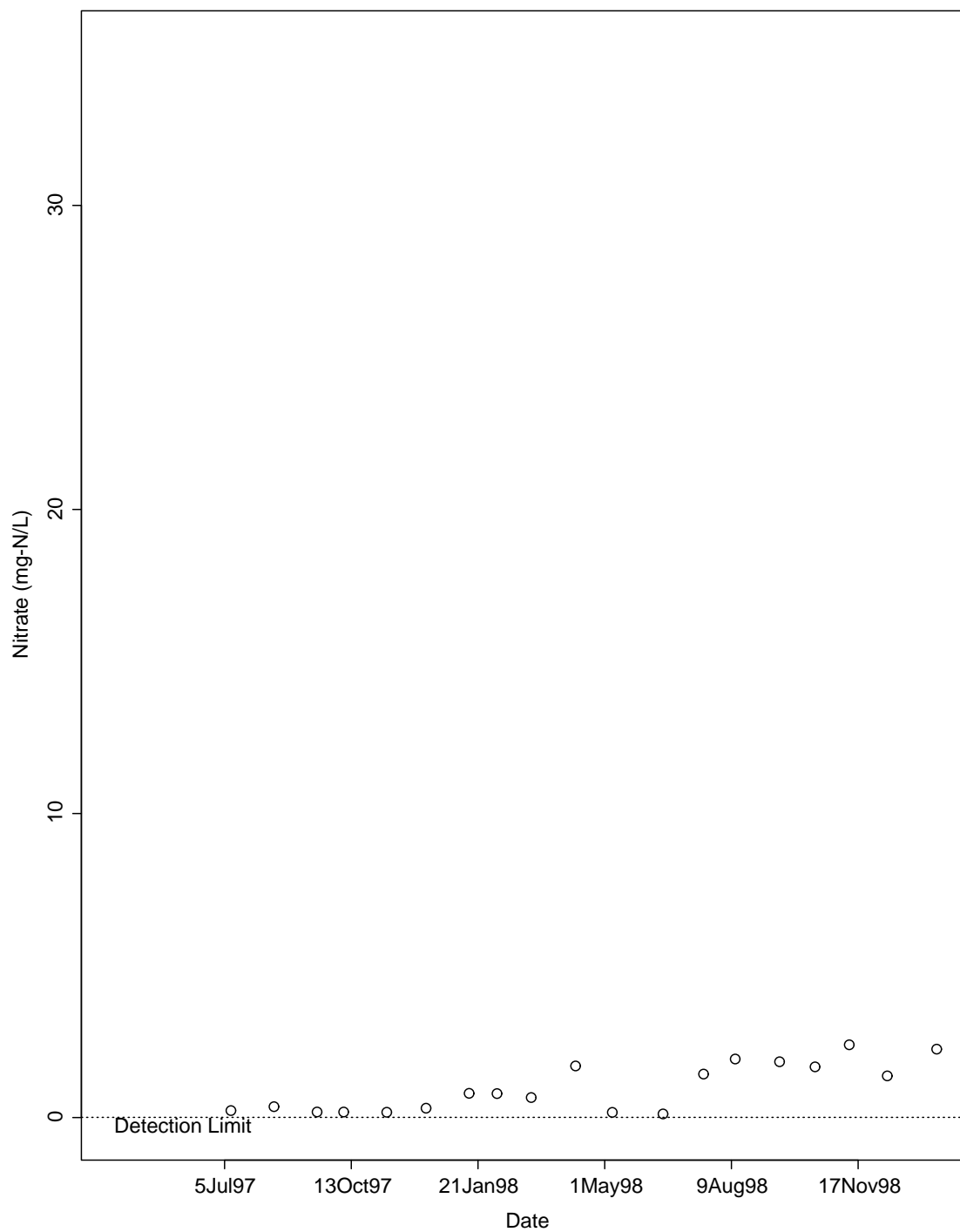


Figure 74: Scatterplot of nitrate concentrations over time for Well 23.

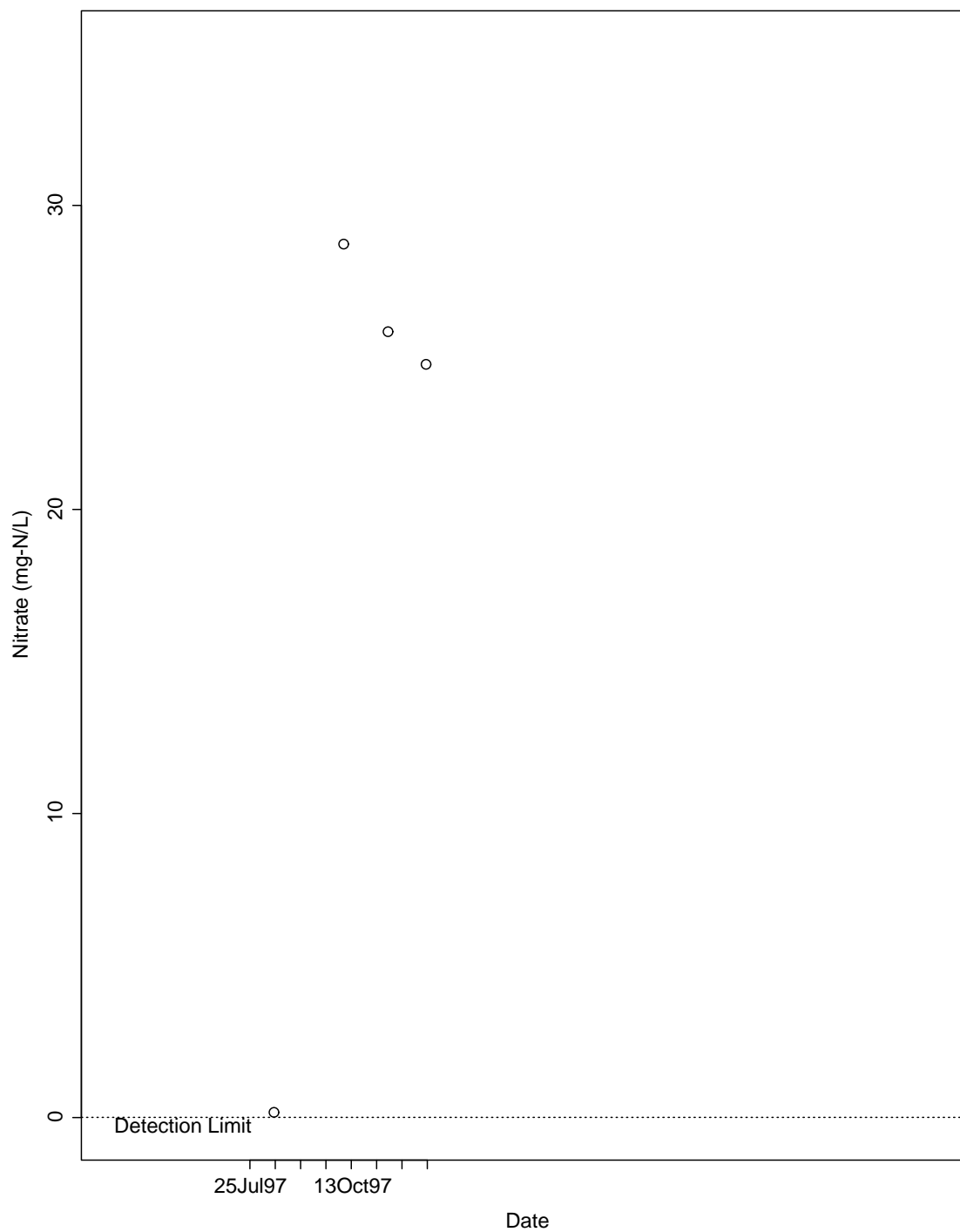


Figure 75: Scatterplot of nitrate concentrations over time for Well 24.

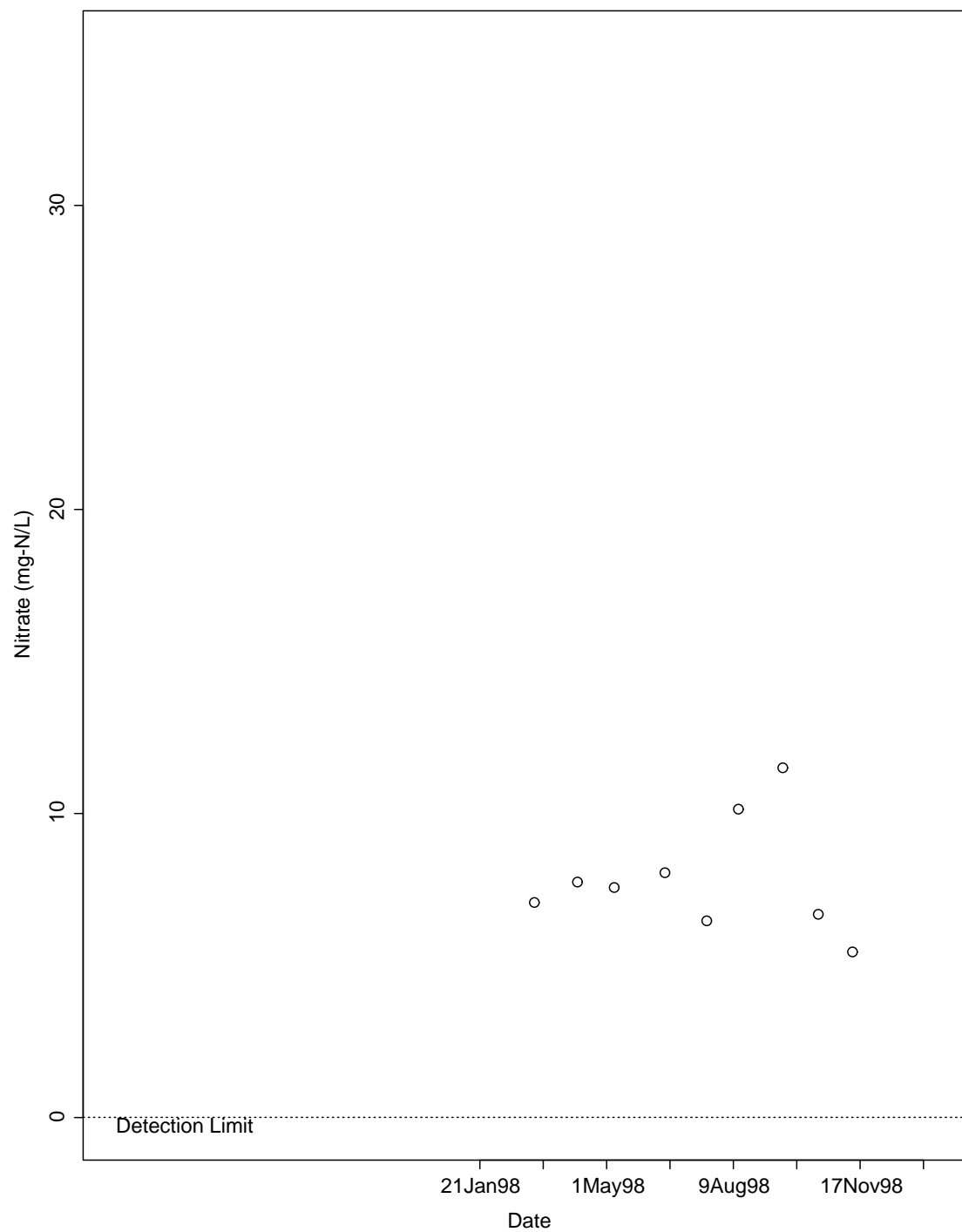


Figure 76: Scatterplot of nitrate concentrations over time for Well 26.

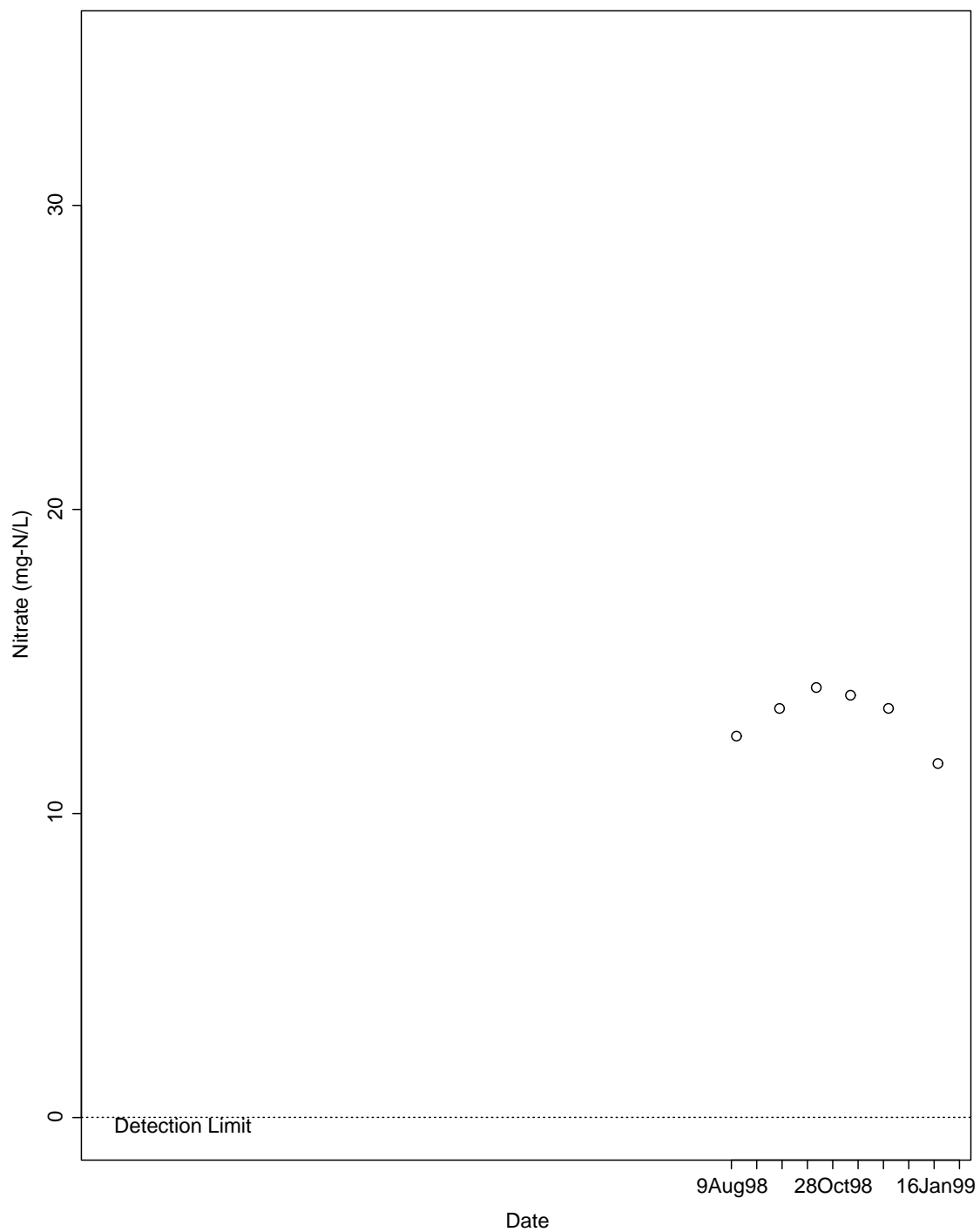
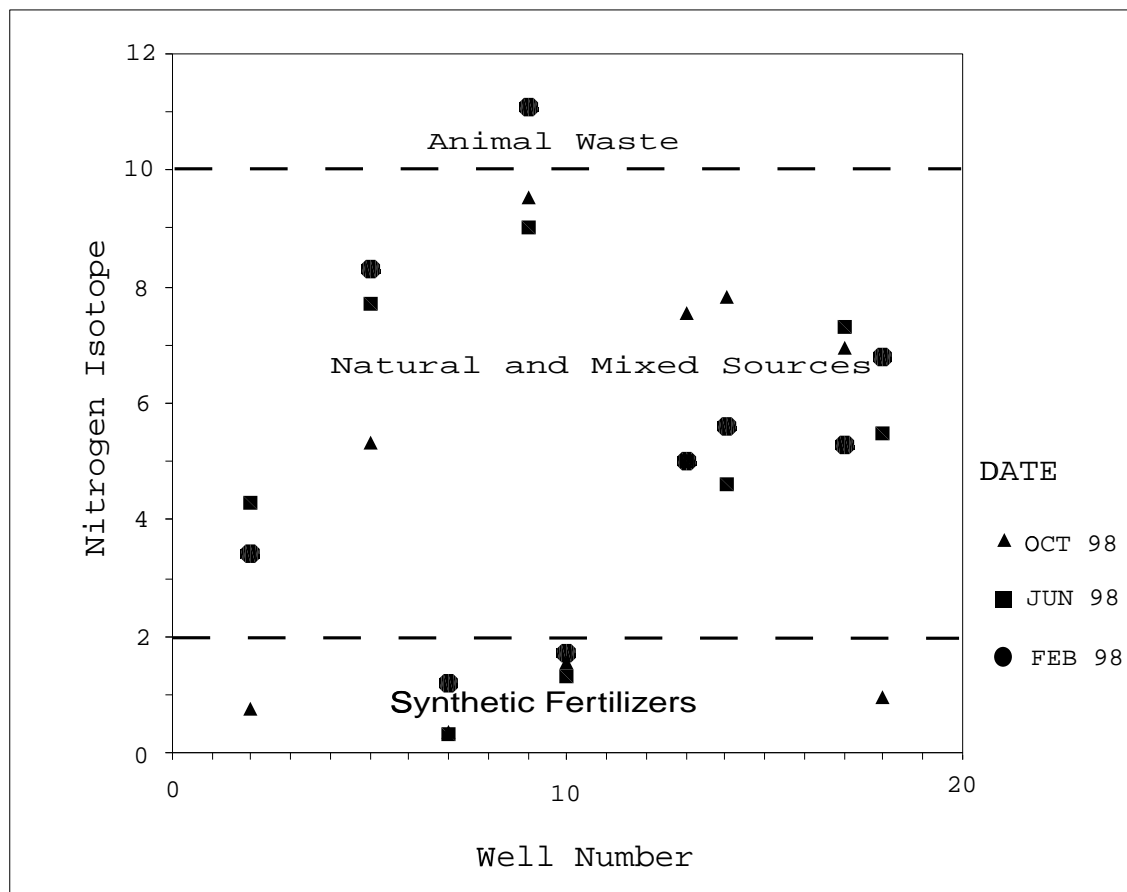
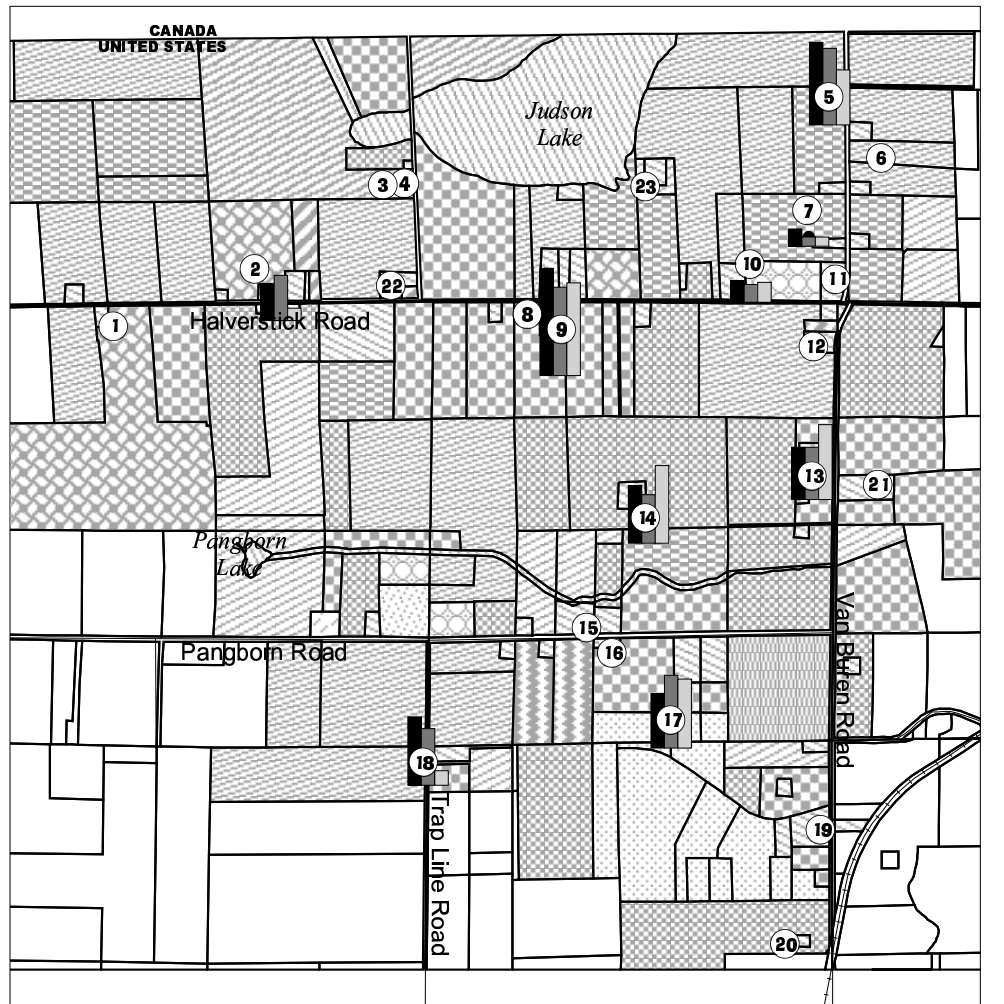


Figure 77: Scatterplot of nitrate concentrations over time for Well 28.

Figure 78: Nitrogen isotope ratios ($\delta^{15}\text{N}$).



Source: Field survey conducted Summer 1997. Nitrogen isotopes sampled in 1998. Base parcel layer from Whatcom County Planning and Development.

0 0.5 1 Miles

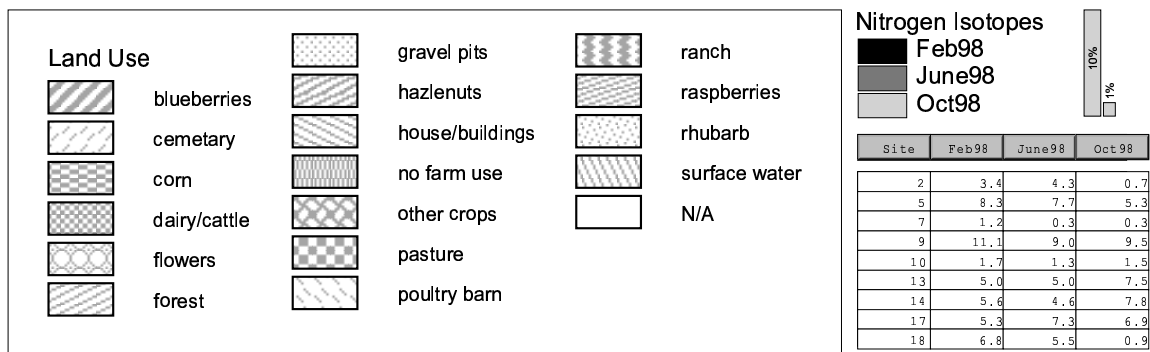


Figure 79: Overlay of nitrogen isotope results (o/oo) and land use. Only regularly sampled sites are shown. See Figure 1 for locations of infrequently sampled sites.

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A Sampling Site Descriptions.

B Field Notes.

C Water Quality and Well Elevation Data.

The 1997/98 Abbotsford/Sumas well data are included on the following pages. These are raw data files that have **NOT** been censored to identify below detection and above detection values. Refer to the text of this report for applicable detection limits and abbreviations. It is essential that any statistical or analytical results that are generated using uncensored data be reviewed by a trained statistician or scientist familiar with statistical uncertainty associated with below detection data.

D Field Duplicate Data.

Sample Date	Site	Total Nitrogen			Nitrate+Nitrite			Ammonia			Chloride		
		Value	Dup	RPD	Value	Dup	RPD	Value	Dup	RPD	Value	Dup	RPD
4/9/97	2	17.156	18.375	7%	15.958	16.809	5%	<0.020	<0.020				
4/9/97	18	22.045	23.482	6%				<0.020	<0.020				
5/6/97	6	12.912	12.281	5%	12.022	11.522	4%	<0.020	<0.020				
5/6/97	14	31.027	31.072	0%	31.016	29.249	6%	<0.020	<0.020				
6/11/97	9	17.425	19.023	9%	16.92	18.581	9%	<0.020	<0.020				
6/11/97	16	6.917	7.937	14%	7.352	7.276	1%	<0.020	<0.020				
7/9/97	4	0.144	0.26	57%				<0.020	<0.020				
7/9/97	19	3.14	4.259	30%	2.775	2.955	6%	<0.020	<0.020				
8/14/97	1	10.35	11.46	10%	10.609	10.74	1%	0.0023	<0.020				
8/14/97	13	12.54	12.6	0%	14.022	14.136	1%	<0.020	<0.020				
9/17/97	5	10.19	10.54	3%	9.83	10.065	2%	<0.020	<0.020				
9/17/97	17	10.08	10.42	3%	10.315	10.434	1%	<0.020	<0.020				
10/8/97	15	4.048	4.134	2%	4.24	4.233	0%	<0.020	<0.020				
10/8/97	7	11.22	9.477	17%	9.468	9.757	3%	<0.020	<0.020				
11/10/97	1	10.331	10.02	3%	9.762	10.735	9%	<0.020	<0.020				
11/10/97	18	28.9	30.199	4%	29.903	31.315	5%	<0.020	<0.020				
12/11/97	7	9.47	9.86	4%	9.863	9.903	0%	<0.020	<0.020				
12/11/97	13	10.215	10.367	1%	10.179	10.663	5%	<0.020	<0.020				
1/15/98	13	9.19	9.73	6%	9.784	9.747	0%	<0.020	<0.020				
1/15/98	17	10.76	10.73	0%	10.697	10.653	0%	<0.020	<0.020				
2/5/98	19	3.592	1.211	99%	2.166	2.318	7%	<0.020	<0.020				
2/5/98	9	12.577	10.847	15%	12.45	13.656	9%	<0.020	<0.020				
3/5/98	8	0.621	0.622	0%	0.619	0.656	6%	<0.020	<0.020				
3/5/98	7	8.921	8.84	1%	8.365	8.398	0%	<0.020	<0.020				
4/8/98	17	10.007	10.321	3%	11.487	11.162	3%	<0.020	<0.020				
4/8/98	2	15.023	14.135	6%	14.494	14.711	1%	<0.020	<0.020				
5/7/98	2	13.358	14.001	5%	15.317	13.389	13%	<0.020	<0.020				
5/7/98	6	11.839	13.366	12%	14.063	14.436	3%	<0.020	<0.020				
6/16/98	13	9.522	9.938	4%	10.705	10.652	0%	<0.020	<0.020				
6/16/98	9	7.82	7.895	1%	8.81	8.608	2%	<0.020	<0.020				
7/19/98	5	14.373	13.636	5%	13.62	14.181	4%	<0.020	<0.020				
7/19/98	18	13.762	12.312	11%	13.781	13.486	2%	<0.020	<0.020				
8/13/98	2	13.405	13.513	1%	13.376	12.855	4%	0.037	<0.020				
8/13/98	17	8.779	8.79	0%	9.032	9.179	2%	<0.020	<0.020				
9/17/98	10	11.501	12.552	9%	11.164	11.482	3%	0.014	<0.020				
9/17/98	28	14.201	14.344	1%	13.455	13.515	0%	0.219	0.173	23%			
10/15/98	10	11.501	11.271	2%	11.906	12.025	1%	0.013	<0.020		2.3	2.3	1%
10/15/98	20	1.951	2.023	4%	2.41	2.429	1%	<0.020	0.019		6.1	6.0	1%
11/11/98	3	0.078	0.095	20%	-0.005	-0.005	0%	<0.020	<0.020		4.9	5.0	1%
11/11/98	19	1.388	1.432	3%	3.283	1.508	74%	0.014	0.031	76%	1.7	1.7	2%
12/11/98	8		1.328		3.065	3.067	0%	<0.020	<0.020		3.8	3.8	1%
12/11/98	21	0.041	1.379	188%	0.014	0.017	19%	0.034	0.034	0%	24.7	24.6	0%
1/19/99	2	12.729	9.441	30%	13.723	13.859	1%	<0.020	<0.020		5.4	5.6	4%
1/19/99	17	9.418	4.462	71%	10.999	10.864	1%	<0.020	<0.020		8.2	8.0	3%
		RSD = 9%			RSD = 5%			RSD = NA			RSD = 1%		

E Kendall's τ Correlation Statistics.

F Cumulative Precipitation Totals for 30 Days Prior To Sampling.

Months	Precip (in)
April 1997	5.94
May 1997	5.59
June 1997	5.15
July 1997	2.81
August 1997	2.52
September 1997	2.19
October 1997	6.60
November 1997	4.42
December 1997	4.96
January 1998	7.30
February 1998	4.72
March 1998	3.59
April 1998	3.75
May 1998	1.38
June 1998	4.29
July 1998	3.08
August 1998	0.00
September 1998	0.12
October 1998	3.18
November 1998	3.62
December 1998	9.23