Section 4
Earthen Manure Storages and Confined Feeding Operations Study

4.1 Introduction

Livestock manure from confined feeding operations (CFOs) is collected and stored using various methods prior to land application, which is the most common utilization of manure in Alberta. Solid manure, which is usually associated with feedlot and poultry operations, is stored in pens or on pads before removal, and then either applied directly to land or temporarily stockpiled prior to land application. Feedlots also typically have catch basins, which store collected/diverted surface water runoff from pens and alleyways. Liquid manure, which is usually associated with dairy and hog operations, is stored in below-ground pits, above-ground tanks, lined lagoons, or earthen manure storages (EMSs).

Prior to amendment of the Agriculture Operation Practices Act (AOPA) in 2002 to provincially regulate the CFO industry, permits for CFOs were issued by or under the responsibility of the local health authorities and municipalities. Many of these permits were issued without storage facility construction or design standards or in some cases, permits were not required.

According to Hendry *et al.* (2007) the prevalence of relatively thick clay aquitards over much of the landscape in Alberta and the lack of extensive shallow aquifer systems suggest that hydrogeologically stable sites for siting suitable manure storage and collection facilities should be common. However, some manure collection and storage facilities, particularly EMSs, may be releasing manure constituents into shallow groundwater (Hendry *et al.* 2007). An EMS constructed prior to 2002 has the highest potential to seep because the liquid manure may be stored in a lagoon that may have relatively little construction, other than the excavation of material to create the lagoon, and is comprised of unaltered natural materials (i.e., no compaction or addition of a compacted clay layer). It is estimated that there are approximately 1000 hog and dairy facilities in the province and about 650 EMSs. The potential seepage rate from EMSs would be reliant on the natural geologic materials; however, the extent and current or potential risk on the groundwater environment in Alberta is uncertain.

The objective of this study is to determine the risks to groundwater quality from seepage at manure collection and storage facilities (Objective 2; Section 1). This study includes five CFOs: two in the Battersea study area and three in the central Alberta study area. Four of these CFOs have an EMS and two have a catch basin. In addition, as part of a separate but related collaborative project, potential groundwater quality impacts were assessed at three of the CFOs using electromagnetic (EM) terrain conductivity, electrical resistivity tomography (ERT), and geophysical borehole logging (induction conductivity and natural gamma). While these methods are less intrusive than drilling, they are not as quantitative as the methods used in the current study.

4.2 Methods

4.2.1 Site Descriptions and Previous Investigations

Five CFOs were selected: two in southern Alberta, near Picture Butte in the Battersea area (CFO-1 and -2), and three in central Alberta, in the Lacombe and Ponoka area (CFO-3, -4 and -5) (Figure 4.1). The CFO-1 site includes a dairy with an EMS and a feedlot with pens and a catch basin. The CFO-2 site is a feedlot with pens and catch basins. The three CFOs in central Alberta are dairies each with an EMS. Selection criteria for the sites included the availability of historical information (i.e., groundwater monitoring requirements for the Natural Resources Conservation Board), expected continuation of the operation (i.e., no plans to decommission within the project timeline), and producer interest and cooperation. All EMSs were initially constructed prior to amendment of AOPA in 2002. Sites were also selected to represent typical hydrogeologic scenarios in Alberta.

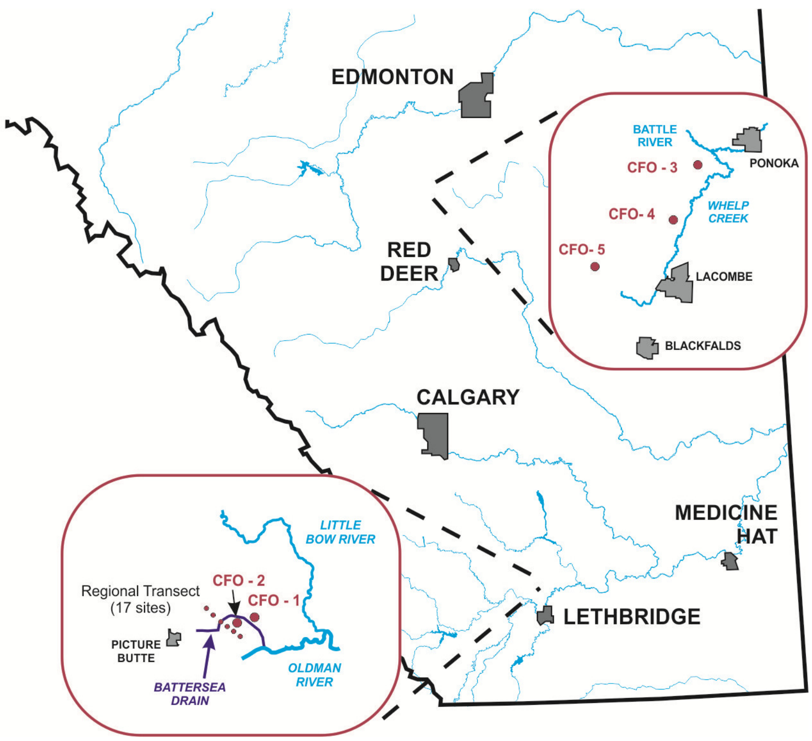


Figure 4.1. The five confined feeding operations (CFO) used in the two project study areas.

CFO-1

The CFO-1 site has a 100-cow dairy operation and a 2000-head beef feedlot facility. The dairy was constructed in 1928, while the feedlot was initiated in the 1960s and expanded to the current capacity in the 1980s. The site includes barns and pens associated with the dairy and feedlot operation, feed storage areas, and a residence, all located in the western portion of the quarter section (Figure 4.2). The EMS is south of the dairy barn, in the west-central part of the quarter section. The EMS has approximate dimensions of 40 m long, 25 m wide, and 3 to 4 m deep. The useable manure storage volume has not been estimated. The feedlot catch basin is south of the feedlot pens, in the central portion of the quarter section. The catch basin has approximate dimensions of 100 m long, 50 m wide, and an unknown depth. A surface water body (slough) is present in the west-central to central portion of the quarter section, with approximate dimensions of 150 m by 125 m and an unknown depth. An irrigation drainage canal is along the south boundary of the quarter section.

The topography at the site is relatively flat. A local topographic high occurs to the west of the site, dropping towards the east and south. Expected shallow groundwater flow, based on topography, is to the east to southeast. Two rivers, approximately 4 km to the south (Oldman River) and 8 km to the east (Little Bow River), represent the nearest major drainage features.

Soil at this site consists primarily of Orthic Dark Brown Chernozems with moderately coarse-textured sediments deposited by wind or water (Alberta Soil Information Center 2001). Typical soil texture includes sandy loam, characterized by fine-grained sand. Recent-aged gravel, sand, silt, and clay ice-contact lacustrine and fluvial deposits, from intermittent superglacial lakes and streams or the margins of ice-floored proglacial lakes, underlay the site. Surficial deposits surrounding the site are generally less than 25 m thick. An area of eolian deposits occurs to the southern edge of the quarter section, consisting of fine- and medium-grained sand. The Oldman Formation is the uppermost bedrock underlying the site.

Five water wells were identified at this site, with an additional eight wells identified on adjacent quarter sections and an additional three identified within a 1.6-km radius, according to water well drilling reports (AEW 2010, unpublished data, AEW Alberta Water Well Database). All water wells indicated completion within surficial deposits, ranging in depth to tops of open intervals from just below ground surface to 9.75 m. Surficial deposit lithology consistently identified sand from surface to approximately 4 to 10 m and clay and sand layers below that. All water wells were completed relatively shallow (<25 m) in depth. No indication of the depth to bedrock was identified in the reports.

This site was pre-classified as representing a permeable or sandy geological/hydrogeological setting (Iwanyshyn 2010, unpublished data, Natural Resources Conservation Board). No previous groundwater investigations were carried out at this site prior to 2010.

CFO-2

Site Description. The CFO-2 site is a beef feedlot with an approximate 5000-head capacity. The site includes pens, feed storage areas, two catch basins, and a residence (Figure 4.3). The feedlot started with 100 to 200 animals when it was constructed in 1974. Each catch basin has approximate dimensions of 31 m long by 15 m wide and 3.5 m deep, although the useable depth is approximately 2 m. Land use to the south and east of the feedlot consists of cropland.

The topography at the site is relatively flat. A local topographic high occurs to the west of the site, dropping towards the east and south. Expected shallow groundwater flow, based on regional topography, is to the east to southeast. However, from the northwest corner of the site, a drainage channel (Battersea Drain) lies approximately 0.8 km to the northwest, which may influence local groundwater flows. There is also an irrigation canal along the property line from the southeast to the northeast.

Soil at this site consists primarily of Orthic Dark Brown Chernozems on medium textured sediments deposited by wind and water (Alberta Soil Information Center 2001). Typical soil texture includes loam and silty loam. The Oldman Formation is the uppermost bedrock underlying the site.

One water well was identified at this site, with an additional eight wells identified on adjacent quarter sections from water well drilling reports (AEW 2010, unpublished data, AEW Alberta Water Well Database). Other than well depth, no additional information was available from these reports.

This site was pre-classified as representing a geological/hydrogeological setting of thick till and clay. The site lies in a lacustrine basin and is between a bedrock high and buried aquifer in the west and an unconfined aquifer of coarse glaciolacustrine sand in the east.

Previous Investigations. One water table well (LB8-1) and three piezometers (LB8-2, -3, -4) were installed along the south edge of the feedlot in 1993 and 1994 as part of a regional study in the Battersea area (Rodvang *et al.* 2001) (Figure 4.3). The water table well had a screen length of 1.6 m with a completion depth of 2.1 metres below ground surface (mbgs) and was completed in fine sandy clay to clay. Piezometers LB8-2, -3, and -4 were screened at 0.6, 2, and 1.9 m intervals at 3.5, 8.7, and 12.6 mbgs, and they were completed in silty clay, clay, and clay loam, respectively. Bedrock was not encountered to the maximum depth (12.6 mbgs) of investigation. These wells were not used in the current study from 2009 to 2011.

CFO-3

Site Description. The CFO-3 site is a 150-cow (expanded from 120 in 2005) dairy operation, which includes barns, corrals, feed storage areas, and a residence. The dairy and EMS were constructed prior to 1997. The EMS is west of the dairy facilities, in the east-central part of the quarter section. The EMS is approximately 56 m long, 25 m wide, and 5 m deep, for a useable manure storage volume of approximately 4,462 m^3. The below barn manure pits have an additional approximate storage volume of 1,877 m^3.

The topography at the site is undulating, with rolling hills. A local topographic high occurs to the southwest of the site, dropping towards the northeast. Expected shallow groundwater flow, based on topography, is towards the northeast. A number of ephemeral ponds occur surrounding the site, with the Battle River approximately 2 km northeast of the site as the nearest major drainage feature.

Recent-aged sand and silt lacustrine deposits underlay CFO-3. Areas of eolian deposits occur south of the site, while fine- and coarse-grained fluvial deposits occur along the river to the northeast (Shetson 1990). Surficial deposits surrounding the site are generally less than 30 m thick. Groundwater use in the surficial deposits surrounding the site is generally limited to areas of significant sand and gravel deposits, with none located at the site.

The Paskapoo Formation is the uppermost bedrock formation underlying the site. The Dalehurst Member of the Paskapoo Formation subcrops in the western part of the County of Ponoka where the site is located (HCL 2003). Sandstone and siltstone generally have the highest permeabilities among the lithologies that compose the Dalehurst Member.

Based on water well driller's logs from or near CFO-3, surficial deposits over the bedrock are generally relatively thin (<3 m). Sandstone and shale were the two dominant bedrock types encountered locally (WorleyParsons 2009). The site was pre-classified as having a geological/hydrogeological setting of thin till overlying permeable bedrock (WorleyParsons 2009).

Previous Investigations. Three water table wells (A-MW1 through A-MW3) were completed at CFO-3 in 2006 as part of an EMS leakage detection system required by the Natural Resources Conservation Board (Figure 4.4). These wells are also used in the current study. The water table wells were screened at 3 m intervals at approximately 9 mbgs and were completed in shale. The annuli of these monitoring well boreholes were backfilled with native material for approximately 3 m above the sand pack, resulting in an effective screened interval of approximately 6 m and spanning into the surficial deposits overlying the bedrock. Bedrock was found to be relatively shallow at the site, with silt and clay deposits overlying the shale from ground surface to approximately 2.9 to 4.8 mbgs.

CFO-4

Site Description. The CFO-4 site is a 350-cow (expanded from 230 in 2009) dairy operation, which includes barns, corrals, feed storage areas, and a residence. The dairy and EMS were constructed around 1995. The EMS is west of the dairy facilities, in the southeast part of the quarter section. The EMS is approximately 61 m long, 41 m wide, and 6 m deep, for a useable manure storage volume of approximately 7,614 m^3. The below barn pits have an additional manure storage volume of approxiately 2,428 m^3.

At CFO-4, topography is somewhat influenced by an ephemeral watercourse. A regional topographic high occurs to the west of the site, dropping towards the east-southeast. Expected shallow groundwater flow, based on topography, is towards the east. A number of ephemeral ponds occur surrounding the site, with a creek approximately 1.5 km to the east being the nearest major drainage feature.

Recent-aged sand and silt lacustrine deposits underlay CFO-4. Areas of eolian deposits occur north and east of the site (Shetson 1990). The site appears to be on the western edge of a regional-scale southwest to northeast trending buried bedrock valley (HCL 2001). Surficial deposits surrounding the site are generally less than 30 m thick. Groundwater use in the surficial deposits surrounding the site is generally limited to areas of significant sand and gravel deposits, which may be present near CFO-4.

The Paskapoo Formation is the uppermost bedrock formation underlying the site. The Upper Lacombe Member of the Paskapoo Formation subcrops in the part of Lacombe County where CFO-4 is located (HCL 2001). Sandstone generally has the highest permeability among the lithologies that compose the Upper Lacombe Member.

Based on water well driller's logs from or near CFO-4, surficial deposits over the bedrock are generally clay and clay till to a depth of approximately 7 mbgs (WorleyParsons 2009). Significant sand deposits were reported in the quarter sections to the west of the site. Sandstone and shale were the two dominant bedrock types encountered locally. The Site was pre-classified as having a geological/hydrogeological setting of thin till overlying permeable bedrock (WorleyParsons 2009).

Previous Investigations. Four water table wells (B-MW1 through B-MW4) were completed at the site in 2002 as part of an EMS leakage detection system as required by the Natural Resources Conservation Board (Figure 4.5). These water table wells were screened at 3 m intervals at approximately 6 to 7.5 mbgs and were completed in sandy clay, clay sand, sand, and/or sandstone. Bedrock was relatively shallow at CFO-4, with sandstone encountered at depths ranging from 6 to 7 mbgs (WorleyParsons 2009). Two of these wells, B-MW1 and B-MW3, are also used in the current study.

CFO-5

Site Description. The CFO-5 site is a 200-cow dairy operation, which includes barns, shops, feed storage areas, and residences. The dairy and EMS were constructed prior to 1996. The EMS is east-northeast of the dairy facilities, in the southern part of the quarter section. The EMS dimensions and useable manure storage volume have not yet been estimated.

The topography at CFO-5 has some variation, with elevation decreasing from east to west. Shallow groundwater flow, based on topography, is expected towards the west. A number of ephemeral ponds, sloughs, and creeks surround the site, with a drainage channel running east to west through the quarter section and Gull Lake approximately 2 km west of the site.

Pleistocene-aged, draped moraine deposits consisting of till with minor amounts of water-sorted material underlay CFO-5. Areas of lacustrine deposits occur east of the site in association with Gull Lake (Shetson 1990). The site may be near a northwest-southeast trending meltwater channel that drains to a major regional buried bedrock valley (HCL 2001). Surficial deposits surrounding the site are generally less than 30 m thick, although thickness greater than 50 m can be found in locations where buried valleys and melt-water channels are present. Groundwater use in the surficial deposits surrounding the site is generally limited to areas of significant sand and gravel deposits, which may occur near the site, associated with the underlying melt-water channel. Similar to CFO-4, the Paskapoo Formation is the uppermost bedrock formation that underlies CFO-5.

Based on water well driller's logs from or near CFO-5, surficial deposits generally consist of a heterogeneous mixture of sand and gravel, clay, and till (WorleyParsons 2009). From water wells drilled within the quarter section, water bearing sand and gravel layers near the ground surface were reportedly up to 12 m thick (WorleyParsons 2009). Shale and sandstone were the two dominant bedrock types encountered locally. The site was pre-classified as having a geological/hydrogeological setting of thick, permeable unconsolidated deposits overlying bedrock (WorleyParsons 2009).

Previous Investigations. Three water table wells (C-MW1 through C-MW3) were completed at CFO-5 in 2007 as part of an EMS leakage detection system required by the Natural Resources Conservation Board (Figure 4.6). These wells are also used in the current study. The water table wells were screened at 3 m intervals at approximately 7.2 and 7.5 mbgs and were completed in clay sand or sandy clay. The sand pack of these monitoring wells extended above the screened interval by approximately 2 m, resulting in an effective screened interval of approximately 5 m. Bedrock was not encountered to the maximum depth (7.5 m) of investigation.

4.2.2 Weather Data

The Iron Springs weather station (latitude 49^o 54' 2", longitude 112^o 44' 24", elevation 893 m) is the closest weather station to the Battersea area. Annual weather data (2009 to 2011) from this site were obtained from the Irrigation Management Climate Information Network (ARD 2010). In addition, the 30-yr average (1971 to 2000) values were obtained from the Lethbridge Canada Department of Agriculture (CDA; now Agriculture and Agri-Food Canada) weather station (latitude 49^o 41' 42", longitude 112^o 46' 3'', elevation 910 m) because of the lack of historical data from the Iron Springs weather station (Environment Canada 2011).

The Crestomere AGCM weather station (latitude 52^o 73' 3", longitude 113^o 90' 3", elevation 855 m) is the closest weather station to CFO-3. Annual weather data (2009 to 2011) from this site were obtained from AgroClimatic Information Service (ACIS) (ARD 2011). No long term historical data were available for the Crestomere weather station. A 4-yr average (2008 to 2011) was used from the Crestomere station for comparison purposes because of a lack of historical data and/or nearby weather stations with historical data.

The Lacombe CDA weather station (latitude 52^o 28' 0", longitude 113^o 45' 0", elevation 847.30 m) is the closest weather station to CFO-4 and -5. Annual weather data (2009 to 2011) from this site were obtained from Environment Canada (2012). The 30-yr average (1971 to 2000) values were obtained from the same station.

4.2.3 Borehole Drilling and Well Installation

CFO-1

From February 2010 to November 2011, a total of 30 groundwater wells were installed at CFO-1 (Figure 4.2). These included 13 water table wells and 17 piezometers (Appendices 2 and 3). A lithologic/borehole log was recorded for boreholes instrumented in 2010 and 2011.

Lithologic logs were only recorded for the deepest borehole when two or more wells were instrumented in a nest.

From late February to early March 2010, eight wells were installed using a combination of hollow stem and solid stem augers. Three water table wells (D-MW1, D-MW2, D-MW3) and two piezometers (D-P10-1, D-P10-2) were installed surrounding the EMS, and three water table wells (D-MW4, D-MW5, and D-MW6) were installed surrounding the catch basin (Figure 4.7). All monitoring wells were installed with a sand pack surrounding the screen, which extended approximately 0.3 m above the screen. A bentonite seal was installed from the top of the sand pack to ground surface. All water table wells were assumed to intersect the shallow, unconfined groundwater bearing zone. Note that D-MW4 and D-MW6 were not logged in the field during installation and, therefore, a borehole log is not available for these wells in Appendix 3

From January to March 2011, 18 groundwater monitoring wells were installed at CFO-1 using a combination of hollow stem and solid stem augers. Wells were installed in nests at assumed upgradient and downgradient directions of the entire CFO, with initial emphasis primarily around the EMS and then the feedlot and catch basin (Figure 4.2). Each nest of wells consisted of one water table well (~7 mbgs) and one or two deep piezometers (20 and 35 mbgs) (Appendices 2 and 3).

Five point velocity probe (PVP) stands were installed at the site in August 2011, with a total of 11 PVP units installed among the five stands: two at PVP1, three at PVP2, two at PVP3, one at PVP4, and three at PVP5 (Figure 4.7, Appendix 2). Details about PVP installation are reported in Subsection 2.2.4.

In November 2011, four piezometers (D-P11-10d, D-P11-14d, D-P11-14e, D-P11-15d) were installed at three existing nests where PVP stands had also been installed. These piezometers were installed with 0.01-m screens and at similar depths to the PVPs (Appendix 2).

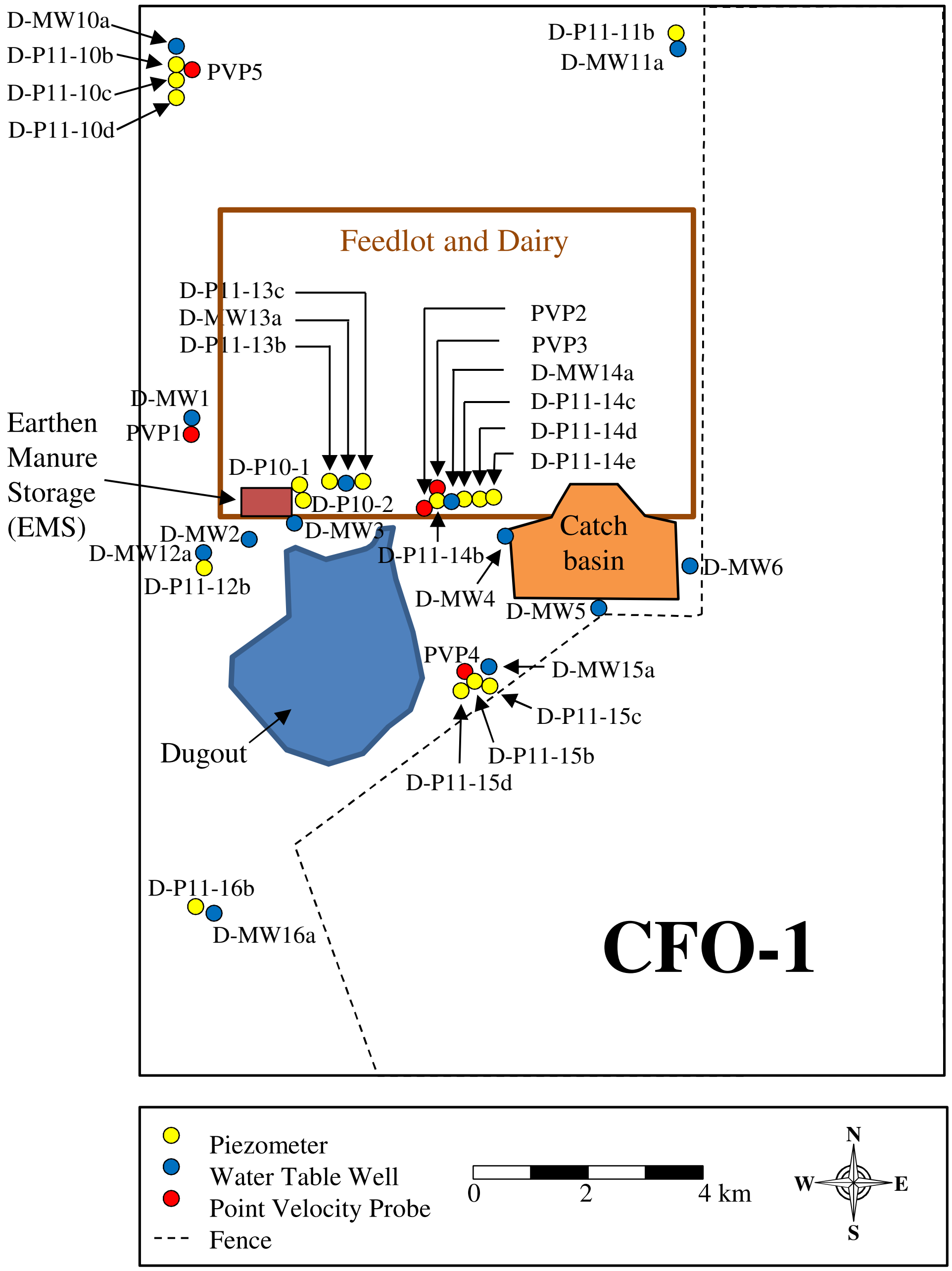


Figure 4.2. Site components and location of groundwater wells and point velocity probe (PVP) stands at CFO-1 in 2011.

CFO-2

From February 2010 to March 2011, a total of 12 groundwater wells were installed at CFO-2 (Figure 4.3). These included nine water table wells and three piezometers (Appendices 2 and 3). Only one (LB8-4) of the four historical wells still exists, though it is not used in the current study. A lithologic/borehole log was recorded for boreholes instrumented in 2010 and 2011. Lithologic logs were only recorded for the deepest borehole when two or more wells were instrumented in a nest.

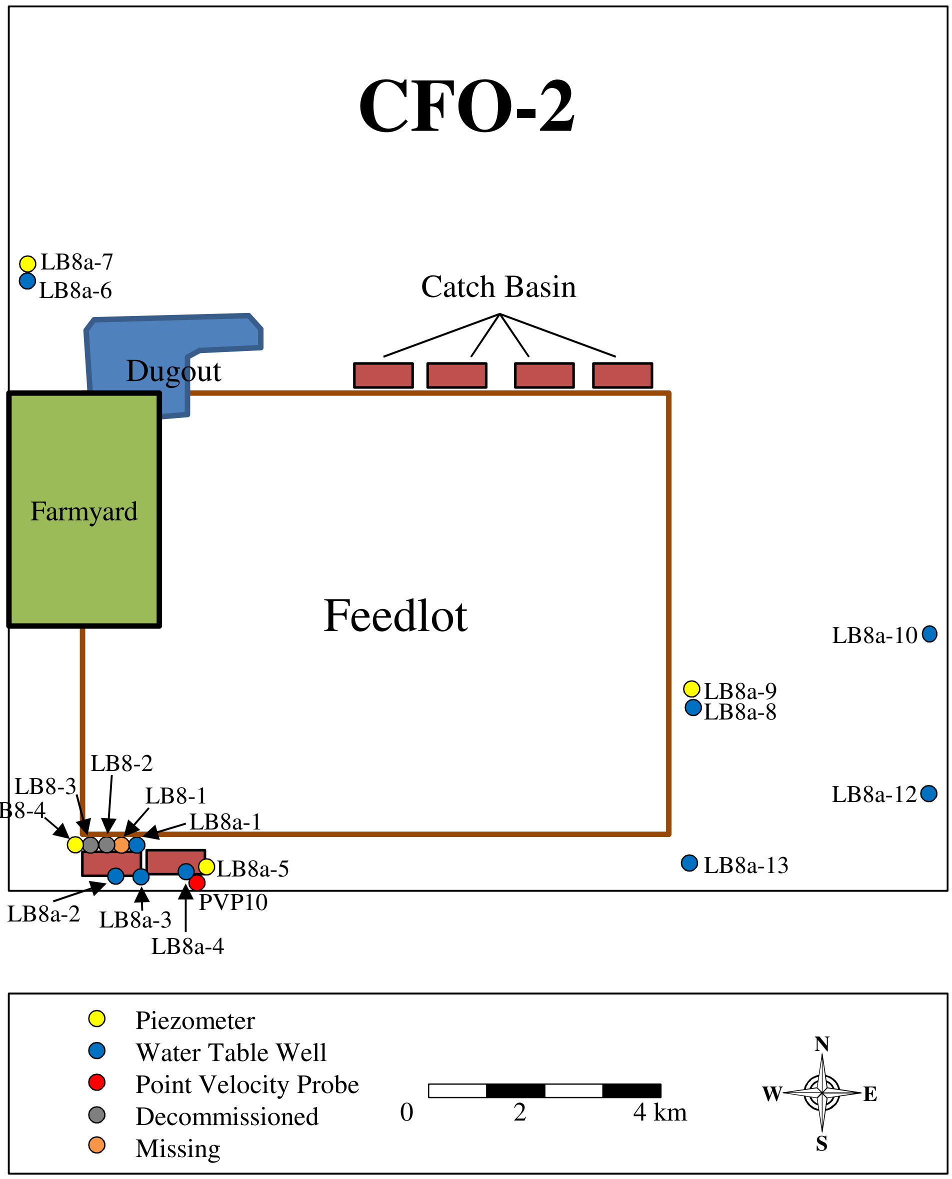


Figure 4.3. Site components and location of groundwater wells and the point velocity probe (PVP) stand at CFO-2 in 2011.

Four water table wells were installed at CFO-2 in February 2010, and one piezometer was installed in December 2010. The wells were located along the southern boundary of the feedlot (Figure 4.3). Three of the wells were installed in a line along the south boundary of two catch basins rather than as a nest. The water table wells are between 7 and 7.1 mbgs and have screen intervals of 3 m. The forth water table well (3 mbgs, 1.5-m screen) was installed along the southwest edge of the feedlot and next to the historical nest of wells, which, with the exception of the deepest piezometer, no longer exists. The new piezometer (20 m deep with a 0.5-m screen) was installed south of the east catch basin next to a water table well (LB8a-5, Figure 4.8).

Seven more wells (five water table wells and two piezometers) were installed in March 2011. Two nests with one water table well and one piezometer were installed in the northwest corner of the site (LB8a-6, -7) and along the eastern edge of the feedlot (LB8a-8, -9). Two more water table wells were installed along the eastern edge of the study site (LB8a-10, -12), and the last water table well was installed in the southeast corner (LB8a-13). All water table wells have screen intervals of 3 m and are between 4.1 and 6.5 mbgs (Appendix 2). Piezometers LB8a-7 and -9 were 9.8 and 9.5 mbgs, respectively, with 0.5-m screens.

In addition to the 12 wells, one PVP stand with one PVP at 4.6 mbgs (PVP10) was installed south of the feedlot and east of the catch basin next to water table well LB8a-4 (Figure 4.8) in August 2011. Details about PVP installation are reported in Subsection 2.2.4.

CFO-3, -4, and -5

Initial drilling and instrumentation at CFO-3, -4, and -5 occurred in 2006, 2002, and 2007, respectively, as part of the EMS leakage detection requirements for each site as previously described. Additional drilling and instrumentation for the current study was initiated in 2008 at the sites. All sites were instrumented with one deep (~ 20 m deep) and one intermediate (~15 m deep) piezometer next to the EMS and four water table wells in an adjacent field receiving manure application. All wells were installed with a sand pack surrounding the screen and a bentonite seal from the top of the sand pack to ground surface. A lithologic/borehole log was recorded for each borehole during drilling and instrumentation (Appendix 3).

At CFO-3, six wells were completed in 2008 (Figure 4.4). Two piezometers (A-P08-16 and A-P08-21) were installed on the north side of the EMS and were screened over 1.5-m intervals to total depths of 15.8 and 20.7 mbgs. Four water table wells (A-C1 through A-C4) were installed in the adjacent field to the west and south of the EMS and were screened over 3-m intervals to depths ranging from 5.8 to 7.0 mbgs (Appendix 2). An optical borehole imager (OBI) was used during drilling of the deepest borehole at CFO-3 in 2008 as a means of identifying horizontal and vertical fractures in the subsurface (WorleyParsons 2009).

At CFO-4, 10 wells were installed from 2008 to 2010 (Figure 4.5). Four water table wells (B-C1 through B-C4) were installed in 2008 within the adjacent field to the west of the EMS and were screened over 3 m intervals to depths ranging from 6 to 7 mbgs (Appendix 2). Six additional boreholes were drilled and instrumented in February and March 2010. Boreholes B-MW2a and B-MW4a were completed as water table wells with 3.0-m screens. Boreholes B-P10-

15e, B-P10-21e, B-P10-15w, and B-P10-20w were completed as piezometers at 14.85, 20.5, 15.0, and 20.0 mbgs, respectively, with 1.5 m screen lengths (Appendices 2 and 3).

At CFO-5, six wells were completed in 2008 (Figure 4.6). Two piezometers (C-P08-14 and C-P08-21) were installed on the west side of the EMS and were screened over 1.5-m intervals to total depths of approximately 14.4 and 21.1 mbgs. Four water table wells (C-C1 through C-C4) were installed in the adjacent field to the northeast and northwest of the EMS and were screened over 3-m intervals to depths of approximately 7 mbgs (Appendix 2).

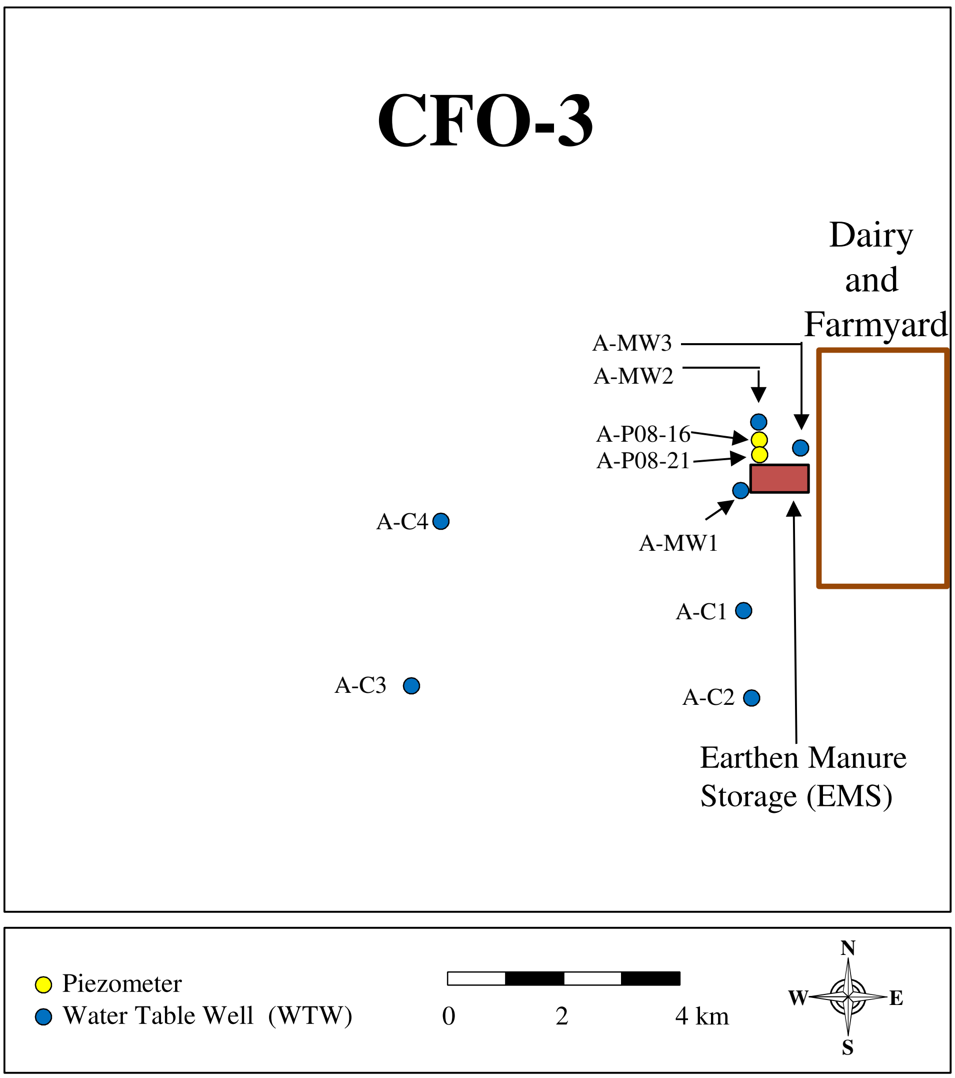


Figure 4.4. Site components and location of groundwater wells at CFO-3 in 2011.

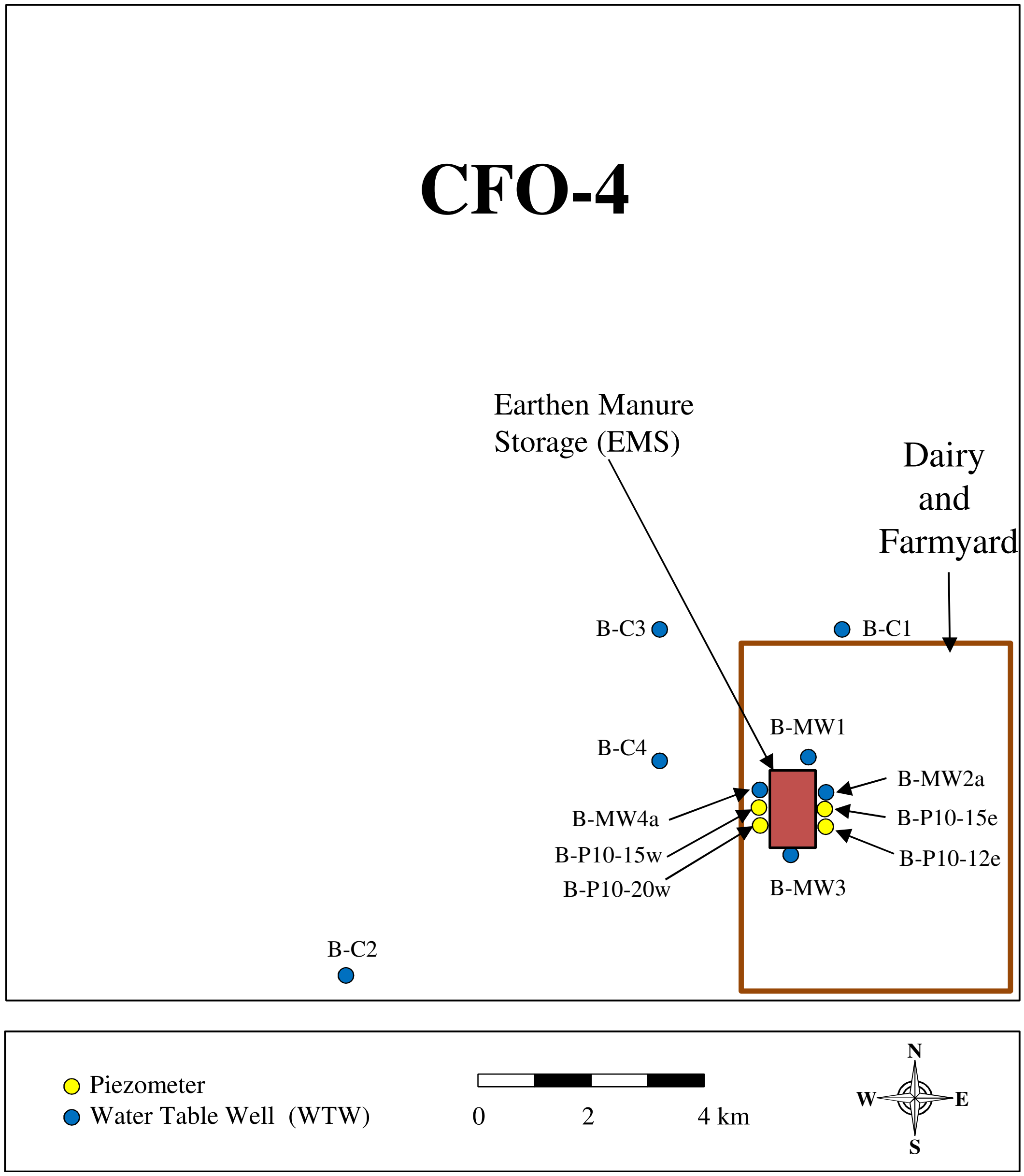


Figure 4.5. Site components and location of groundwater wells at CFO-4 in 2011.

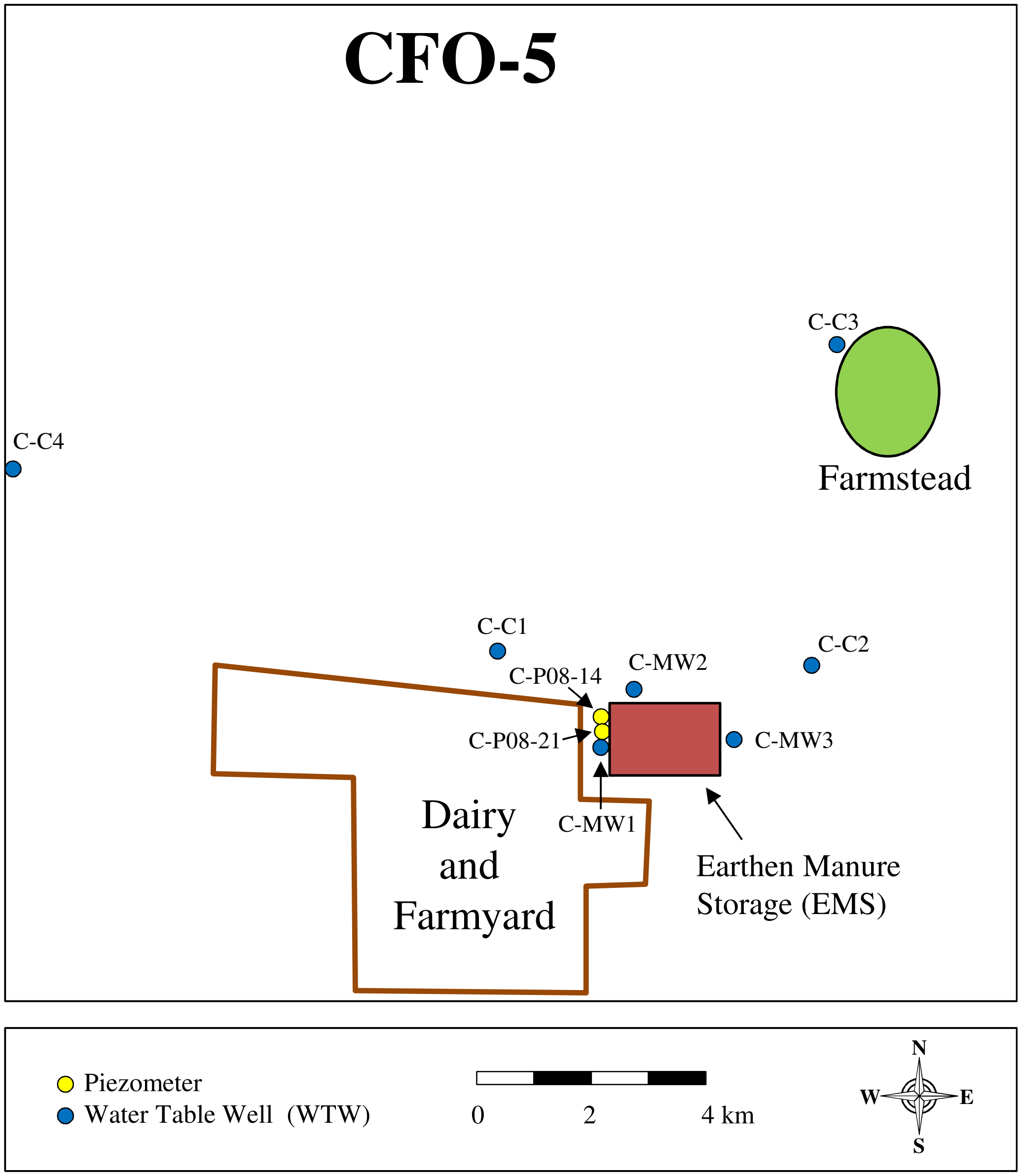


Figure 4.6. Site components and location of groundwater wells at CFO-5 in 2011.

4.2.4 Soil Core Sampling and Analysis

Core samples were collected during borehole drilling at CFO-1, -2, and -4 in 2010 and again at CFO-1 and -2 in 2011. Core samples were collected during the borehole drilling at CFO-3, -4, and -5 in 2008 but were not analyzed and subsequently discarded.

CFO-1

An 8- to 15-cm core sample was collected from the centre of each incremental foot depth (0.3 m) from D-P10-1 in March 2010 (Table 4.1, Figure 4.7). These cores were sent to the University of Saskatchewan (U of S) where each core was split into two cores: one used for isotope analysis and the other used for physical analysis (gravimetric, volumetric, and bulk density), and later for chemical analysis. Samples were collected to a depth of about 20 m.

After the core from D-P10-1 was analyzed for physical properties by the U of S, the samples were sent to Alberta Agriculture and Rural Development (ARD) for chemical analysis. The samples were dried and ground to pass through a 2-mm sieve. Chemical analysis was completed for every depth to 9 m. However, it was later discovered that these samples had been stored wet for a minimum of 6 mo at room temperature, and as a result, there was concern about the accuracy of the chemical analysis, particularly for nitrate nitrogen (NO_3^--N). Therefore, a new soil core was collected by re-drilling a borehole within 1 m of the original well in September 2011. During the re-drilling, a soil core (15 cm long) was collected above every foot mark depth starting at 1 ft (0.30 m) (Table 4.1, Figure 4.7). Samples were collected to a depth of about 6 m. The samples were immediately air dried and ground to pass through a 2-mm sieve and were analyzed for chemical parameters by ARD. The re-drilled boreholes were back-filled to at least 3 mbgs with bentonite and filled to the surface with a natural pack.

At D-P11-10b, -14b, and -15b, a soil core (8 cm long) for isotope analysis was removed above each foot mark depth starting at 1 ft (0.30 m) below ground surface (Table 4.1, Figure 4.7) in March 2011. In addition, soil cores for chemical (15 cm long) and physical (8 cm long) analysis were removed below every foot mark starting at the ground surface. Samples were collected to about 20 mbgs. Chemical analysis was completed for every foot mark depth down to a approximately 10 mbgs, with the remaining cores stored for future analysis.

A 15-cm core for chemical analysis was also collected from above each foot mark depth starting at 1 ft (0.30 m) below ground surface at D-P11-10d, -14d, -14e, and -15d in November 2011 (Figure 4.7). These samples were air dried and stored for future chemical analysis.

Core samples were also collected from all other nests installed at CFO-1 in January and February 2011, either from the deepest piezometer or from the water table well if only one well was installed, using disturbed sampling. Core segments 30- to 50-cm long were collected from the bottom of every 1.5-m incremental layer (Table 4.1, Figure 4.7). Drilling was completed at eight wells using a hollow stem auger. Total well depths ranged from approximately 20 to 34 m.

Table 4.1. Boreholes soil sampled at CFO-1 in 2010 and 2011.

Well name[z]	Well type	Depth (m)	Sampling date	Description
D-P10-1	Water table	18.6	Mar 2010 and Sept 2011[y]	Every foot plus isotopes[x]
D-P10-2	Piezometer	8.0	Feb 2010	ns[w]
D-MW1	Water table	5.0	Feb 2010	ns
D-MW2	Water table	5.98	Feb 2010	ns
D-MW3	Water table	3.7	Feb 2010	ns
D-MW4	Water table	4.2	Feb 2010	ns
D-MW5	Water table	6.8	Feb 2010	ns
D-MW6	Water table	6.7	Feb 2010	ns
D-MW10a	Water table	7.2	Jan 2011	ns
D-P11-10b	Piezometer	20.0	Jan 2011	Every foot plus isotopes[v]
D-P11-10c	Piezometer	34.0	Jan 2011	Every 1.5 m[u]
D-P11-10d	Piezometer	13.0	Nov 2011	Every foot – placed in storage[t]
D-MW11a	Water table	7.0	Jan 2011	ns
D-P11-11b	Piezometer	20.0	Jan 2011	Every 1.5 m
D-MW12a	Water table	7.0	Feb 2011	ns
D-P11-12b	Piezometer	20.1	Feb 2011	Every 1.5 m
D-MW13a	Water table	7.0	Mar 2011	ns
D-P11-13b	Piezometer	20.0	Mar 2011	Every 1.5 m
D-P11-13c	Piezometer	34.0	Feb 2011	Every 1.5 m starting at 20.5 m
D-MW14a	Water table	7.0	Feb2011	ns
D-P11-14b	Piezometer	20.0	Feb 2011	Every foot plus isotopes[v]
D-P11-14c	Piezometer	34.0	Feb 2011	Every 1.5 m
D-P11-14d	Piezometer	1.3	Nov 2011	Every foot – placed in storage[t]
D-P11-14e	Piezometer	8.5	Nov 2011	Every foot – placed in storage[t]
D-MW15a	Water table	7.0	Feb 2011	ns
D-P11-15b	Piezometer	20.0	Feb 2011	Every foot plus isotopes[v]
D-P11-15c	Piezometer	34.0	Feb 2011	Every 1.5 m
D-P11-15d	Piezometer	12.6	Nov 2011	Every foot – placed in storage[t]
D-MW16a	Water table	6.0	Jan 2011	ns
D-P11-16b	Piezometer	20.0	Jan 2011	Every 1.5 m

[z] Nomenclature conventions include "D" from CFO-1 site, "MW" for water table well and "P" for piezometer.
[y] The second date is for the re-drill borehole near the original well.
[x] Within the center of each incremental foot layer, the top 7 to 8 cm was sampled for physical and chemical analysis and the bottom 7 to 8 cm was sampled for isotope analysis. Re-drills used the bottom half of each incremental foot layer.
[w] ns = not sampled.
[v] Within each incremental foot layer, the top 15 cm was sampled for chemical analysis, the middle 8 cm for physical analysis, and the bottom 8cm for isotope analysis.
[u] The bottom 30 to 50 cm sampled from every incremental 1.5-m layer.
[t] The bottom 15 cm sampled from every incremental foot layer for chemical analysis.

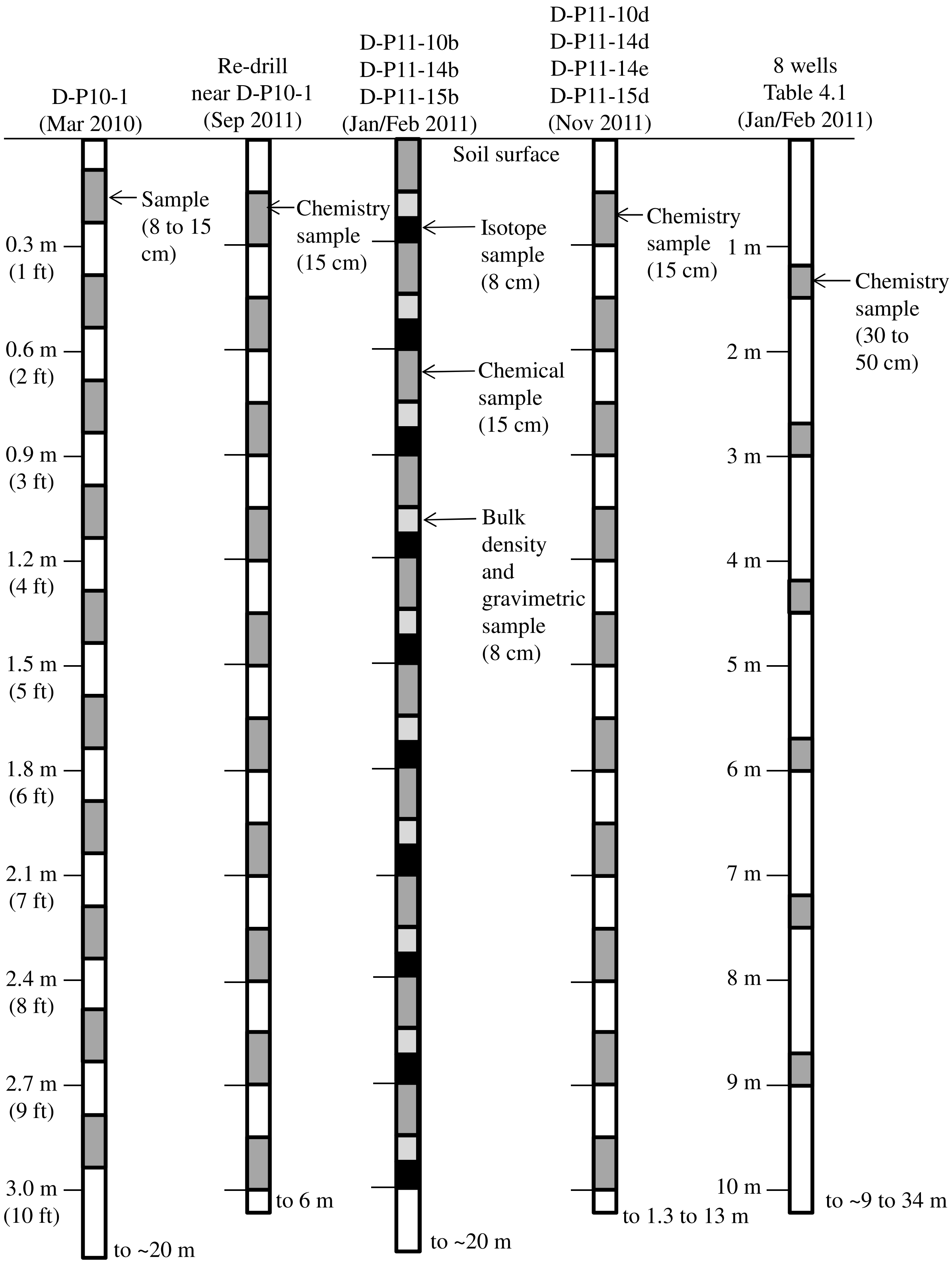


Figure 4.7. Soil sampling profiles for various boreholes at CFO-1 in 2010 and 2011 for isotope, physical, and chemical analyses.

Soil chemical analysis was carried out by ARD for the following parameters (Appendix 5):

- pH (saturated paste extract)
- Electrical conductivity (EC) (saturated paste extract)
- Anions: nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^--N), chloride (Cl^-) bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulphate sulphur (SO_4^{2-}-S), and phosphate phosphorus (PO_4^{3-}-P) (saturated paste extract)
- Cations: ammonium nitrogen (NH_4^+-N), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) (saturated paste extract)
- Extractable NO_3^--N and NH_4^+-N (10:1 ratio of 2M potassium chloride (KCl):soil)
- Extractable PO_4^{3-}-P (modified Kelowna extraction)
- Particle size analysis (hydrometer method)
- Gravimetric moisture content (oven dried)
- Sodium absorption ratio (calculated)

Note that not all samples were analyzed for all parameters.

CFO-2

A soil core (7 to 8 cm long) was removed below each foot depth mark starting at 1 ft (0.30 m) below ground surface (Table 4.2, Figure 4.8) from LB8a-5 in December 2010 and sent to the U of S for isotope analysis. In addition, a soil core (7 to 8 cm long) for physical analysis at U of S and later chemical analysis at ARD was removed above every other foot mark depth starting at 2 ft (0.61 m) below the ground surface. Samples were collected to a depth of about 20 m.

As with the core collected from D-P10-1 in 2010, the core from LB8a-5 was analyzed for physical properties by the U of S and sent to ARD for chemical analysis where it was discovered the cores had been stored wet for a minimum of 6 mo at room temperature. As a result, there was concern about the accuracy of the chemical analysis, particularly for NO_3^--N. Therefore, a new soil core was collected by re-drilling a borehole within 1 m of the original well in November 2011. During the re-drilling, a soil core (15 cm long) was collected above every foot mark depth starting at 1 ft (0.30 m), and a second soil core (7 to 8 cm long) was collected below every foot mark depth starting at 1 ft (0.30 m) (Table 4.2, Figure 4.8). Samples were collected to a depth of about 10 m. The samples were immediately air dried and ground to pass through a 2-mm sieve and were analyzed for chemical parameters by ARD. Further details regarding soil chemical analysis can be found in Appendix 5. Samples were analyzed for isotope analysis at the U of S. The re-drilled boreholes were back-filled to at least 3 mbgs with bentonite and filled to the surface with a natural pack.

At CFO-2, seven boreholes were sampled by collecting 30- to 50-cm long core segments from the bottom of every 1.5-m incremental layer (Table 4.2, Figure 4.8). Drilling was completed using a solid stem auger for LB8a-1 and -4 and a hollow stem auger for LB8a-7, -9, -11, -12, and -13. Chemical analyses were carried out by ARD and were the same as for the borehole samples from CFO-1 (Appendix 5).

Table 4.2. Boreholes soil sampled at CFO-2 in 2010 and 2011.				
Well name	Well type	Depth (m)	Sampling date	Description
LB8a-1	Water table	3.0	Feb 2010	Every 1.5 m[z]
LB8a-2	Water table	7.1	Feb 2010	ns[y]
LB8a-3	Water table	7.0	Feb 2010	ns[y]
LB8a-4	Water table	7.0	Feb 2010	Every 1.5 m[z]
LB8a-5	Piezometer	20.0	Dec 2010 and Nov 2011[x]	Every foot plus isotopes[w]
LB8a-6	Water table	4.8	Mar 2011	ns[y]
LB8a-7	Piezometer	9.8	Mar 2011	Every 1.5 m[z]
LB8a-8	Water table	6.5	Mar 2011	ns[y]
LB8a-9	Water Table	9.5	Mar 2011	Every 1.5 m[z]
LB8a-10	Piezometer	4.1	Mar 2011	Every 1.5 m[z]
LB8a-12	Piezometer	5.6	Mar 2011	Every 1.5 m[z]
LB8a-13	Piezometer	5.7	Mar 2011	Every 1.5 m[z]

[z] The bottom 30 to 50 cm sampled from every incremental 1.5-m layer.

[y] ns = not sampled.

[x] The second date is for the re-drill borehole near the original well.

[w] Within the each incremental foot layer, the top 7 to 8 cm (15 cm for the re-drill) was sampled for physical and chemical analysis and the bottom 7 to 8 cm was sampled for isotope analysis.

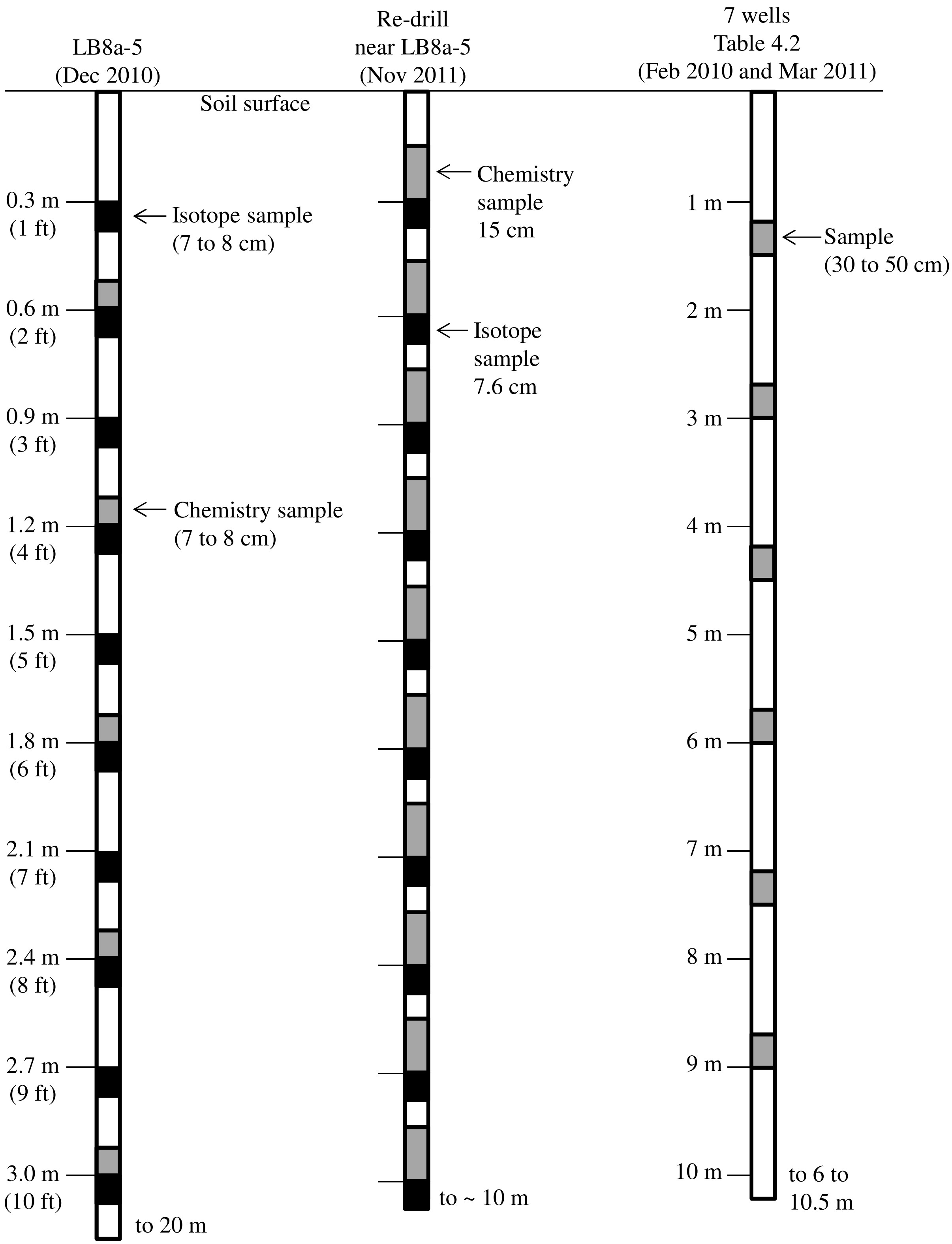


Figure 4.8. Soil sampling profiles for various boreholes at CFO-2 in 2010 and 2011 for isotope, physical, and chemical analyses.

CFO-4

Core segments 30- to 50-cm long were collected from four boreholes (B-MW2a, B-MW4a, B-P10-20w, and B-P10-21e) using a hollow stem auger in February and March 2010. The core segments were collected from the bottom of every 1.5-m incremental layer. Total well depths ranged from 7.5 to 20.5 mbgs. Chemical analyses were carried out by ARD and were the same as for the deep borehole samples at CFO-1 and -2 (Appendix 5).

4.2.5 Well Elevation Surveying

Groundwater wells at CFO-1 and CFO-2 were surveyed for geodetic elevations in October 2010 and November 2011 by Brown Okamura and Associates Ltd. of Lethbridge, Alberta. The survey was conducted using a survey grade global positioning system (GPS) unit. Vertical elevations were determined relative to mean sea level.

Groundwater wells installed at CFO-3, -4, and -5 in 2008 were surveyed for geodetic elevations in November 2008 by WorleyParsons. The survey was conducted using a survey grade GPS. Vertical elevations were established relative to mean sea level. Wells installed at CFO-4 in 2010 were not surveyed.

4.2.6 Well Development

Well development was initiated at all sites shortly after wells were installed in 2008, 2010, and 2011 and prior to collection of the first water samples. Well development consisted of removing water from the wells using a polyethylene bailer (1 L), Waterra pump, or purge pump. A minimum of two well volumes were removed from each well in order to remove fine particles from around the well screen, improve the rate of water moving into the well, and stabilize the aquifer to produce samples representative of the aquifer. Well development was carried out for a longer period for some wells in the sandier portions of the study area at CFO-1 until water turbidity was visibly reduced.

4.2.7 Groundwater Monitoring

Groundwater Elevation

Groundwater elevations were determined using manual measurements, pressure transducer measurements, and well survey measurements. The depth to groundwater was measured by lowering a sounding tape into each water table well and piezometer and recording the depth to water from a mark placed on the inside of the well casing. If a pressure transducer was present in a well, the water level was measured with the pressure transducer in the well. The depth to groundwater was measured in all groundwater wells during each groundwater purging and sampling event. Additional measurements were taken on a monthly basis starting in November 2011when water sampling was changed to a quarterly basis. Measurements were recorded on field sheets for subsequent entry into an electronic database.

Pressure transducers (Levelogger Gold, Model 3001, Solinst Canada Ltd.) were used to record changes in absolute pressure (i.e., water column pressure plus barometric pressure) in 4-h intervals in order to determine water height. At the central Alberta sites, pressure transducers were installed in February 2009 in A-C3, A-MW2, and A-P08-16 at CFO-3, in B-MW2, B-MW3, and B-C-4 at CFO-4, and in C-C-2, C-MW1, and C-P08-14 at CFO-5. In the Battersea area, pressure transducers were installed in 2010 in D-MW3 and D-P10-2 at CFO-1 and in LB8a-1 and LB8a-6 at CFO-2. Two pressure transducers in the Battersea area (LB4-2x for CFO-2 and LB21-2 for CFO-1) and two at the central CFOs (A-C3 for CFO-3 and C-MW1 for CFO-4 and -5) were installed above the water level and used to measure ambient barometric pressure, which was used to barometrically correct the water levels (Barologger Gold, Model 3001, Solinst Canada Ltd). The pressure transducer data were reviewed based on the manual measurements, and the data and height of the pressure transducers were adjusted as required to match the manual measurements.

Contour plots were prepared using Surfer 9 fort CFO-1, 2, and -5 (Version 9.2.397 © 1993-2009. Golden Software, Inc., Golden, Colorado, United States). Contours were prepared with grids generated using the Kriging method of interpolation. Contour plots for CFO-3 were prepared using ArcGIS 10.0 (ArcGIS Desktop Release 10.0 © 1999-2010. ESRI Inc., Redlands, California, United States), with grids generated using the Spline method of interpolation.

A pressure transducer was installed at each EMS to measure the liquid manure levels. The levels were recorded every 4 h starting in June 2010 at CFO-3, -4, and -5 and in December 2011 at CFO-1. The pressure transducers were lost in the EMSs at CFO-1 and -3 between fall 2010 and winter 2011 and no data were collected.

Groundwater Purging

Prior to groundwater sampling, wells were purged using a dedicated polyethylene bailer (1 L) or whale pump at CFO-3, -4, and -5 and a dedicated polyethylene bailer (1 L) or Waterra pump at CFO-1 and -2. Wells were purged until three well volumes of water had been removed or until the water table well was dry or the groundwater level was at the top of the well screen in the piezometers. Purge water was disposed adjacent to the wells. All equipment was thoroughly rinsed with deionized water and dried with a paper towel between wells.

If a pressure transducer was present in a well, it was removed after the depth to water was measured but prior to well purging. The total well depth was measured after the pressure transducer, if present, was removed. Total well depth was measured to examine whether the effective screen interval had changed as a result of silting in the well.

Groundwater Sampling and Analysis

Groundwater samples were collected three to eight times from groundwater wells at the CFOs in 2010, depending on accessibility to the wells and when the wells were installed and developed (Appendix 6). Wells were sampled four times in 2011. Groundwater sampling was changed to quarterly sampling in 2011 as it was determined an adequate baseline had been established and seasonal trends could still be observed.

Groundwater samples were collected 7 to 14 d after purging at CFO-1 and -2, depending on the recovery rate of the water in the well, and the day after purging at CFO-3, -4, and -5. Sample bottles were triple rinsed with sample water before filling. One, 1-L high density polyethylene bottle was filled with as little headspace as possible from all sites for chemical analysis, and one, 1-L high density polyethylene bottle was filled from CFO-1 and -2 for isotopic analysis. One, 250-mL glass bottle was filled with as little headspace as possible for total organic carbon analysis in August (CFO-1 and-2) or October (CFO-3, -4, ad -5) 2011. After collection, samples were placed in coolers with ice packs or frozen 1-L water bottles. Samples were submitted to the ARD laboratory in Lethbridge on the same day as sampling at CFO-1 and -2 and the day after sampling at CFO-3, -4, and -5.

In-field measurements of pH, electrical conductivity (EC), dissolved oxygen (DO), and temperature were measured in a spare sample bottle using the first bail from the wells (WTW multi 3400i and 3500i with Oxical-cx (DO and EC) and SenTix 41 (pH) probes, Global Water Instrumentation, Inc.). Field measurements were also measured using a peristaltic pump and flow through cell at some of the water table wells at CFO-3, -4, and -5. Field alkalinity was determined once for all wells in August (CFO-1 and -2) or October (CFO-3, -4, and -5) 2011 (Alkalinity Test Kit, Model AL-DT, HACH Company).

Groundwater samples were analyzed in the laboratory for nutrients, anions, and cations (Appendix 7). Nutrients included TN, NO_3^--N, NO_2^--N, ammonia nitrogen (NH_3-N), TP, total dissolved phosphorus (TDP), and PO_4^{3-}-P; cations included Ca^{2+}, Mg^{2+}, Na^+, and K^+; and anions included SO_4^{2-}, Cl^-, HCO_3^-, and CO_3^{2-}. Other parameters analyzed included dissolved total carbon (D-TC), dissolved non-purgeable organic carbon (D-NPOC), and dissolved inorganic carbon (D-IC). Chemical analyses were completed by the laboratory within 24 h of sample collection for nutrients and anions, with TN analyzed as soon as the samples were received, and TDP and TP analyzed within 7 d. Samples for cation analysis were filtered, preserved with nitric acid (HNO_3), and analyzed within 7 d. Dissolved total carbon and D-NPOC analyses were completed within 2 wk of sample collection.

Groundwater samples were analyzed at the U of S Isotope Laboratory (SIL) for deuterium (^2H) and oxygen-18 (^{18}O). Isotopic data are not presented in this report.

All groundwater data were validated to ensure fractions of N and P did not exceed the totals (TN and TP) and that individual samples met the principle of electrical neutrality. Duplicate groundwater samples were collected at a rate of 10% of samples collected per day and submitted for analysis as part of the quality control/quality assurance protocol. Trip blanks consisting of deionized water were also submitted to the laboratory but were not submitted for every sampling event. Relative percent difference was examined for duplicate samples. Quality control data are not presented in this report.

4.2.8 Geophysical Investigations

A geophysical investigation was carried out at the CFO-3 where EC readings were recorded using a direct-push EC probe and Geoprobe track rig (Geoprobe© 7730DT). This investigation was conducted by the University of Alberta and Natural Resources Conservation Board staff on August 5, 6, and 18, 2010. A total of 25 locations were sampled near the perimeter of the EMS by logging continuous EC readings from ground surface to refusal. Refusal was assumed to be a result of the relatively shallow bedrock and ranged from approximately 5 to 10 mbgs.

A geophysical investigation was carried out at CFO-4 by WorleyParsons on October 26 and 27, 2011. The investigation included the use of electromagnetic terrain conductivity (EM31, EM38), electrical resistivity tomography (ERT), and geophysical borehole logging (induction conductivity and natural gamma). The EM31 and EM38 measurements were taken about 1 m apart along survey lines spaced about 5 m apart. One, 100-m long ERT line was used along the east end of the EMS. Borehole induction conductivity and natural gamma logs were measured in five wells (B-C4, B-MW1, B-MW2a, B-MW3, and B-MW4a) at the site. Further details are in WorleyParsons (2012).

On October 24 and 25, 2011, additional geophysics work was performed at CFO-1and included the use of EM31, EM38, and ERT units as described above for the CFO-4. However, at CFO-1, two ERT lines were used, roughly perpendicular to each other: one 80 m long and the other 120 m long. Borehole induction conductivity and natural gamma logs were measured in five wells (D-MW1, D-MW3, D-P11-10c, D-P11-13c, and D-P11-14c) at the site. Further details are in WorleyParsons (2012).

No geophysical investigations were performed at CFO-2, CFO-3, or CFO-5 in 2010 or 2011.

4.2.9 Manure Sampling and Analysis

Liquid manure samples were collected in September 2010 at CFO-3. Liquid manure from the EMS was collected in three, 1-L bottles. The samples were collected after the EMS had been agitated, and bottles were filled from the spigot emptying the EMS into a truck. Samples were stored in a freezer for future analysis.

Liquid manure samples were collected from the EMS at each of the dairy sites (CFO-1, -3, -4, and -5) in 2011. An extended sampling pole to obtain a vertical profile sample was constructed, and samples were collected from each side of the EMS where possible. Samples were thoroughly mixed in a bucket, and two, 1-L bottles were filled with a composite sample. The remaining manure sample was discarded back into the EMS, and the procedure was repeated a total of three times. Samples were placed in plastic bags and stored in a freezer for future analysis (Appendix 10) by ALS Group environmental laboratory in Saskatoon, Saskatchewan.

4.2.10 Statistical Analysis

Descriptive statistics were carried out using SYSTAT 13 (Version 13.00.05, SYSTAT Systems, Inc. 2009, Chicago, Illinois, United States). The minimum measurable detection limit (MMDL) was used when reporting concentration ranges (i.e., minimum concentrations detected), but a value of half the MMDL was used in mean and median calculations. Minimum method detection limits for each parameter are listed in Appendix 7.

4.3 Results and Discussion

Results from groundwater and soil analyses completed by ARD are presented in the following sections; however, results from groundwater and soil isotopic analyses completed by the University of Saskatchewan are not presented in this progress report.

4.3.1 Weather

Total annual precipitation received in 2009, 2010, and 2011 in the Battersea area (CFO-1 and -2) was 384, 451, and 391 mm, respectively. Total annual precipitation was above the 30-yr average of 365 mm for all three years. Further details about weather in the Battersea area are in Subsection 2.3.1.

Total annual precipitation received in 2009, 2010, and 2011 near Crestomere, the closest station to CFO-3, was 291, 483, and 531 mm, respectively (Figure 4.9). The highest monthly precipitation occurred in July for all three years, followed by June in 2010 and 2011 and May in 2009.

Total annual precipitation received in 2009, 2010, and 2011 near Lacombe, the closest station to CFO-4 and -5, was 295, 531, and 496 mm, respectively (Figure 4.10). Similar to Crestomere, The highest monthly precipitation occurred in July for all three years, followed by June in 2010 and 2011 and May in 2009.

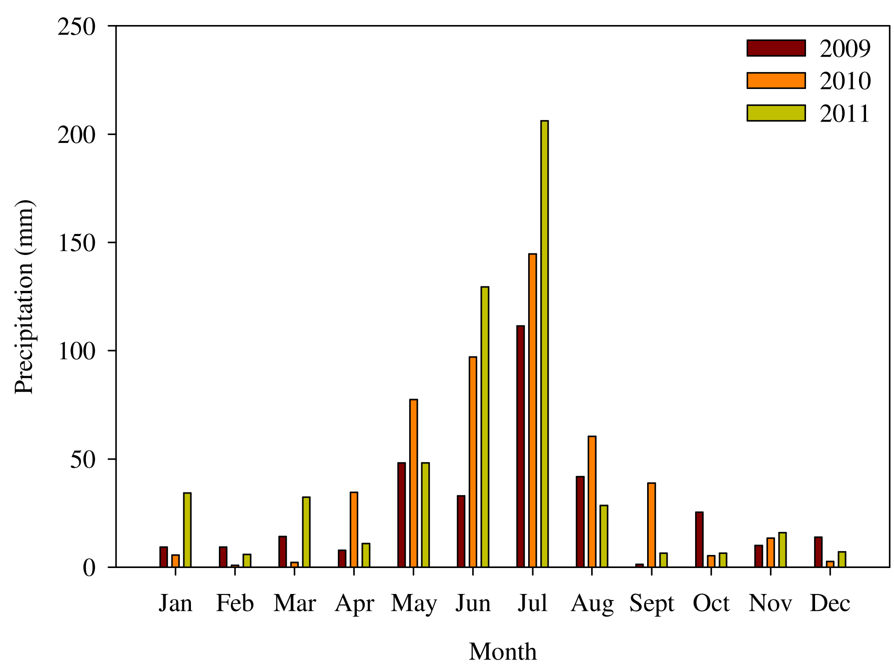


Figure 4.9. Monthly precipitation comparisons for CFO-3 near Crestomere from 2009 to 2011.

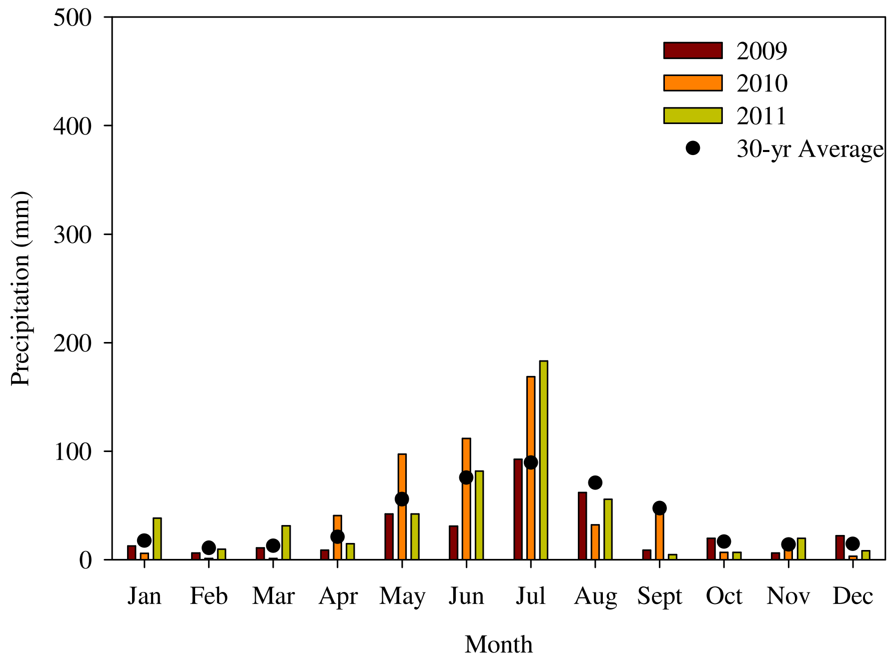


Figure 4.10. Monthly precipitation comparisons for CFO-4 and -5 near Lacombe from 2009 to 2011.

4.3.2 Stratigraphy

CFO-1

Stratigraphy encountered in 2010 and 2011 at CFO-1 was generally permeable material from the surface to 10 mbgs. In boreholes near the EMS, clay was described as being present below 20 m, to the maximum depth of investigation at 34 mbgs (Figure 4.11). In boreholes throughout the remainder of the site, silty and sandy clay were typically encountered deeper than 8.5 mbgs to the maximum depths of investigation at 34 mbgs. The depth to bedrock was not determined, as bedrock was not encountered within the maximum depth of investigation (34 mbgs). Details of the stratigraphy recorded during drilling at CFO-1 are included on the borehole logs in Appendix 3.

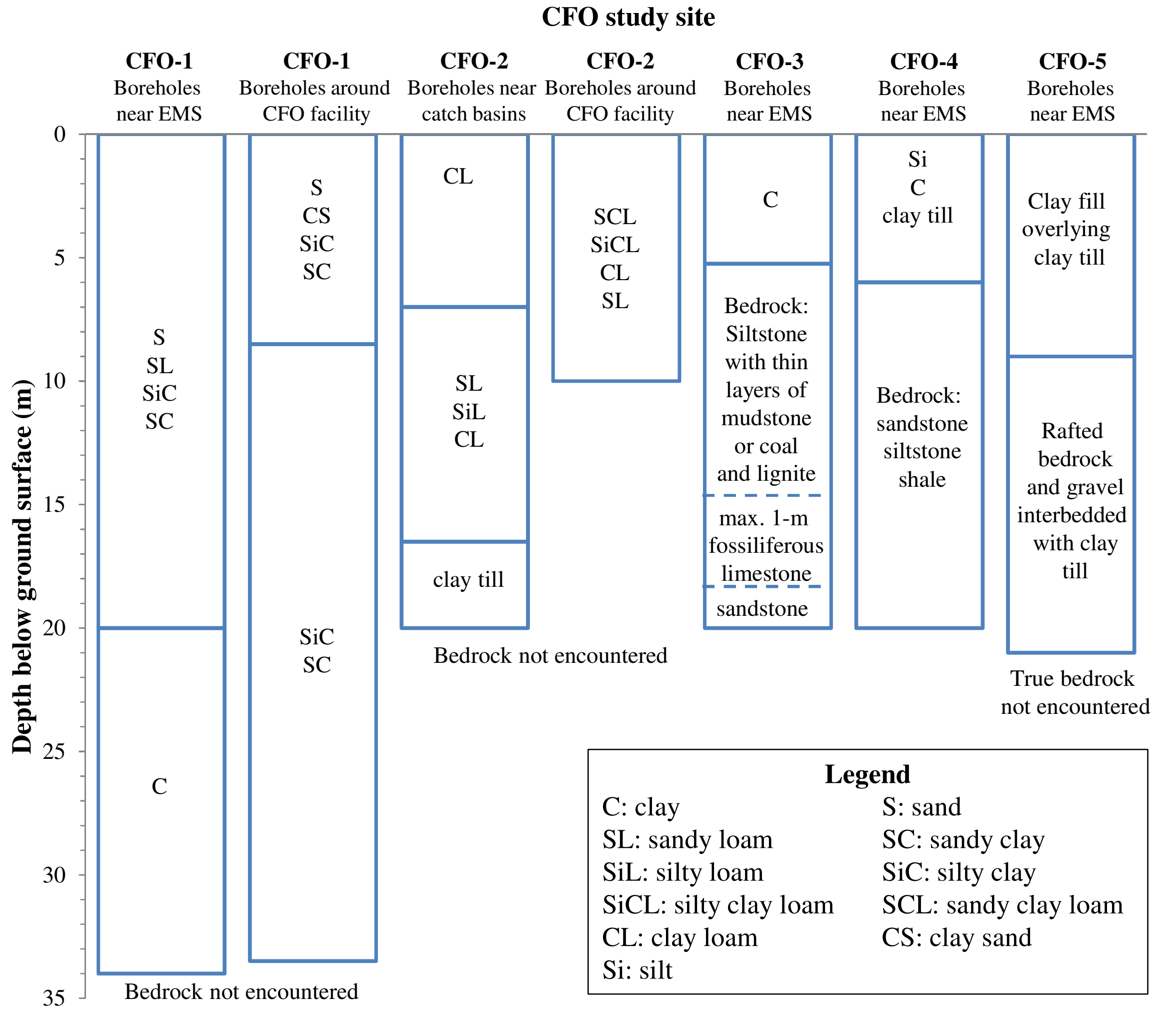


Figure 4.11. Generalized stratigraphy for each confined feeding operation (CFO) study site. The actual stratigraphy of individual boreholes is shown in Appendix 3.

CFO-2

Surficial deposits encountered at locations surrounding the catch basins and around the CFO-2 consisted of clay loam, sandy clay loam, silty clay loam, and clay (Figure 4.11). In the deepest borehole (LB8a-5), sandy loam, silty loam and clay loam were found from 7 to 16.5 mbgs, followed by clay till from 16.5 to 20 mbgs. Wells along the eastern edge of the study site (LB8a-10 and LB8a-12) were similar to other wells around the site in the upper 1 to 2 mbgs, though sand was encountered from 1.5 to 4.5 mbgs at LB8a-10 (Appendix 3). Bedrock was not encountered at the site during drilling in 2010 and 2011.

CFO-3

Surficial deposits at boreholes surrounding the EMS at CFO-3 consisted of silty clay to a depth of 5.25 mbgs (Figure 4.11). Bedrock was predominantly siltstone from 5.3 to 20.7 mbgs, interbedded with a thin layer of mudstone (from 16.5 to 18.0 mbgs), and sandstone was encountered from 20.7 to 21.0 mbgs (maximum depth of the investigation). Thin coal and lignite layers were observed throughout the bedrock deposits and up to approximately 1 m thick fossiliferous limestone layers were found at approximately 14.3 and 19.9 mbgs. The bedrock was often fractured. The optical borehole imager indicated frequent sub-horizontal fracturing in the upper approximately 15 mbgs, below which fracturing appeared less common (WorleyParsons 2009). Active groundwater flow was expected in the bedrock fractures. Surficial deposits at boreholes in the adjacent field consisted of silt, clay, and clayey till to depths ranging from 1.8 to 3.6 mbgs. Bedrock consisted of interbedded siltstone and shale to the maximum depth investigated (7 mbgs). Oxidized lenses, seams, and layers were also noted.

CFO-4

Surficial deposits at CFO-4 consisted of silt, clay, and clay till to depths of approximately 4.5 to 6 mbgs (Figure 4.11; Worley Parsons 2009). Bedrock consisted of sandstone, siltstone, and shale from approximately 4.5 to 6 mbgs to the maximum depth investigated (20 mbgs; Appendix 3).

CFO-5

Surfical deposits at borehole locations surrounding the EMS at CFO-5 consisted of clay fill overlying clay till to a depth of 9 mbgs (Figure 4.11; Worley Parsons 2009). Thin gravel and sand lenses were described at ground surface and at 3 mbgs. Oxidized sand lenses and seams were noted within the clay and clay till surficial deposits at boreholes in the adjacent field. Below 9 m near the EMS, rafted bedrock and possibly gravel were interbedded with clay till. The depth to the top of true bedrock was not determined by this investigation; however, it appears to be deeper than 21 mbgs.

4.3.3 Soil Chemistry

Chloride and NO_3^--N concentrations in soil saturated-paste extracts differed among boreholes collected at CFO-1. Soil NO_3^--N concentrations in D-P11-14c and -15c were low with no pattern observed from the soil surface down to 35 mbgs (<0.5 mg L^{-1}). Chloride concentrations from the two boreholes were slightly elevated at the surface (82 and 25 mg L^{-1}, respectively) but decreased quickly with depth and ranged from 3 to 35 mbgs. In contrast, elevated Cl^- and NO_3^--N concentrations were observed between 8 and 9 mbgs in D-P11-13c (Figure 4.12). Chloride and NO_3^--N concentrations reached up to 199 and 78 mg L^{-1}, respectively, and remained low deeper than 15 mbgs. Similar patterns in Cl^- and NO_3^--N concentrations were observed in D-P11-10c and D-P11-11b (not shown).

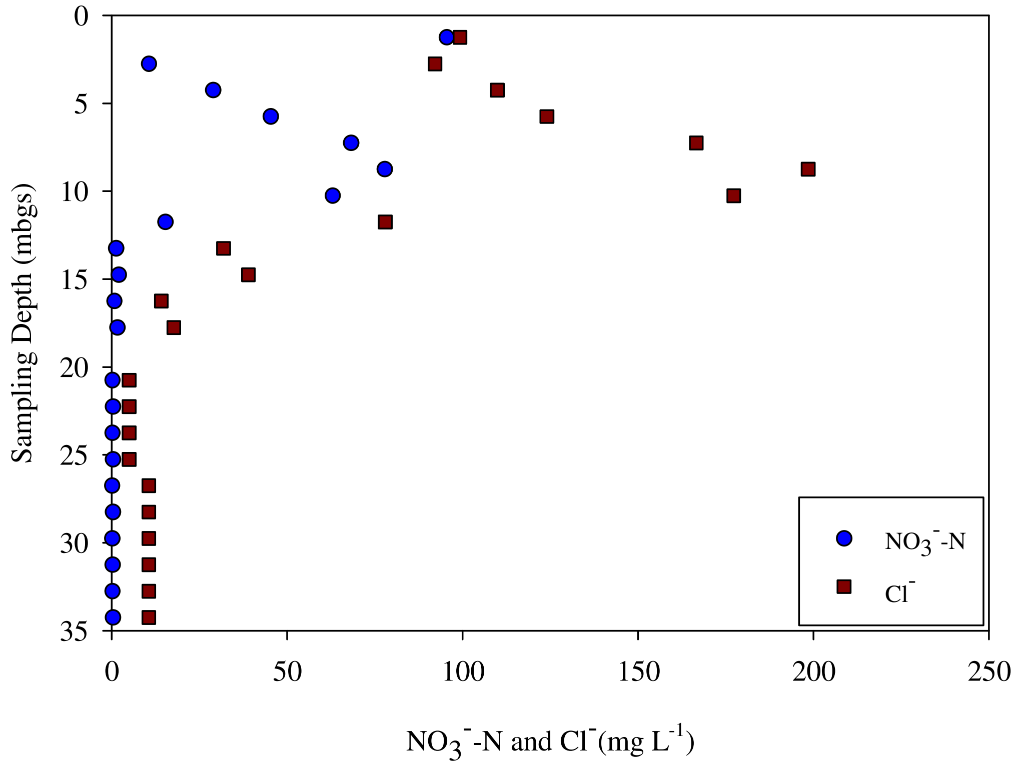


Figure 4.12. Chloride (Cl^-) and nitrate nitrogen (NO_3^--N) concentrations in soil saturated-paste extracts at D-P11-13c in February 2011.

Chloride and NO_3^--N concentrations in soil saturated-paste extracts differed among boreholes drilled at CFO-2. Similar to some of the piezometers at CFO-1, elevated Cl^- and NO_3^--N concentrations were observed between 1 and 6 mbgs for most of the boreholes. However, Cl^- and NO_3^--N concentrations were initially elevated at the surface and decreased with increasing depth to the end of the borehole (~10 mbgs) at LB8a-9 (Figure 4.13a). No increases in concentrations were observed at depth. In contrast, Cl^- and NO_3^--N concentrations increased with depth at LB8a-13 to the end of the borehole (~ 6 mbgs) (Figure 4.13b). Chloride and NO_3^--N concentrations reached 141 and 84 mg L^{-1}, respectively. It is uncertain if the increase in concentrations at LB8a-13 would have continued or if further drilling would have revealed a similar pattern to concentrations observed in some of the other boreholes.

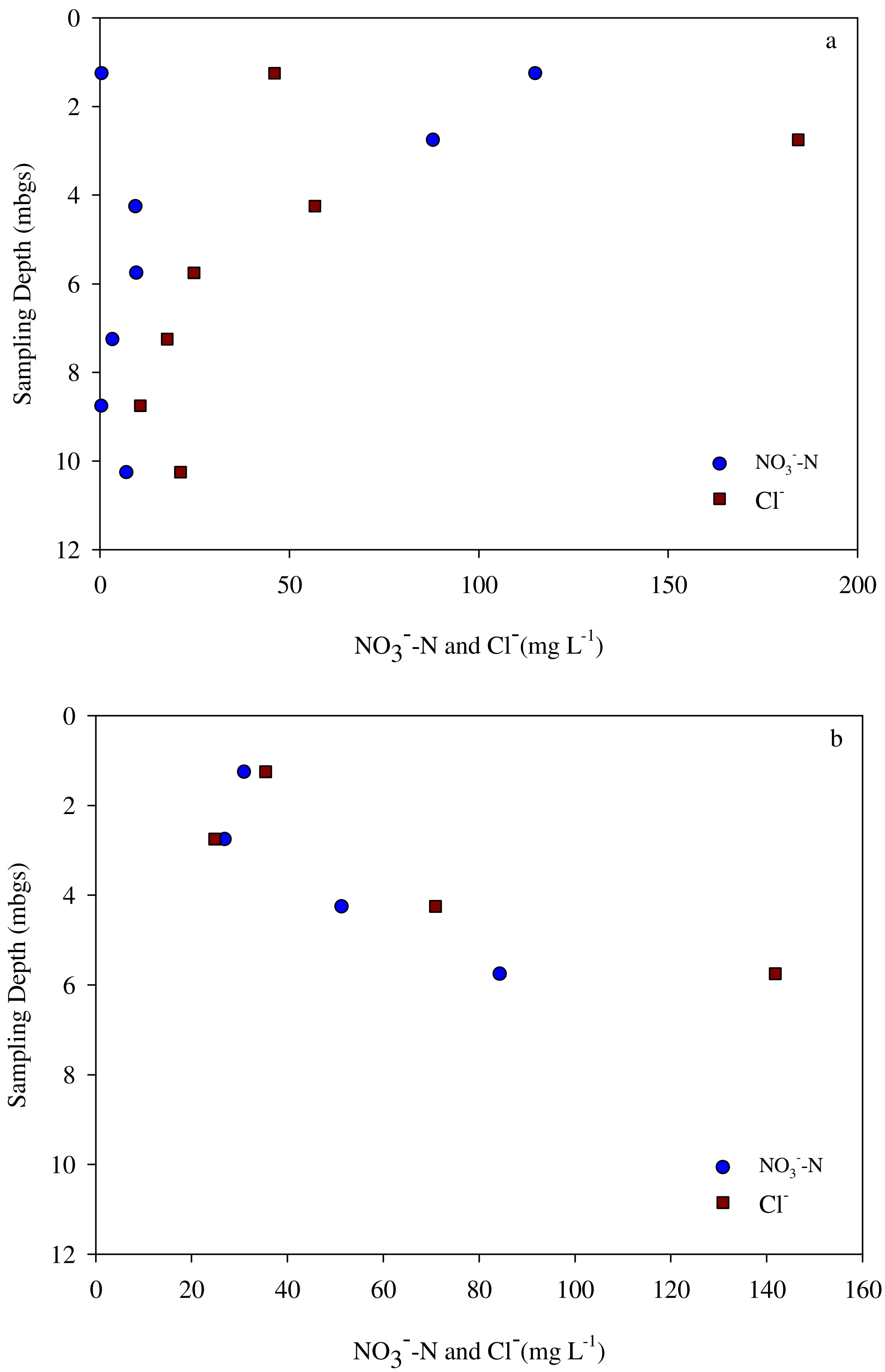


Figure 4.13. Chloride (Cl^-) and nitrate nitrogen (NO_3^--N) concentrations in soil saturated-paste extracts at (a) LB8a-9 and (b) LB8a-13 in March 2011.

4.3.4 Groundwater Elevation Monitoring

CFO-1

Groundwater flow direction was generally to the east and southeast at CFO-1 (Figure 4.14), was generally consistent among monthly measurements.

For water table wells assumed to be screened in the shallowest groundwater bearing zone, the order from highest groundwater elevation to lowest was generally D-MW10a, D-MW1, D-MW2, D-MW3, D-MW12a, D-MW13a, D-MW14a, D-MW15a, D-MW4, D-MW5, D-MW6, D-MW16a, and D-MW11a. Groundwater levels at D-MW1 increased from May to July, decreased through to February 2011, increased again to July 2011, and then decreased through the fall (Appendix 8). Groundwater levels at D-MW2 and D-MW3 decreased slightly from May 12 to 25, increased to September 2010, decreased to February 2011, and then increased through the remainder of 2011 (with a slight decrease between July and August). Groundwater levels at D-MW4 and D-MW5 remained relatively unchanged throughout the monitoring period in 2010 and 2011, with the exception of a slight decrease in both water table wells in October 2011 (Appendix 8). Groundwater levels at D-MW6 remained relatively constant from May to July in 2010, decreased through 2010, increased slightly in February 2011, and then decreased and remained relatively constant through the remainder of 2011. Groundwater levels at D-MW10a, -11a, and -16a remained relatively constant from July to October 2011, though a slight overall decrease was observed. Groundwater levels at D-MW12a, -13a, -14a, and -15a also remained relatively constant throughout 2011, though a slight overall increase was observed.

For piezometer D-P10-2, installed near the EMS and completed at approximately 8 mbgs, the groundwater elevation notably increased from July to September 2010, decreased through to February 2011, and generally increased through the remainder of 2011, with the exception of July 26 to August 9 (Appendix 8). This pattern is relatively similar to that of D-MW3, the nearest well to D-P10-2.

For the intermediate piezometers, those completed at approximately 20 mbgs, the order from highest to lowest groundwater elevation was generally D-P11-10b, D-P11-12b, D-P11-13b, D-P11-14b, D-P11-15b, D-P10-1, D-P11-16b, and D-P11-11b. The levels in D-P10-1 increased by 2.31 m from July to August 2010 and then decreased by 1.62 m from August to September 2010 (Appendix 8). The change in groundwater levels is interesting since groundwater elevations in a piezometer at this depth (18.5 mbgs) are generally expected to change minimally during a short period. Similarly, relatively large variations were observed in D-P10-1 during 2011. The other intermediate piezometers displayed similar patterns in 2011, remaining relatively constant from July 26 to October 3, 2011, though a slight overall decrease was observed in D-P11-10b, -11b, -15b, and -16b and a slight overall increase was observed in D-P11-12b, -13b, and -14b before decreasing on October 18, 2011. This may be an artifact of purging activities on October 3, where full recovery of the wells had not occurred by October 18 when sampling occurred, though this was not observed between purging on July 26 and sampling on August 9.

For the deepest piezometers, those completed approximately 34 mbgs, the order from highest to lowest groundwater elevation was generally D-P11-10c and D-P11-14c (they were similar), D-P-11-13c, and D-P11-15c. The exception was on October 18 when D-P11-13c was relatively much higher than any of the other piezometers, and the groundwater elevation at D-P11-14c was greater than at D-P11-10c (Appendix 8).

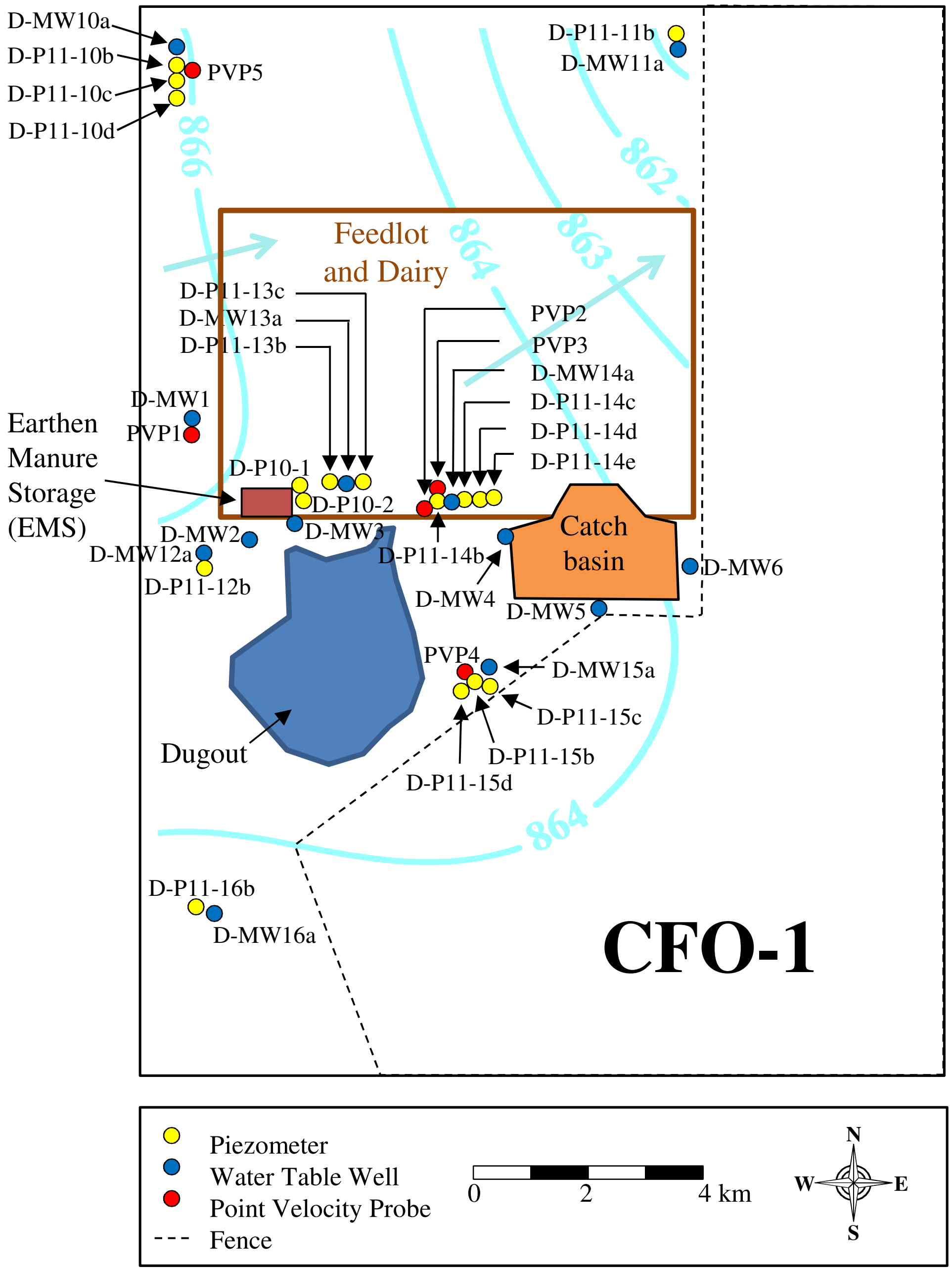


Figure 4.14. Shallow groundwater elevation at CFO-1 in October 2011 (1-m contour interval; numbers represent metres above sea level; arrows indicate inferred groundwater flow direction).

CFO-2

Groundwater flow direction at CFO-2 was primarily to the northwest through the majority of the area where the facility exists (Figure 4.15). The primary groundwater flow direction to the northwest was toward the Battersea Drain and was consistent with local topography.

Groundwater elevation was typically highest in the spring in the water table wells with the highest elevation measured from April to June 2010 and in May and June 2011 (Appendix 8). Groundwater elevation decreased during the summer and fall. Groundwater elevation in water table well LB8a-4, near the eastern catch basin, was highest in spring 2010 but did not show the same patterns in 2011 (Appendix 8).

The northwest corner of CFO-2 may be an area of groundwater discharge, depending on the time of year, as indicated by the higher groundwater elevations measured in LB8-7 compared to LB8a-6 in March 2011 (Appendix 8). Note that groundwater elevations were similar in the two wells in October 2011. Groundwater elevation may be impacted by the Battersea Drain, which is approximately 0.8 km to the northwest.

The water table showed a general increase from 2010 to 2011, and groundwater elevation recorded through pressure transducers at LB8a-1 and LB8a-6 captured the water table response to precipitation events in 2011 (Figure 4.16).

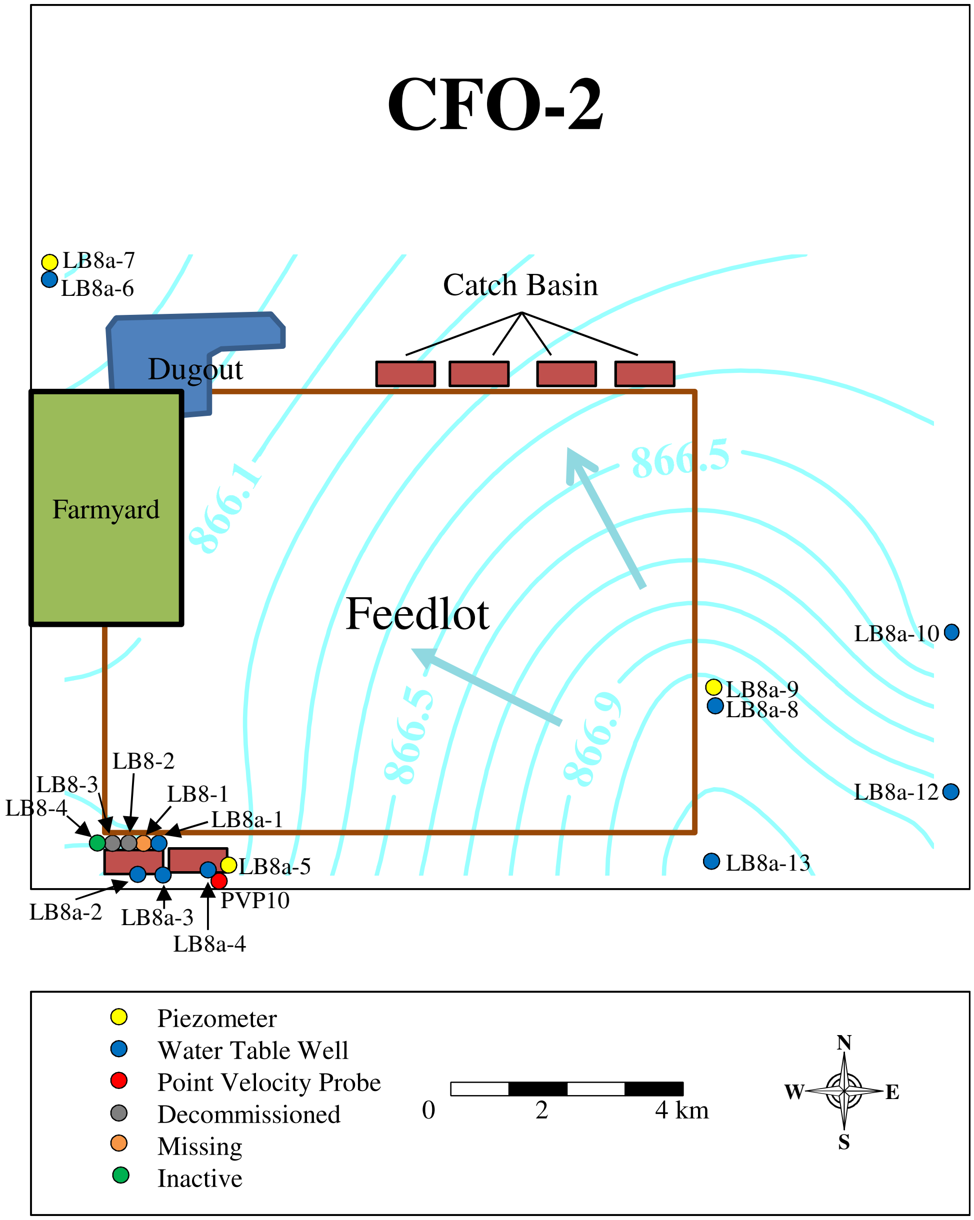


Figure 4.15. Shallow groundwater elevation at CFO-2 in October 2011 (0.1-m contour interval; numbers represent metres above sea level; arrow indicates inferred groundwater flow direction).

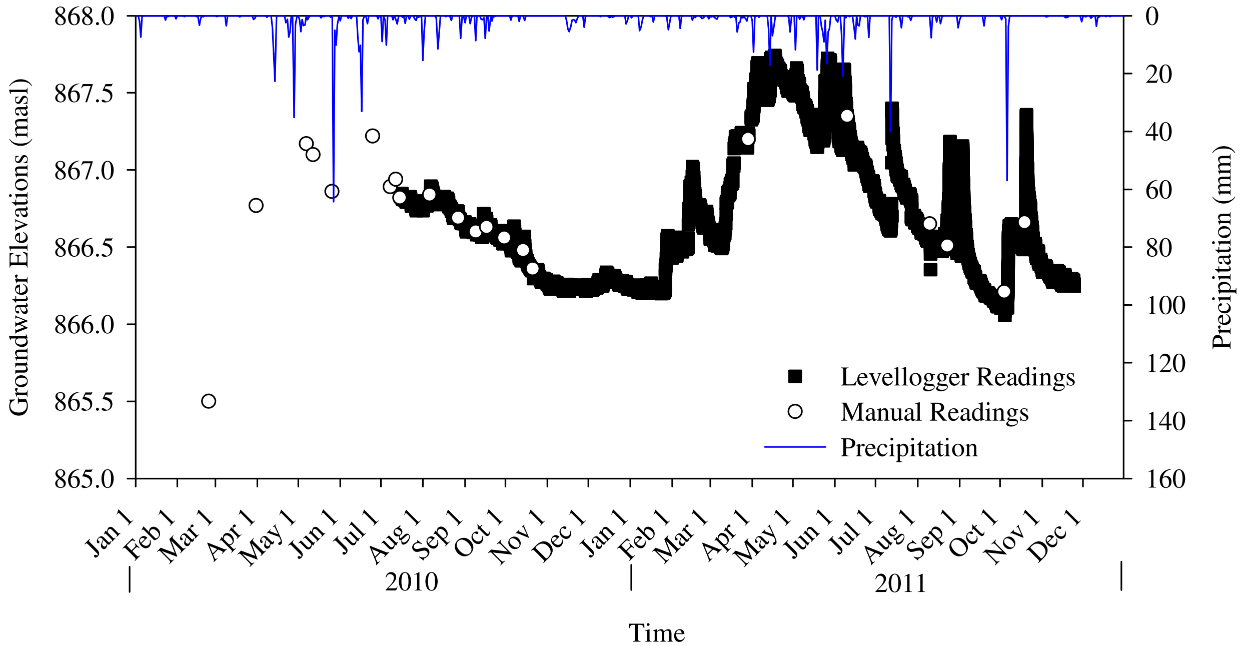


Figure 4.16. Groundwater elevation and precipitation at water table well LB8a-1.

CFO-3

Groundwater flow direction at CFO-3 was to the east-northeast (Figure 4.17), and this was consistent with local topography and previous investigations in 2008 by WorleyParsons (2009). Groundwater elevation was typically highest in the summer months of each year, with the water table showing a general increase from 2009 to 2011 (Appendix 8). This pattern was most noticeable in A-C3, the most upgradient water table well at the site. Groundwater elevations in the deeper piezometers were also greatest during the summer months and generally increased from 2009 to 2011.

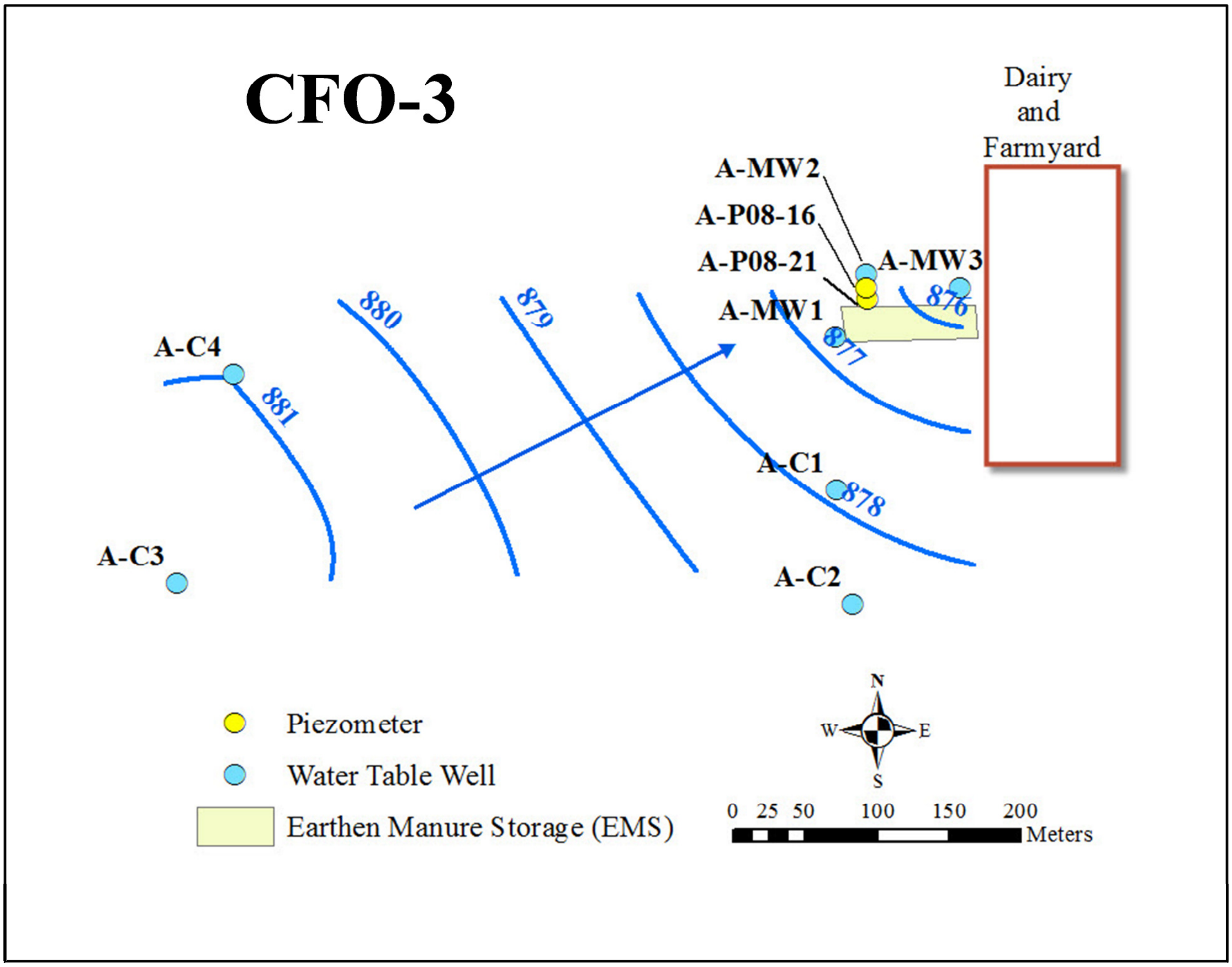


Figure 4.17. Shallow groundwater elevation at CFO-3 in October 2011 (1-m contour interval; numbers represent metres above sea level; arrow indicates inferred groundwater flow direction).

CFO-4

Groundwater flow direction at CFO-4 was predominantly to the northeast, and this was consistent with the local topography and previous investigations (WorleyParsons 2009). However, the flow direction was less certain immediately around the EMS, and the direction may change throughout the year. Survey data still needs to be obtained for all wells at the site, and these data will aid in flow direction interpretation. Groundwater elevations in the water table wells at CFO-4 were relatively constant in 2009, increased from June to November 2010, decreased in winter 2010, peaked during the summer in 2011, and decreased again through the end of 2011 (Appendix 8). The overall water table level at CFO-4 generally increased from 2009 to 2011.

CFO-5

A predominant groundwater flow direction at CFO-5 could not definitively be determined. Flow direction altered between east and west, depending on time of year, though it may be predominantly to the west (Figure 4.18). The area appears to potentially be a groundwater discharge zone at times during the year, as groundwater elevations in deeper piezometers (C-P08-14 and C-P08-21) were similar or greater than groundwater elevations in the shallower water table wells during 2009 and parts of 2010 and 2011 (Figure 4.19). Overall, the water table displayed a slight increase in elevation, while the deeper groundwater elevations remained relatively similar from 2009 to 2011 (Appendix 8).

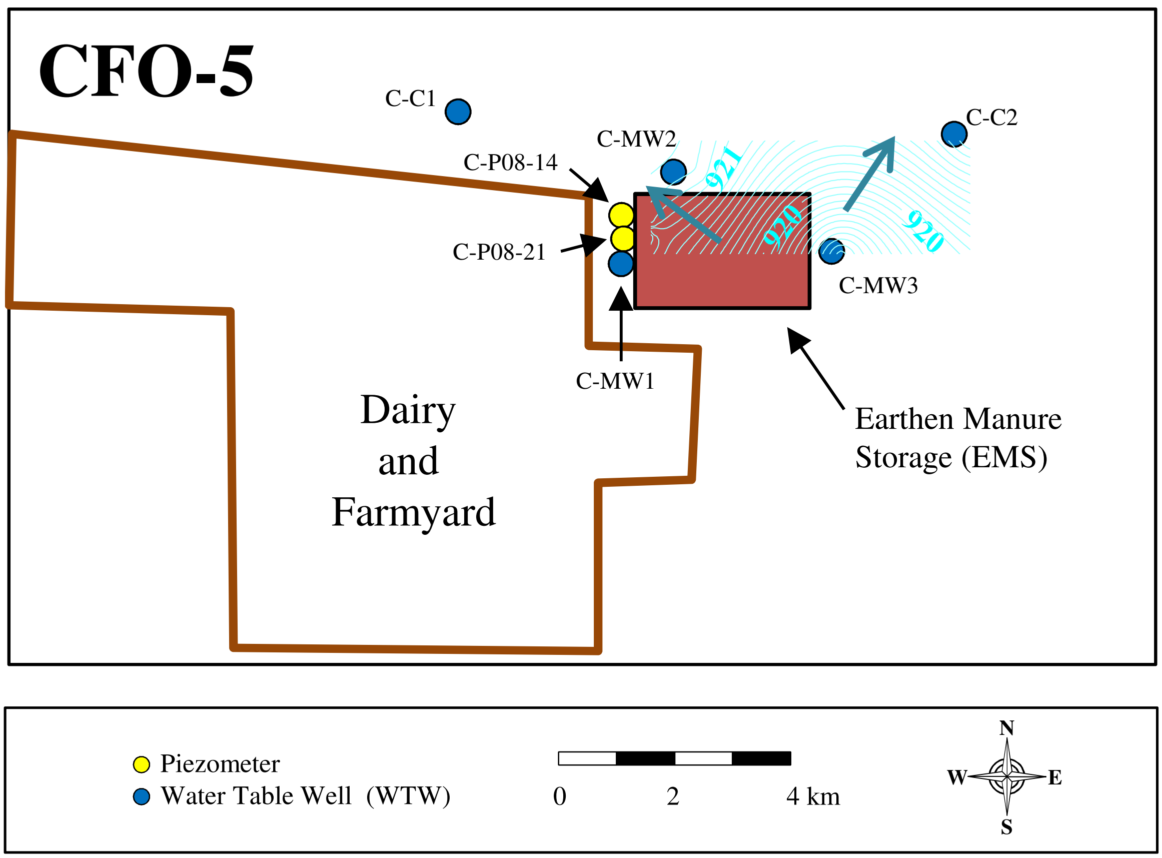


Figure 4.18. Shallow groundwater elevation at CFO-5 in October 2011 (0. 5-m contour interval; numbers represent metres above sea level; arrows indicate inferred groundwater flow direction).

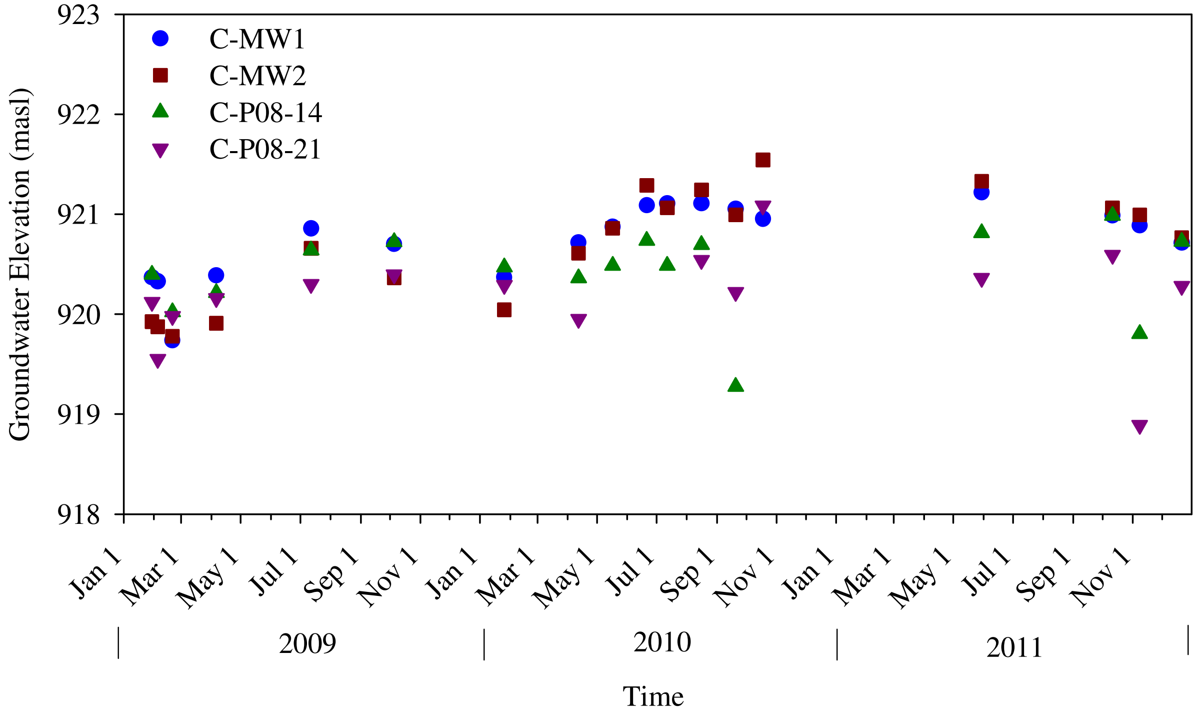


Figure 4.19. Groundwater elevation in metres above sea level (masl) in two water table wells (C-MW1 and C-MW2) and two piezometers (C-P08-14 and C-P08-21) at CFO-5.

4.3.5 Groundwater Quality

CFO-1

Concentrations varied among well nests and well completion depths. Chloride concentrations at CFO-1 ranged from the MMDL to 1109 mg L^{-1} (Table 4.3). Nitrate N concentrations ranged from the MMDL to 22 mg L^{-1}. Ammonia N concentrations ranged from the MMDL to 426 mg L^{-1}.

Among the water table wells at CFO-1, the highest Cl^-, NO_3^--N, and NH_3-N concentrations were measured in different wells (Figures 4.20 and 4.21; Appendix 10). Chloride and NH_3-N concentrations were highest in D-MW3, a water table well on the downgradient side of the EMS, while the highest NO_3^--N concentration was measured in D-MW11a, a downgradient well in the northeast corner of the site, and would not be expected to be directly impacted by the feedlot or dairy facilities. Chloride concentrations were also high in D-MW2, another water table well near the EMS, as well as D-MW11a and D-MW6, which is the most downgradient well from the catch basin. Nitrate N concentration was elevated in D-MW1, the most upgradient well near the EMS, and D-MW13a, a well downgradient of the EMS and feedlot pens. It appears that the EMS is impacting concentrations measured in D-MW3, but it is uncertain if the EMS, or a combination of the EMS and feedlot, is impacting other shallow wells downgradient from the EMS, such as D-MW13a and D-MW6. It is also uncertain as to what is influencing the elevated Cl^- and NO_3^--N concentrations measured in D-MW11a.

Table 4.3. Mean, minimum (min.), and maximum (max.) concentrations of chloride (Cl^-), nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_3-N) for individual wells at CFO-1 in 2010 and 2011.

	Cl^-			NO_3^--N			NH_3-N		
	Min.	Max.	Mean^y	Min.	Max.	Mean^y	Min.	Max.	Mean^y
Well^z	------ (mg L^{-1})^x ------			------ (mg L^{-1})^x ------			------ (mg L^{-1})^x ------		
D-MW1	11	144	75	1.79	12.58	6.27	0.05	0.05	0.05
D-MW2	301	727	482	0.25	3.55	2.05	0.05	0.05	0.05
D-P10-1	5	5	5	0.05	0.05	0.05	0.69	0.85	0.77
D-P10-2	60	96	77	9.99	22.23	16.49	0.12	2.84	0.95
D-MW3	829	1109	1000	0.05	3.78	0.81	227	426	319
D-MW4	26	46	37	0.05	0.05	0.05	0.05	0.05	0.05
D-MW5	26	46	37	0.05	0.05	0.05	0.05	0.05	0.05
D-MW6	355	400	381	0.05	0.05	0.05	3.46	7.78	4.60
D-MW10a	238	238	238	0.05	0.71	0.27	0.26	0.42	0.34
D-P11-10b	43	57	47	0.05	7.07	2.52	0.05	0.59	0.37
D-P11-10c	14	18	15	0.05	0.05	0.05	0.80	0.90	0.85
D-MW11a	372	486	447	10.32	19.92	15.91	0.05	0.13	0.10
D-P11-11b	18	21	19	0.05	0.05	0.05	1.10	1.26	1.17
D-MW12a	89	89	89	2.31	3.00	2.69	0.05	0.23	0.11
D-P11-12b	99	142	118	1.51	3.93	2.80	0.15	0.36	0.23
D-MW13a	39	74	51	2.46	10.8	5.46	0.14	0.60	0.35
D-P11-13b	18	21	20	0.05	0.05	0.05	0.55	0.63	0.60
D-P11-13c	50	74	60	0.05	0.94	0.41	1.00	1.07	1.03
D-MW14a	5	5	5	0.05	0.05	0.05	0.18	0.26	0.23
D-P11-14b	5	14	10	0.05	0.05	0.05	0.74	0.94	0.86
D-P11-14c	14	18	15	0.05	0.05	0.05	0.57	0.78	0.67
D-MW15a	14	14	14	0.05	0.05	0.05	0.05	0.05	0.05
D-P11-15b	5	11	7	0.05	0.05	0.05	0.65	0.76	0.70
D-P11-15c	50	85	72	0.05	0.05	0.05	0.40	0.81	0.55
D-MW16a	71	74	72	0.12	0.20	0.15	0.11	0.19	0.14
D-P11-16b	35	39	37	0.05	0.05	0.05	0.74	0.76	0.75

^{z} D-P11-10d, D-P11-14d, D-P11-14e, and D-P11-15d were instrumented in Nov. 2011 and are not included in the table as no data were collected. They will be included in subsequent years.
^{y} Standard deviations are reported in Appendix 19.
^{x} Values less than the MMDL were set at half the MMDL: 5 mg L^{-1} for Cl^- and 0.05 mg L^{-1} for NO_3^--N and NH_3-N.

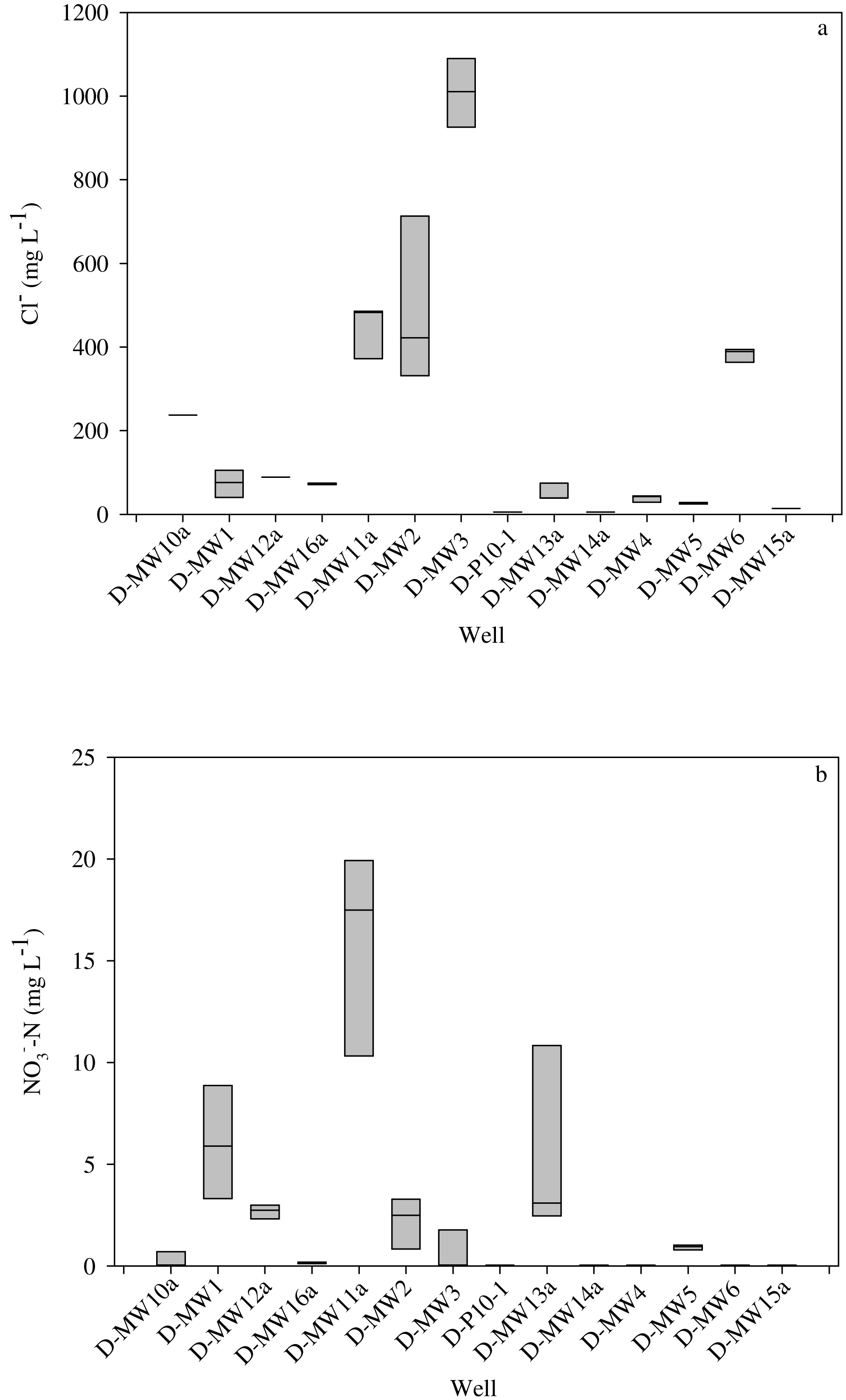


Figure 4.20. Concentrations of (a) chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in 2010 and 2011 in water table wells at CFO-1 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median.

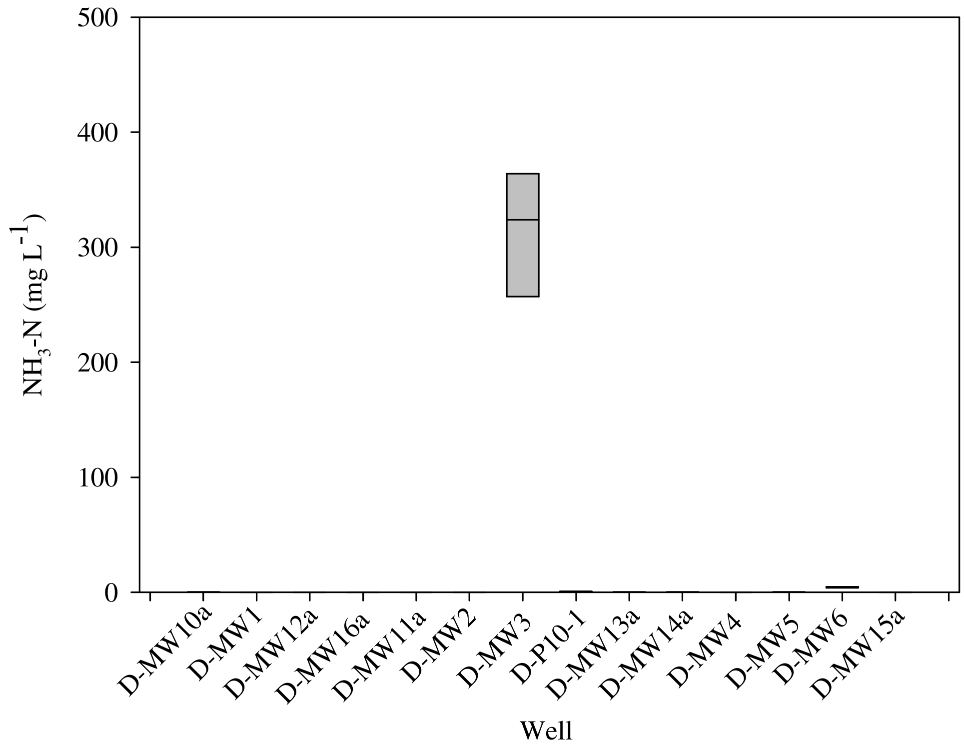


Figure 4.21. Ammonia nitrogen (NH_3-N) concentrations in 2010 and 2011 in water table wells at CFO-1 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median.

Among the wells at the north end of CFO-1, the highest NO_3^--N and Cl^- concentrations were measured in D-MW11a (10 to 20 mg L^{-1} and 132 to 468 mg L^{-1}, respectively, Table 4.3). Nitrate N concentrations in the remaining wells were generally less than 1 mg L^{-1} with concentrations generally less than the MMDL in the deep piezometers, except for one sample at D-P11-10b in June 2011. Chloride concentrations were higher in the water table wells in the two nests at the north end of the site than in the deep piezometers. No seasonal patterns were observed for NO_3^--N or Cl^- concentrations in the water table well or piezometers at the north end of the site (data not shown).

Of the wells surrounding the EMS, NO_3^--N concentrations were highest in the deepest piezometer (D-P10-2) and ranged from the MMDL to 22 mg L^{-1}(Table 4.3). The majority of samples collected from wells surrounding the EMS had less than 5 mg L^{-1} NO_3^--N, though the farthest upgradient well near the EMS (D-MW1) typically had the highest concentrations of the shallow water table wells. In contrast, the highest Cl^- concentrations (~ 300 to 1000 mg L^{-1}) were measured in water table wells D-MW2 and D-MW3 (Table 4.3). Ammonia N concentrations were commonly low (< 2.0 mg L^{-1}), except in D-MW3 where concentrations ranged from 227 to 426 mg L^{-1} (Table 4.3). Nitrate N and Cl^- concentrations in wells surrounding the EMS varied throughout the sampling season. Though no temporal patterns were observed, Cl^- concentrations appeared greatest during the summer months (Figure 4.22). Elevated Cl^-, NO_3^--N, and NH_3-N concentrations in the wells surrounding the EMS may indicate impact from the manure storage. The elevated concentrations in the deep piezometer may also indicate downward vertical movement of contaminants. The higher NH_3-N concentrations measured in D-MW3 may indicate a specific area of the EMS is leaking or leaking more than other areas of the EMS. Also, water table well D-MW3 is on the presumed downgradient side of the EMS.

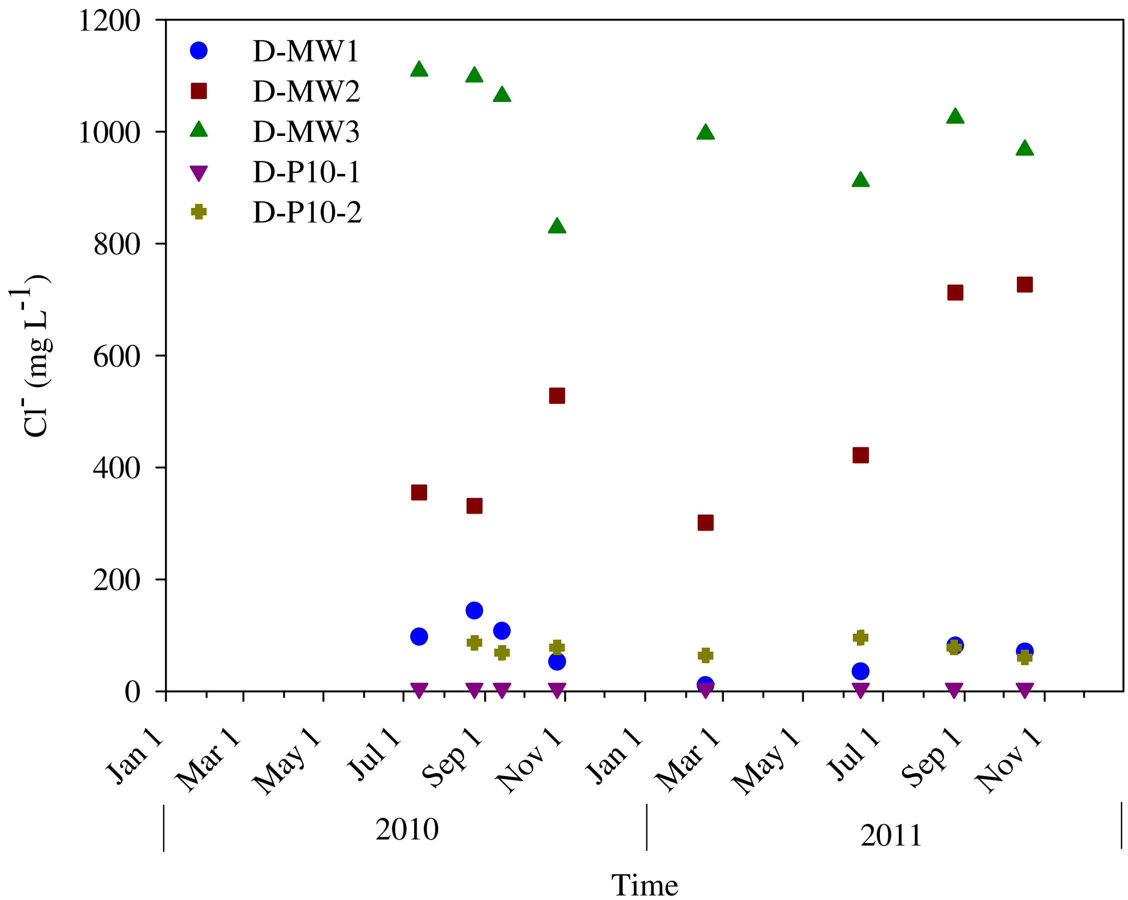


Figure 4.22. Chloride (Cl^-) concentrations in wells surrounding the EMS at CFO-1 in 2010 and 2011.

Of the wells east of the EMS and south of the feedlot pens, the highest NO_3^--N concentration was measured in the deepest piezometer at D-P11-13a, with a range of 2.5 to 10.8 mg L^{-1} (Table 4.3). Nitrate N concentrations in the majority of samples collected from wells in the east-central part of the site were less than 4 mg L^{-1}, with most close to or less than the MMDL. Chloride concentrations ranged from the MMDL to 75 mg L^{-1}, with the highest Cl^- concentrations measured in the deepest piezometer (D-P11-13c) and the shallow water table well (D-P11-13a; Table 4.3). Ammonia N concentrations were typically near or below 1.0 mg L^{-1} in the wells, with concentrations relatively higher in the deeper piezometers in nests 13 and 14. A seasonal pattern was not apparent for NO_3^--N, Cl^-, or NH_3-N in the wells in the east-central part of CFO-1 (data not shown).

Nitrate N concentrations measured in water table wells surrounding the catch basin were all below 1.5 mg L^{-1}, with the majority of samples less than the MMDL (Table 4.3). Chloride concentrations ranged from 25 to 46 mg L^{-1} in D-MW4 and D-MW5; however, concentrations were 8 to 16 times higher in D-MW6 than in the other two wells. Ammonia N concentrations were also elevated in D-MW6 relative to the other water table wells surrounding the catch basin No temporal patterns in NO_3^--N, Cl^-, or NH_3-N were observed in wells adjacent to the catch basin (data not shown).

Nitrate N concentrations in all wells along the south and southeastern boundaries of CFO-1 were less than 5 mg L^{-1}, with the majority of samples less than the MMDL (Table 4.3). Nitrate N and Cl^- concentrations were higher in Nest 12, located south and slightly west of the EMS and dairy barns, compared to Nests 15 and 16, which are further away from the facilities (Figure 4.20, Table 4.3). Chloride concentrations were higher in the deepest piezometer (D-P11-12c) than in the shallower piezometer (D-P11-12b) or water table well (D-MW12a). Generally, a seasonal pattern was not observed for NO_3^--N or Cl^- concentrations in the wells along the south and southeast borders of the site (data not shown). Nitrate N and Cl^- concentrations decreased from the first sampling event in D-P11-12b; however, the data set only contained three samples for the well.

CFO-2

Concentrations varied among well nests and well completion depths at CFO-2 (Appendix 10). Chloride concentrations at CFO-2 ranged from the MMDL to 620 mg L^{-1} (Table 4.4). Nitrate N concentrations ranged from the MMDL to 134 mg L^{-1}. Ammonia N concentrations ranged from the MMDL to 2.14 mg L^{-1}. Although different wells were monitored, Cl^- and NO_3^--N concentrations were similar to historical measurements (1994 to 2001; Rodvang *et al.* 2001).

Among the water table wells at CFO-2, the highest Cl^-, NO_3^--N, and NH_3-N concentrations were measured in different wells (Figures 4.23 and 4.24). Ammonia N concentrations appeared to be elevated in the downgradient wells, specifically LB8a-6 and LB8a-7 (Figure 4.24). Although Cl^- concentrations were high in LB8a-6, the most downgradient water table well, higher concentrations were measured in LB8a-10, a water table well upgradient of the feedlot pens on the eastern boundary of the site. Interestingly, NO_3^--N concentrations were also elevated in LB8a-13, in the southeast corner of the site, upgradient of the feedlot and LB8a-10.

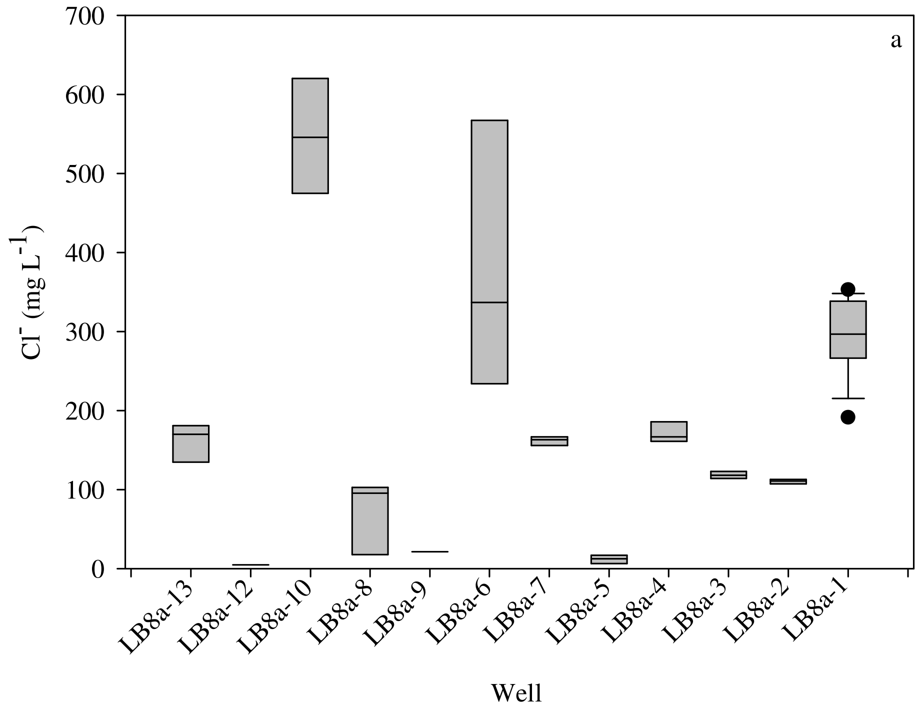
Elevated Cl^- and NO_3^--N concentrations in several wells indicated influences from an anthropogenic source. Nearly all water table wells at CFO-2, with the exception of LB8a-4 and LB8a-12, had minimum NO_3^--N concentrations greater than 10 mg L^{-1}. However, it is uncertain whether the elevated NO_3^--N came from the CFO or other activities in the area as two of the upgradient wells had the highest NO_3^--N concentrations (LB8a-13 and LB8a-10). As expected, Cl^-, NO_3^--N, and NH_3-N concentrations were low in the deepest piezometer, (LB8a-5).

Generally, Cl^- and NO_3^--N concentrations did not show seasonal patterns. Concentrations in LB8a-1 fluctuated and appeared to decrease from June to August 2010 with an increase again in the fall of 2010 (Figure 4.25). Concentrations also appeared lower in 2011 than in 2010. The lower concentrations may be a result of higher groundwater elevation in 2011 than in 2010, possibly causing a dilution effect. Chloride and NO_3^--N concentrations also decreased from February to October 2011 in LB8a-5, the deepest piezometer, and from August to November 2011 in LB8a-6 (Figure 4.25). Once data are obtained for a full year and multiple seasons, LB8a-6 should be assessed to determine if the Battersea Drain has an impact on groundwater elevation and the resulting concentrations.

Table 4.4. Mean, minimum (min.), and maximum (max.) concentrations of chloride (Cl^-), nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_3-N) for individual wells at CFO-2 in 2010 and 2011.

	Cl^-			NO_3^--N			NH_3-N		
	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]
Well	------ ($mg\ L^{-1}$)[y] ------			------ ($mg\ L^{-1}$)[y] ------			------ ($mg\ L^{-1}$)[y] ------		
LB8a-1	191	353	287	48.3	109	80.3	0.19	1.33	0.70
LB8a-2	106	118	111	33.6	46.3	39.9	0.05	0.30	0.16
LB8a-3	113	135	120	43.3	60.0	49.6	0.05	0.38	0.24
LB8a-4	160	191	172	1.21	12.7	9.51	0.05	0.23	0.14
LB8a-5	5	18	12	0.05	0.15	0.09	0.57	0.64	0.60
LB8a-6	234	567	379	25.4	117	64.6	1.37	2.14	1.77
LB8a-7	156	167	162	0.05	0.05	0.05	0.69	0.80	0.75
LB8a-8	18	103	72	0.05	31.1	19.4	0.25	0.43	0.31
LB8a-9	21	21	21	0.05	0.10	0.07	0.45	0.49	0.48
LB8a-10	475	620	547	70.0	91.0	80.5	0.05	0.05	0.05
LB8a-12	5	5	5	0.12	0.43	0.26	0.05	0.05	0.05
LB8a-13	135	181	162	97.74	134	117	0.05	0.05	0.05

[z] Standard deviations are reported in Appendix 10.
[y] Values less than the MMDL were set at half the MMDL: 5 $mg\ L^{-1}$ for Cl^- and 0.05 $mg\ L^{-1}$ for NO_3^--N and NH_3-N.



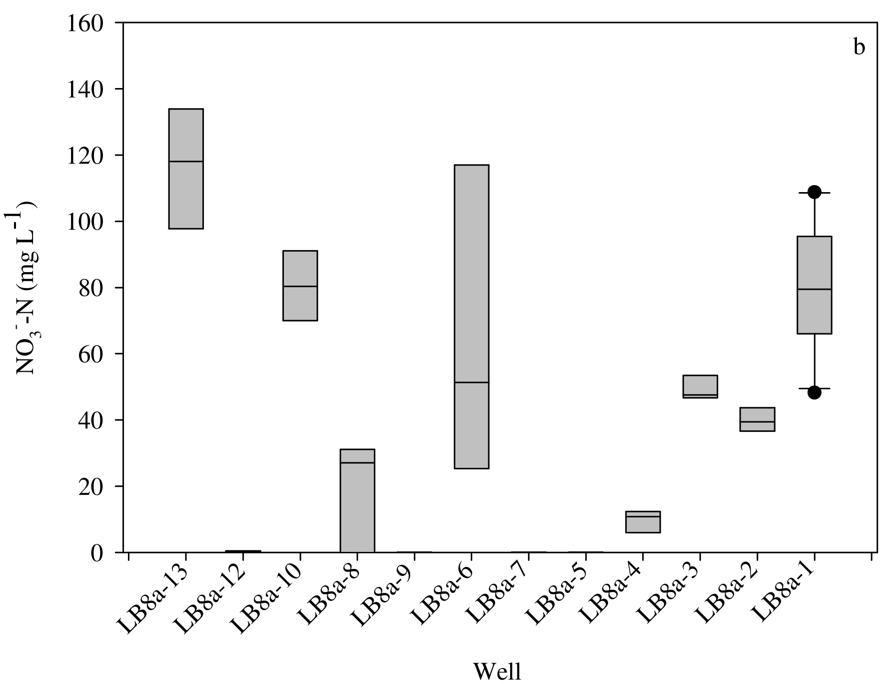


Figure 4.23. Concentrations of (a) chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in 2010 and 2011 in wells at CFO-2 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

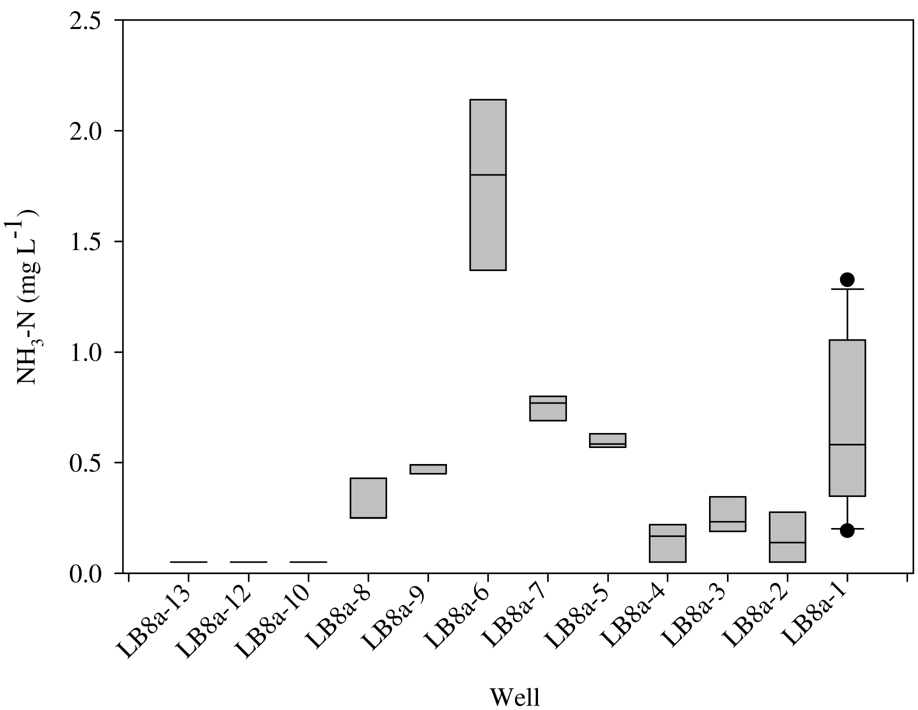


Figure 4.24. Ammonia nitrogen (NH_3-N) concentrations in 2010 and 2011 in wells instrumented at CFO-2 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

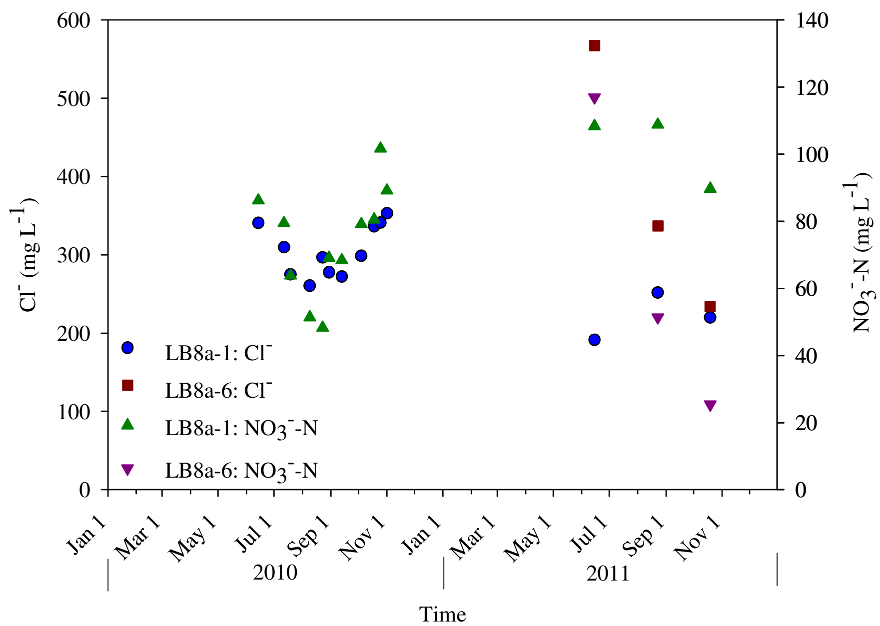


Figure 4.25. Nitrate nitrogen (NO_3^--N) and chloride (Cl^-) concentrations at CFO-2 for LB8a-1 (2010 and 2011) and LB8a-6 (2011).

CFO-3

Chloride concentrations ranged from the MMDL to 479 mg L^{-1} (Table 4.5). The relatively higher Cl^- concentrations greater than 160 mg L^{-1} were measured in the water table wells surrounding the EMS (A-MW1, A-MW2, A-MW3; Figure 4.26a). However, elevated values were also observed in the upgradient well. It is unclear why concentrations in A-C3, upgradient of the EMS and dairy facility, were elevated, though it may be related to agricultural activities in the adjacent fields (i.e., manure spreading and/or fertilizer application).

Nitrate N concentrations at CFO-3 ranged from the MMDL to 71 mg L^{-1} (Table 4.5). Nitrate N concentrations were highest in two water table wells: A-MW1 adjacent to the EMS and A-C3 in a field upgradient of the EMS and dairy facility (Figure 4.26b). Nitrate N concentrations in A-MW2 were also elevated, which was where the highest concentrations were measured during previous monitoring (2006 to 2008; WorleyParsons 2009). Nitrate N concentrations in A-MW3 were generally less than 5 mg L^{-1} with the exception of one spike (46 mg L^{-1}) in May 2010, while concentrations measured in the deep piezometers were at or near the MMDL.

Ammonia N concentrations ranged from the MMDL to 0.60 mg L^{-1} (Table 4.5). The majority of detectable NH_3-N concentrations were observed downgradient of the EMS in A-MW3 as well as upgradient of the EMS, dairy facilities, and adjacent field in A-C3 (Figure 4.27).

Table 4.5. Mean, minimum (min.), and maximum (max.) concentrations of chloride (Cl^-), nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_3-N) for individual wells at CFO-3 in 2010 and 2011.

	Cl^-			NO_3^--N			NH_3-N		
	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]
Well	------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------		
A-C3	5	92	39	0.32	71.0	24.37	0.05	0.05	0.05
A-MW1	72	168	111	8.50	49.9	29.73	0.05	0.18	0.06
A-MW2	194	365	253	11.1	21. 6	14.90	0.05	0.05	0.05
A-P08-16	5	5	5	0.05	0.17	0.09	0.30	0.51	0.43
A-P08-21	5	5	5	0.05	0.05	0.05	0.53	0.60	0.57
A-MW3	152	479	389	0.05	46.0	5.40	0.05	0.55	0.15

[z] Standard deviations are reported in Appendix 10.
[y] Values less than the MMDL were set at half the MMDL: 5 mg L^{-1} for Cl^- and 0.05 mg L^{-1} for NO_3^--N and NH_3-N.

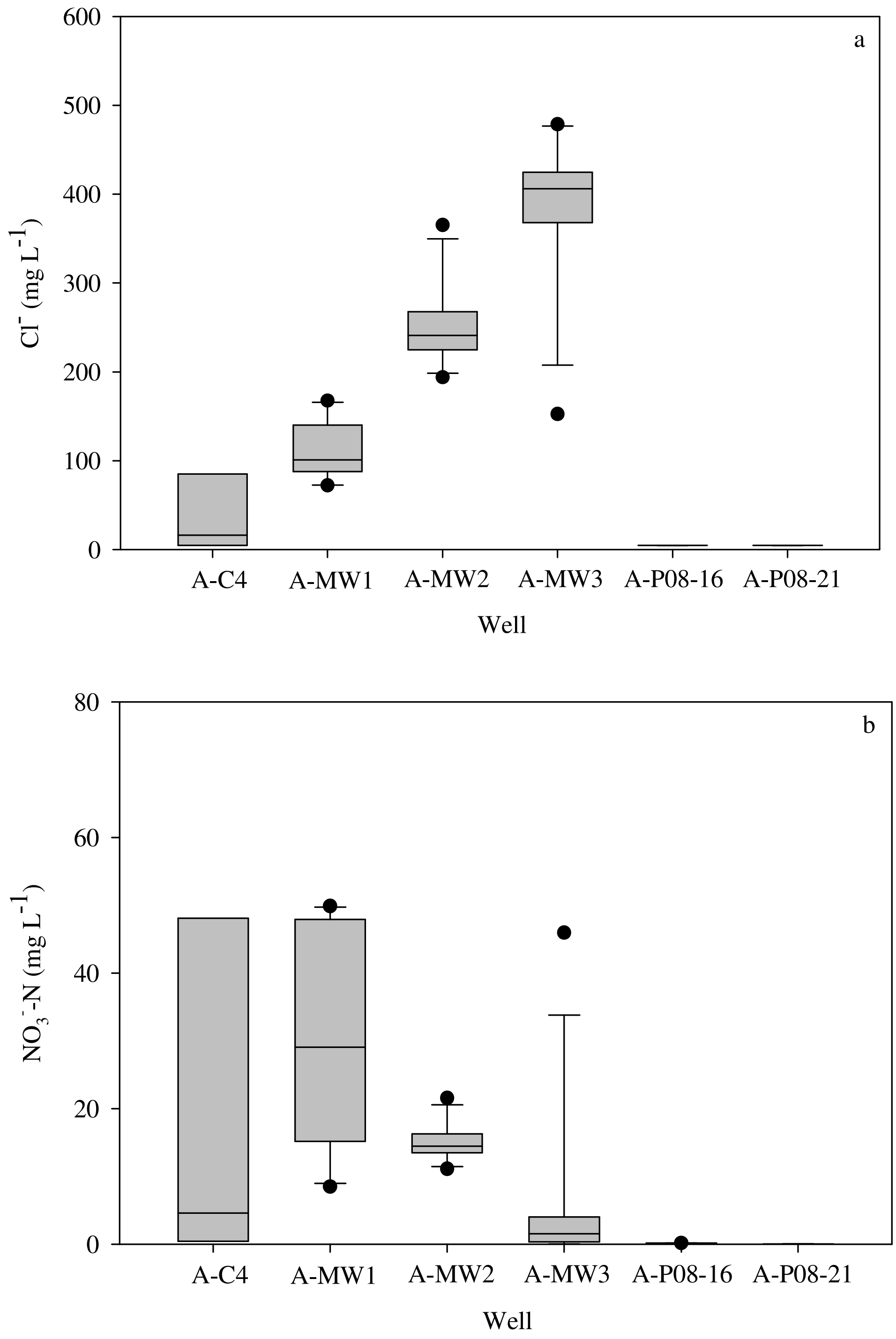


Figure 4.26. Concentrations of (a) Chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in 2010 and 2011 in wells at CFO-3 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

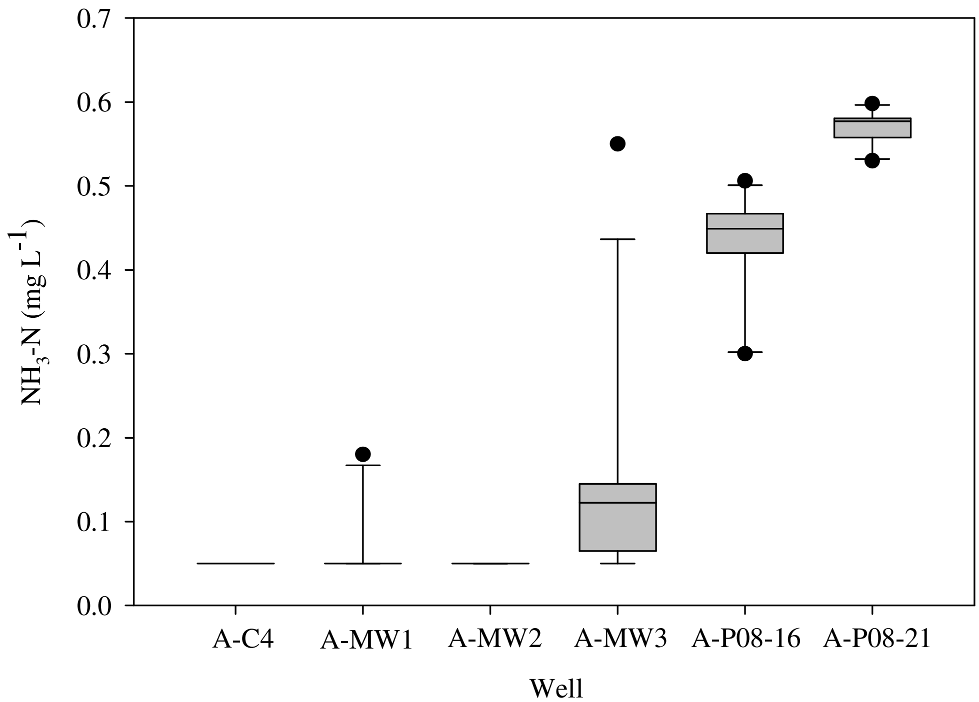


Figure 4.27. Ammonia nitrogen (NH_3-N) concentrations in 2010 and 2011 in wells at CFO-3 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

Nitrate N and Cl^- concentrations changed with time in some of the wells and remained relatively constant in other wells (Figure 4.28). Nitrate N and Cl^- concentrations measured in the upgradient well (A-C3) were elevated from June to October 2011 compared to 2010 or early 2011. Nitrate N and Cl^- concentrations in A-MW1 decreased initially during the spring and summer 2010 before increasing again in the summer and decreasing in the fall 2011. Chloride concentrations in A-MW2 increased with time, specifically during the summer and fall 2011, while NO_3^--N concentrations varied without exhibiting a seasonal or temporal pattern. Nitrate N and Cl^- concentrations in A-MW3 displayed some variation. While NO_3^--N concentrations displayed relatively little variation, yearly maximum values were observed in the summer and were relatively low throughout the rest of the year. Chloride concentrations at A-MW3 displayed an overall increase from 2010 to 2011 and followed a similar pattern, with yearly maximum values observed during the summer. Relatively little variation in NH_3-N concentrations was observed for either water table wells or piezometers, though concentrations increased slightly in summer 2011 in A-MW3.

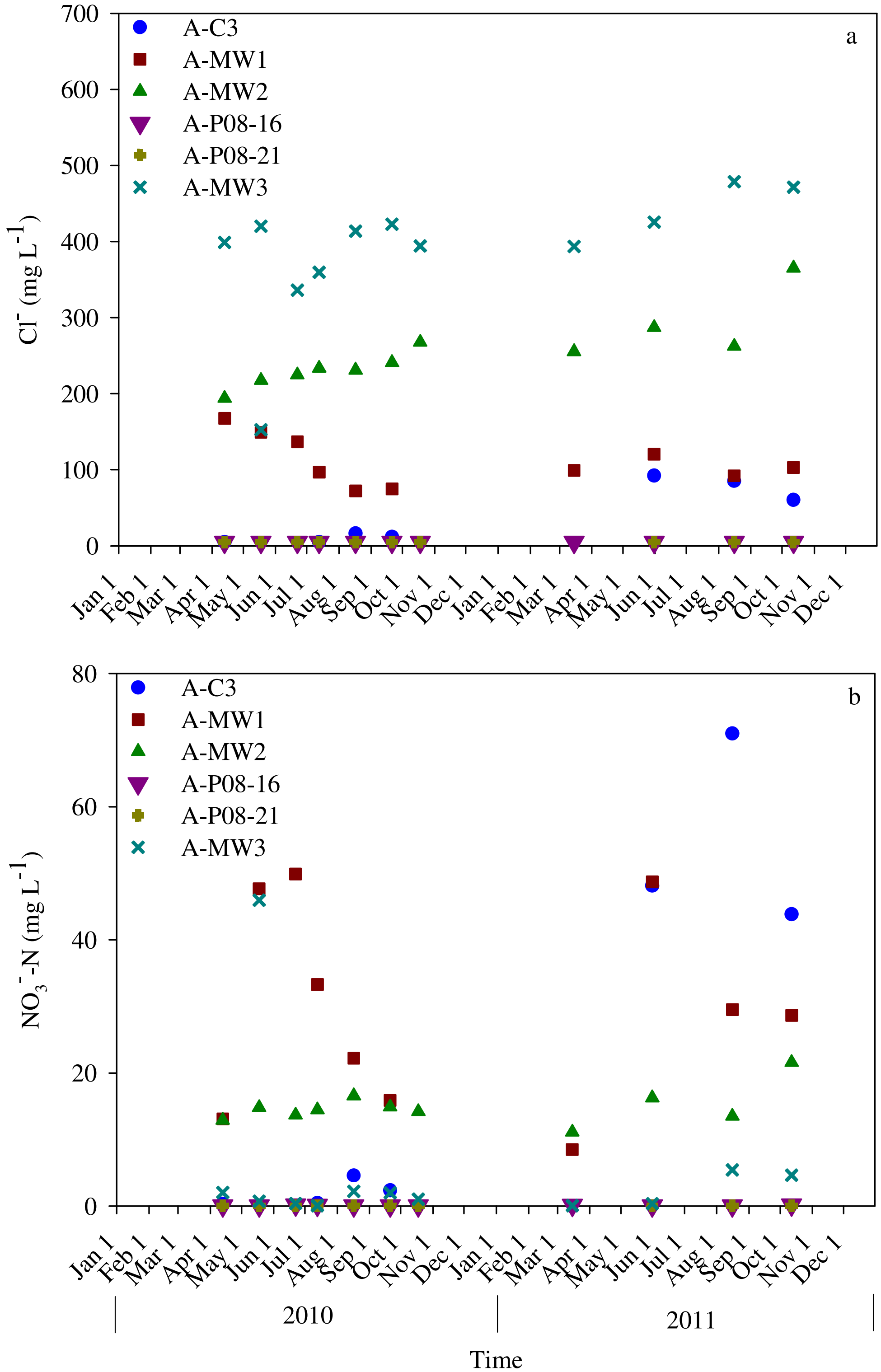


Figure 4.28. Concentrations of (a) chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in wells at CFO-3 from 2010 to 2011.

CFO-4

Chloride concentrations at CFO-4 ranged from the MMDL to 771 mg L^{-1} (Table 4.6). The highest Cl^- concentrations were observed in B-MW1 and B-MW2a, with elevated Cl^- concentrations also measured in B-MW3 and B-MW4a (Figure 4.29a). All of these wells are relatively shallow water table wells adjacent to the sides of the EMS. The farthest upgradient monitoring well at the site, B-C4, had relatively low Cl^- concentrations, ranging from the MMDL to 18 mg L^{-1}. Chloride concentrations for all of the deeper piezometers were typically at or near the MMDL, except for B-P10-21e, which ranged from 11 to 26 mg L^{-1}.

Nitrate N concentrations at CFO-4 ranged from the MMDL to 42 mg L^{-1} (Table 4.6). The highest NO_3^--N concentratns were measured in B-MW3 and B-MW4a, although elevated values were observed in B-MW1 and B-MW2a (Figure 4.29b). The most upgradient well at the site, B-C4, had low NO_3^--N concentrations, which were generally less than 1.0 mg L^{-1}. Nitrate N concentrations were at the MMDL in nearly all of the deeper piezometers, except for a few samples from B-P10-21e, which were still relatively low (<0.25 mg L^{-1}).

Ammonia N concentrations at CFO-4 ranged from the MMDL to 0.23 mg L^{-1} (Table 4.6). The most consistent detectable NH_3-N concentrations occurred in the deeper piezometers, which remained relatively low and nearly constant (Figure 4.30).

Table 4.6. Mean, minimum (min.), and maximum (max.) concentrations of chloride (Cl^-), nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_3-N) for individual wells at CFO-4 in 2010 and 2011.

	Cl^-			NO_3^--N			NH_3-N		
	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]
Well	------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------		
B-C4	5	18	8	0.05	0.78	0.33	0.05	0.05	0.05
B-MW3	142	342	235	0.13	41.8	21.3	0.05	0.23	0.07
B-MW4a	92	320	210	14.0	36.5	25. 6	0.05	0.05	0.05
B-P10-15w	5	5	5	0.05	0.05	0.05	0.15	0.18	0.16
B-P10-20w	5	5	5	0.05	0.05	0.05	0.16	0.18	0.17
B-MW2a	365	571	469	0.05	3.57	1.28	0.05	0.14	0.09
B-P10-15e	5	5	5	0.05	0.05	0.05	0.12	0.23	0.19
B-P10-21e	11	26	19	0.05	0.21	0.11	0.14	0.17	0.16
B-MW1	121	771	511	1.09	9.60	3.83	0.05	0.05	0.05

[z] Standard deviations are reported in Appendix 10.
[y] Values less than the MMDL were set at half the MMDL: 5 mg L^{-1} for Cl^- and 0.05 mg L^{-1} for NO_3^-- N and NH_3-N.

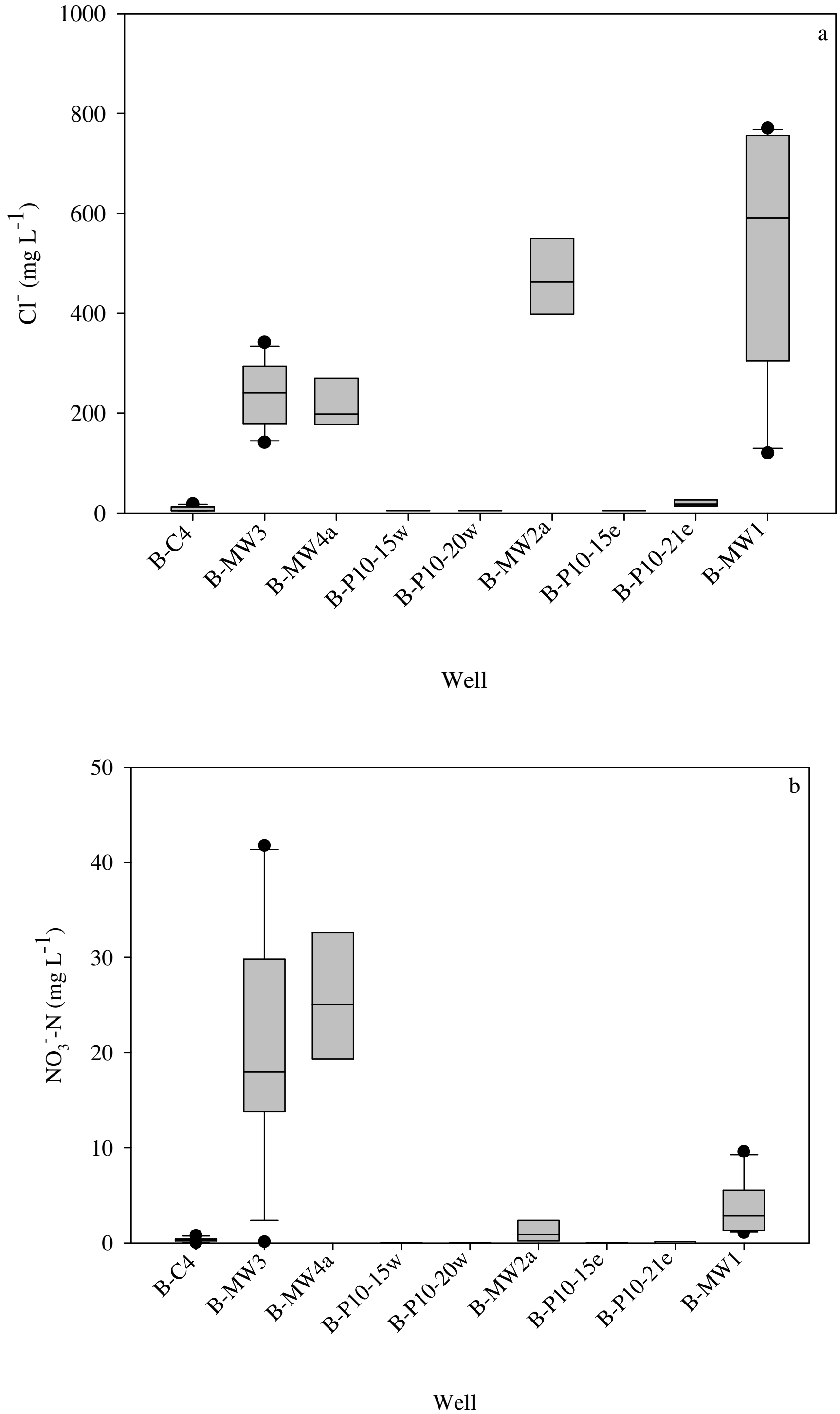


Figure 4.29. Concentrations of (a) chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in 2010 and 2011 in wells at CFO-4 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

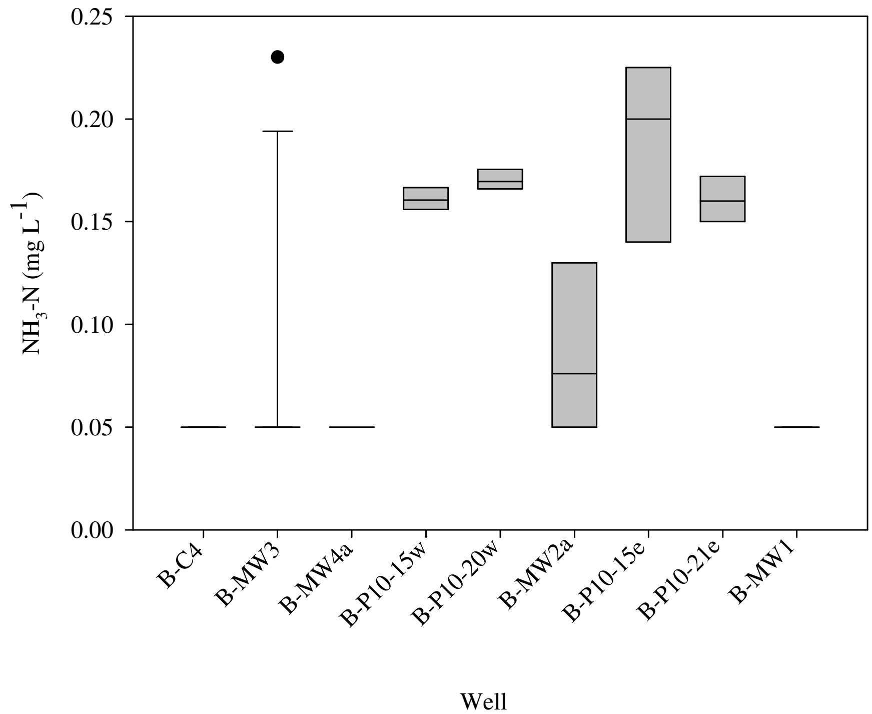


Figure 4.30. Ammonia nitrogen (NH_3-N) concentrations in 2010 and 2011 in wells at CFO-4 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

Nitrate N and Cl^- concentrations fluctuated with time in most of the water table wells surrounding the EMS. The highest Cl^- concentrations measured in the water table wells surrounding the EMS typically occurred in the spring each year, while the highest concentrations for the upgradient well typically occurred in the winter. However, strong seasonal or temporal patterns were not obvious. Nitrate N concentrations in B-MW4a generally decreased with time from 14 to 33 mg L^{-1} (Figure 4.31a). Similarly, NO_3^--N concentrations in B-MW1 decreased with time from spring to fall 2010 and remained relatively constant through to fall 2011, although the yearly maximum concentrations occurred in the spring. Nitrate N concentrations were typically highest during winter in the most upgrdaient water table well (B-C4) and overall concentrations were relatively low. Obvious seasonal variations were not observed for NO_3^--N concentrations. Although NO_3^--N and Cl^- concentrations generally remained constant in the deeper piezometers, and were at or near the MMDL, concentrations decreased from fall 2010 to fall 2011 in B-P10-21e (Figure 4.31b).

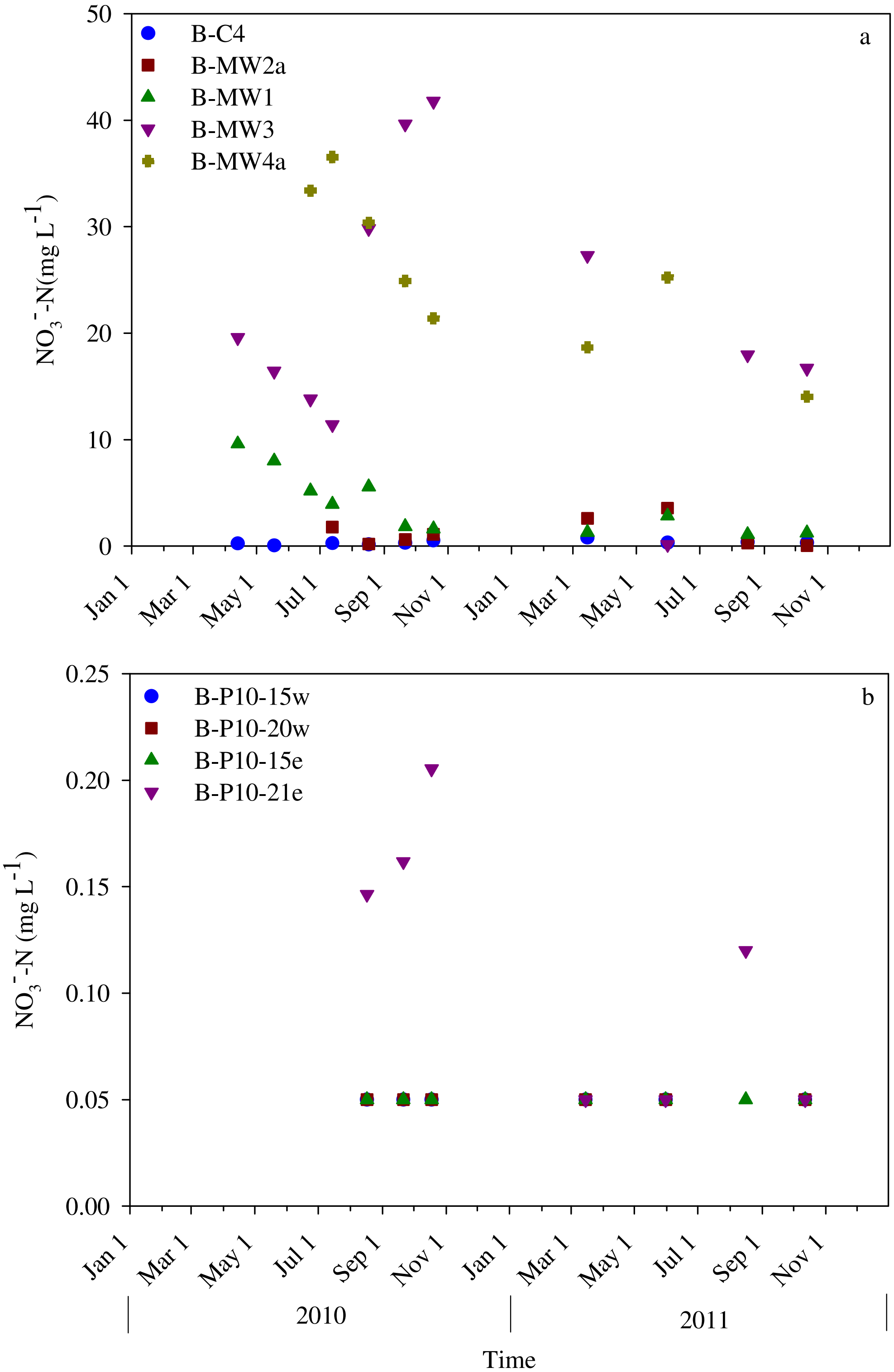


Figure 4.31. Nitrate nitrogen (NO_3^--N) concentrations with time in (a) water table wells and (b) piezometers at CFO-4 in 2010 and 2011.

CFO-5

Chloride and NO_3^--N concentrations at CFO-5 were generally higher in shallow water table wells surrounding the EMS than in the upgradient field water table well or deeper piezometers surrounding the EMS (Table 4.7). Previous investigations also found that almost all parameter concentrations were elevated above that expected to be background at C-MW1, the assumed downgradient monitoring well (WorleyParsons 2009). Chloride concentrations ranged from the MMDL to 943 mg L^{-1}. Chloride concentrations in C-MW1, a shallow water table well by the EMS, ranged from 18 to 189 times higher than concentrations in the deeper piezometers surrounding the EMS, as well as the upgradient water table well in the field. Elevated Cl^- concentrations in the shallow water table wells surrounding the EMS may be indicative of contamination, although contaminant movement does not appear to be vertical near the EMS (Figure 4.32a). Nitrate N concentrations ranged from the MMDL to 25 mg L^{-1} (Table 4.7). Although NO_3^--N concentrations measured in C-MW2 ranged from the MMDL up to 9 mg L^{-1}, the majority of samples collected at CFO-5 had concentrations of less than 1 mg L^{-1} (Figure 4.32b).

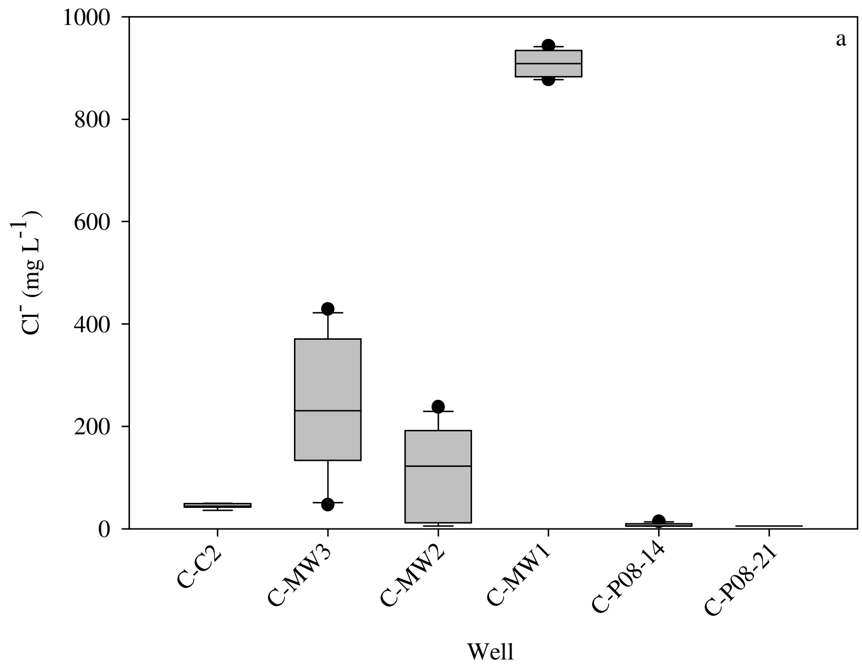
Ammonia N concentrations at CFO-5 ranged from the MMDL to 1.13 mg L^{-1} (Table 4.7). Although NH_3-N was detectable in almost all samples, except for C-C2, concentrations were generally relatively low (<1.0 mg L^{-1}). Concentrations were slightly higher in C-MW1 relative to C-MW2 and C-MW3, which were similar and were slightly higher than those in C-C2. Observed NH_3-N concentrations were highest in the deeper piezometers relative to the water table wells (Figure 4.33).

No temporal or seasonal patterns were apparent for Cl^-, NO_3^--N, or NH_3-N concentrations at CFO-5 (data not shown).

Table 4.7. Mean, minimum (min.), and maximum (max.) concentrations of chloride (Cl^-), nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_3-N) for individual wells at CFO-5 in 2010 and 2011.

	Cl^-			NO_3^--N			NH_3-N		
	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]	Min.	Max.	Mean[z]
Well	------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------			------ (mg L^{-1})[y] ------		
C-MW1	5	238	108	0.05	9.38	1.96	0.16	0.21	0.18
C-P08-14	5	13.9	6.79	0.05	0.05	0.05	0.69	0.92	0.81
C-P08-21	5	4.96	4.96	0.05	0.05	0.05	0.85	0.92	0.89
C-MW2	5	238	108	0.05	9.38	1.96	0.16	0.21	0.18
C-MW3	47	429	241	0.05	25.2	2.44	0.05	0.29	0.22
C-C2	36	49.6	44.6	0.05	0.30	0.13	0.05	0.05	0.05

[z] Standard deviations are reported in Appendix 10.
[y] Values less than the MMDL were set at half the MMDL: 5 mg L^{-1} for Cl^- and 0.05 mg L^{-1} for NO_3^-- N and NH_3-N.



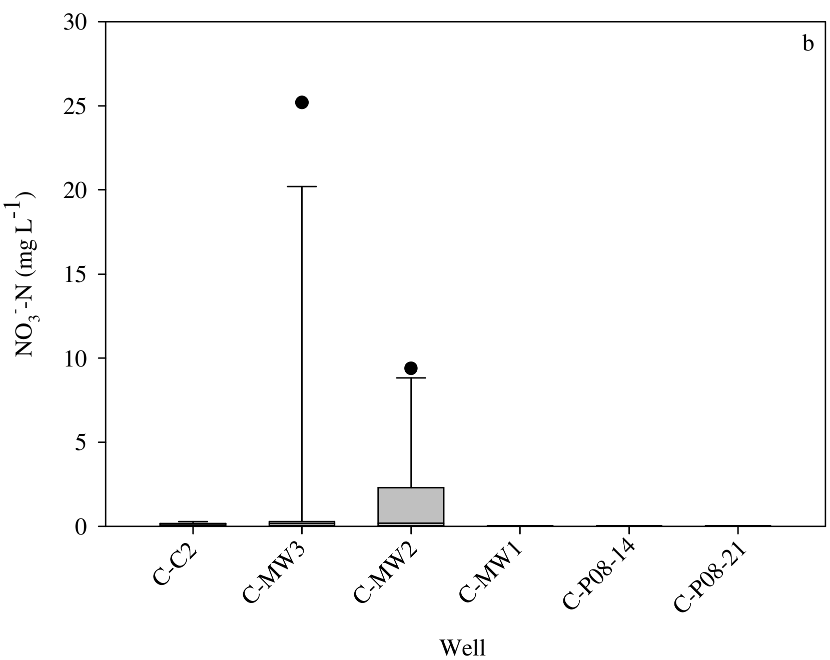


Figure 4.32. Concentrations of (a) chloride (Cl^-) and (b) nitrate nitrogen (NO_3^--N) in 2010 and 2011 in wells at CFO-5 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

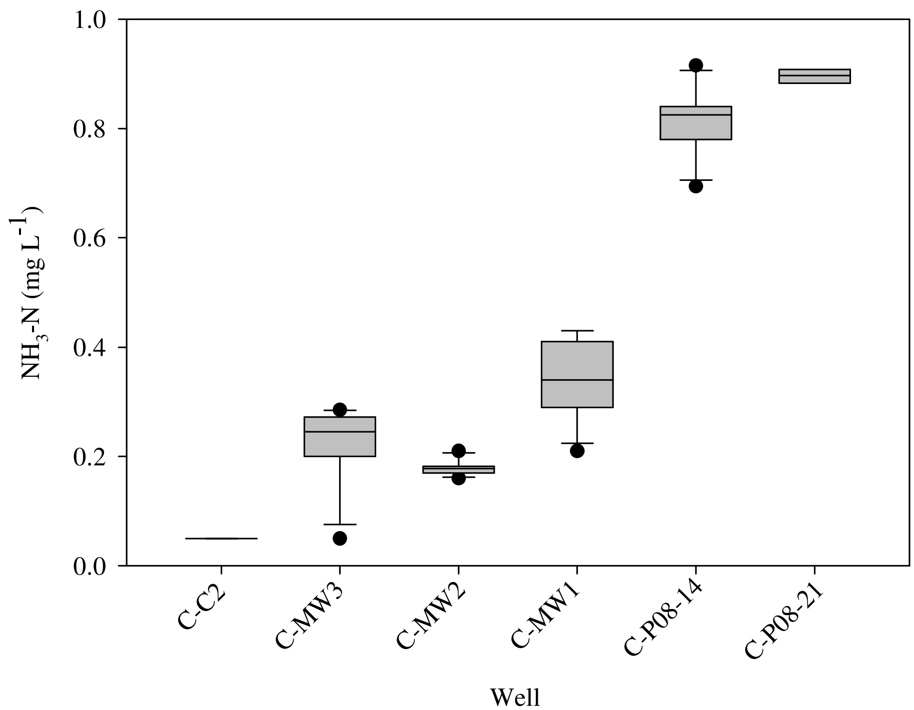


Figure 4.33. Ammonia nitrogen (NH_3-N) concentrations in 2010 and 2011 in wells at CFO-5 displayed generally from upgradient (left) to downgradient (right). Boxplots stretch from the 25th percentile to the 75th percentile with the horizontal line in the middle of the box representing the median. Whiskers (error bars) above and below the box represent the 10th and 90th percentiles, while dots represent outlying data points. Whiskers and outliers were not computed or presented for wells with less than the required nine data points.

4.3.6 Geophysical Investigations

In October 2011, the EM31 measurements at CFO-1 ranged from 25 to 128 mS m^{-1}, with a mean of 57 mS m^{-1} (standard deviation of 20 mS m^{-1}). The maximum depth of investigation of the EM31 was about 6 m (WorleyParsons 2012). Generally, the majority of the relatively high readings were observed near the EMS and to the east of the EMS, in the assumed direction of groundwater flow. The relatively low EC values were observed 50 m east and beyond the EMS. Other areas of relatively high EC included west of the catch basin and in the southwest corner of CFO-1. The extent of the geophysical survey was limited by site access (i.e., fences and water body) and capabilities of the EM31 (i.e., penetration depth of conductivity readings). Results from the survey suggest that a groundwater plume of high conductivity may be east of the EMS.

The EM31 results at CFO-1 delineated zones of elevated terrain conductivity values south of the EMS, along the south and east edges of the EMS, and extended to the east adjacent to the pens in the northeast corner of the site (Figure 4.34) (WorleyParsons 2012). The absence of elevated EM38 (maximum depth of penetration is about 1.5 m) terrain conductivity values south of the EMS suggest the potential salinity impacts are likely deeper than 1.5 mbgs in this area.

The increase in elevated terrain conductivity anomalies in the east portion of the site (i.e., between the feedlot pens and catch basin) from the EM31 to the EM38 data sets suggests that the potential salinity impacts are primarily concentrated in the near surface. The elevated terrain conductivity anomalies located in the eastern portion of the site may be due to salinity impacts originating from livestock waste but are unlikely to have originated from the EMS. The ERT results delineated a zone of elevated conductivity values extending from as shallow as 1 mbgs to as deep as 7 mbgs. These ERT results correlated with EM results, the borehole induction conductivity log from D-MW3, and relatively high shallow groundwater salinity concentrations. The ERT also detected elevated conductivity to depths of 24 mbgs adjacent to the southeast corner of the EMS, although these cannot be correlated to groundwater chemistry or lithology in the same spot at this time (i.e., it may represent a clay layer or deeper salinity impacts resulting from the downward migration of impacted groundwater through the existing sand). Induction conductivity and gamma logs from background wells correlated with borehole lithologies and did not indicate any significant impact. Conductivity values in a sandy layer at D-MW3, a water table well near the EMS, were elevated and correlated with high Cl^- and NH_3-N concentrations measured in the well. The elevated conductivity values and concentrations in D-MW3 imply seepage from the EMS has occurred.

At CFO-3, logged EC readings from direct-push measurements, taken in August 2010, ranged from 0 to 420 mS m^{-1}. The EC values generally were higher near the EMS and near the bottom of the soil profile (i.e., top of the bedrock or total depth of investigation). No observable plume was identified through sampling activities, as EC readings were not noticeably greater in the assumed downgradient direction of groundwater flow as compared to upgradient readings. Generally, readings were higher to the east and north of the EMS, although background readings may have potentially been affected by activities on the cropped field upgradient of the EMS. Higher readings near the EMS occurred near the bedrock surface, while higher EC readings near the field occurred relatively close to the ground surface (i.e., shallower).

The EM results at CFO-4 delineated elevated terrain conductivity zones surrounding the EMS and extending towards the north (Figure 4.35) (WorleyParsons 2012). Groundwater chemistry data from the wells adjacent to the EMS and within the zones of elevated terrain conductivity suggest groundwater impacts from 2.9 to 7.5 mbgs. The ERT line between the lagoon and the building on the east side of the EMS delineated conductivity values along the length of the EMS within the top 5 mbgs. This correlated with the EM results and corresponded to depths of impacted groundwater at B-MW2. There were also elevated conductivity values to depths of approximately 16 mbgs on the east side of the EMS, although the origin of this (i.e., salinity impacts or other) is unknown. Elevated terrain conductivity values observed north of the EMS and building may be due to impacts to the shallow groundwater originating from the EMS; however, due to the lack of intrusive information north and east of the EMS, this interpretation cannot be confirmed. Conductivity and gamma logs collected in the water table wells fit with the recorded lithologies. However, conductivity values recorded above 4 mbgs in the water table wells near the EMS were unusually high for clay, indicating seepage from the EMS may have occurred. A definitive interpretation based on the induction conductivity and gamma logs was not possible due to poor background readings.

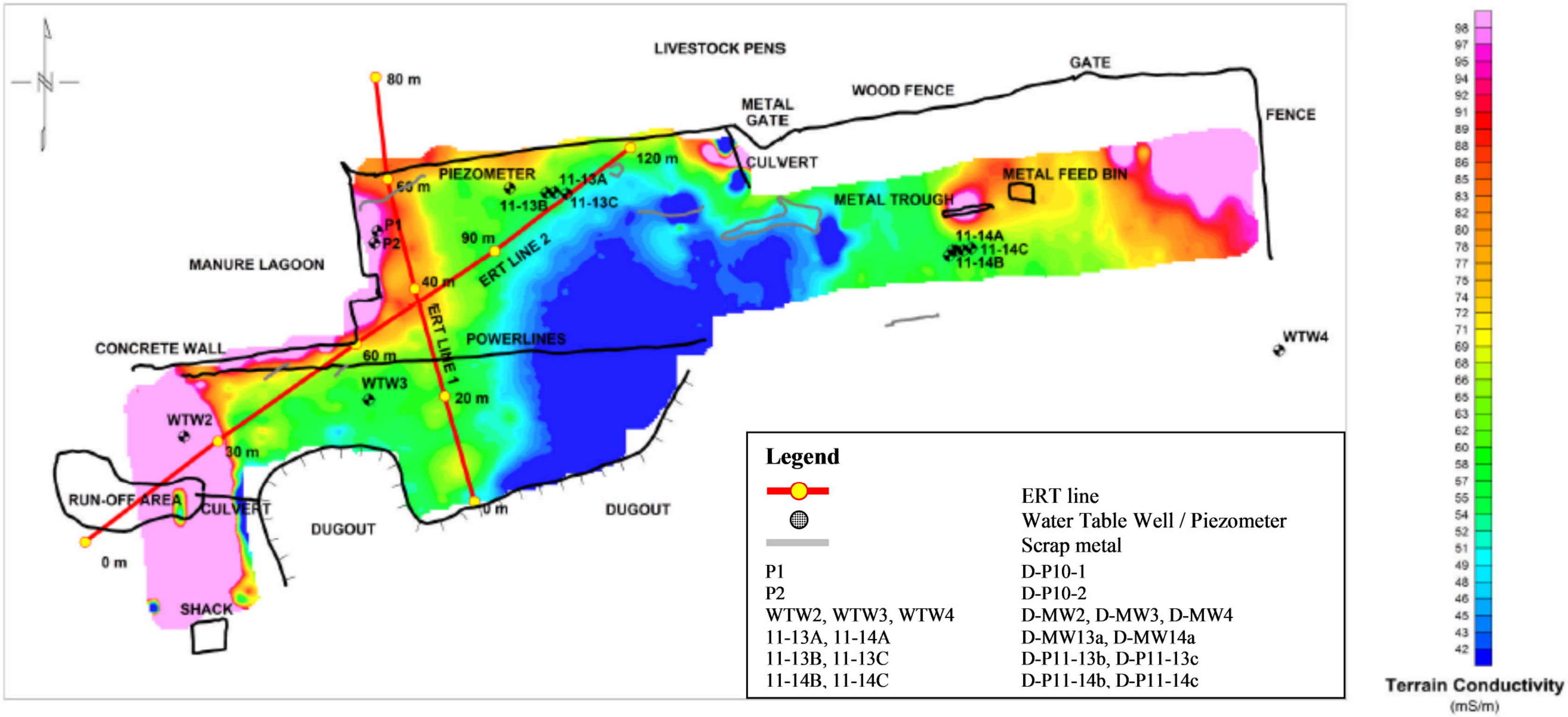


Figure 4.34. The EM31 terrain conductivity at CFO-1 in October 2011. Adapted from WorleyParsons (2012).

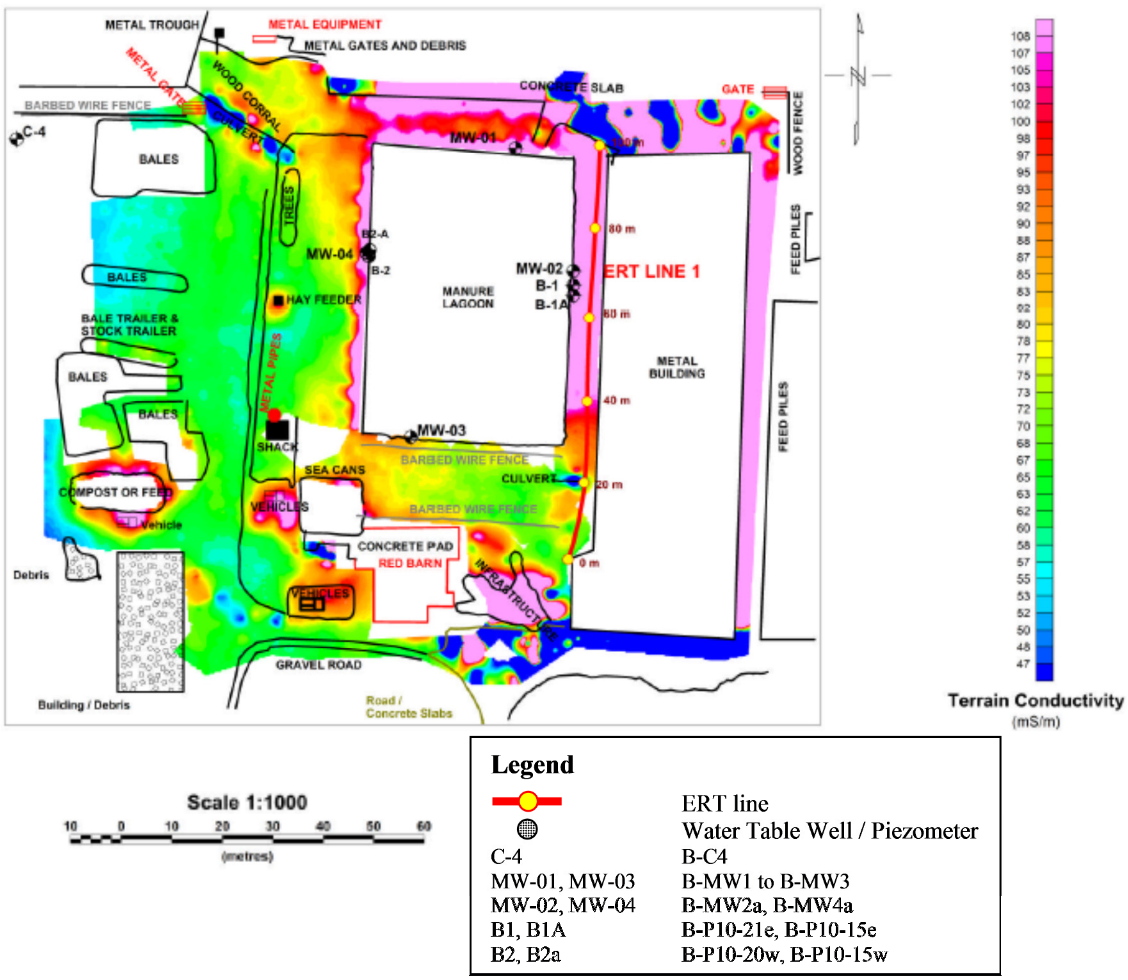


Figure 4.35. The EM31 terrain conductivity at CFO-4 in October 2011. Adapted from WorleyParsons (2012).

4.4 Summary and Future Work

4.4.1 Summary

Five CFOs were selected to determine the risks to groundwater quality from manure collection and storage facilities: two in southern Alberta, near Picture Butte in the Battersea area (CFO-1 and -2), and three in central Alberta, in the Lacombe-Ponoka region (CFO-3, -4 and -5). The CFO-1 site includes a dairy with an EMS and a feedlot with pens and a catch basin. The CFO-2 site is a feedlot with pens and catch basins. The three CFOs in central Alberta are dairies, each with an EMS. The sites represent different geological/hydrogeological conditions. The following are key findings from each CFO.

Nitrate N, Cl^-, and NH_3-N concentrations varied among nest locations and well completion depths at CFO-1. The highest NO_3^--N, Cl^-, and NH_3-N concentrations were measured in wells surrounding the EMS. Elevated concentrations in the wells surrounding the EMS may indicate the impact of the liquid manure storage. Elevated NO_3^--N and NH_3-N concentrations in a deep piezometer near the EMS may indicate downward movement of contaminants. Similar results were observed for the catch basin. Generally, a temporal trend was not observed at CFO-1.

Ammonia N concentrations at CFO-2 were highest in the downgradient wells, specifically at LB8a-6 and LB8a-7. However, Cl^- and NO_3^--N concentrations were elevated throughout the site, including wells upgradient of the feedlot pens on the east and southeast boundary of the site, downgradient wells, and wells near the catch basins. Chloride, NO_3^--N, and NH_3-N concentrations were low in the deepest piezometer. Elevated Cl^- and NO_3^--N concentrations greater than 10 mg L^{-1} in nearly all water table wells at CFO-2 indicate agricultural activities are influencing shallow groundwater; however, the elevated concentrations in the upgradent wells indicate the source may be from manure spreading areas upgradient of the CFO in addition to the CFO itself. Downward movement for manure constituents from the CFO is not occurring.

Nitrate N and Cl^- concentrations at CFO-3 were generally higher in water table wells surrounding the EMS, with concentrations in the deepest piezometers less than or close to the MMDL. Elevated concentrations in the wells surrounding the EMS may indicate the impact of the liquid manure storage. Fluctuations with time were observed in some of the shallower water table wells with no seasonal or temporal patterns observed in deep piezometers.

Nitrate N and Cl^- concentrations at CFO-4 were elevated in the water table wells surrounding the EMS relative to the background well and deep piezometer. However, the highest NO_3^--N and Cl^- concentrations were not found in the same wells. Ammonia N concentrations were typically low in all wells. These data suggest the EMS may be impacting the shallow groundwater. Chloride and NO_3^--N concentrations fluctuated with time in shallow water table wells near the EMS at CFO-4; however, a strong seasonal or temporal pattern was not observed for Cl^-.

Chloride and NO_3^--N concentrations at CFO-5 were generally higher in shallow water table wells surrounding the EMS than in the upgradient field water table well or deeper piezometers surrounding the EMS. Ammonia N concentrations were generally low, but relatively higher in the deeper piezometers and the water table well downgradient from the EMS compared to the other water table wells. No temporal or seasonal pattern was apparent for NO_3^--N or Cl^- concentrations at CFO-5. Similar to the other CFOs, the elevated concentrations in the shallow wells around the EMS indicate leaching from the liquid manure storage may be impacting the shallow groundwater. Elevated NH_3-N concentration at depth also indicates manure constituents have moved to depth at this site.

Preliminary geophysical investigation at CFO-1 suggested that a groundwater plume of higher conductivity may be east from the EMS. The EM31 results at CFO-1 delineated zones of elevated terrain conductivity values south of the EMS, along the south and east edges of the EMS, and extending to the east adjacent to the pens in the northeast corner of the site. The potential salinity impacts are likely deeper than 1.5 mbgs south of the EMS, while the potential salinity impacts are primarily concentrated in the near surface in the east portion of the site (i.e., between the feedlot pens and catch basin).

Geophysical investigation at CFO-3 did not identify a significant observable plume, as electrical conductivity readings were not noticeably greater in the assumed downgradient direction of groundwater flow from the EMS as compared to upgradient readings. Higher readings near the EMS occurred near the bedrock surface, while higher EC readings near the field occurred closer to the ground surface (i.e., shallower).

At CFO-4, the EM results showed elevated terrain conductivity zones surrounding the EMS and extending towards the north. Combined results suggested groundwater impacts from 2.9 to 7.5 mbgs. There were also elevated conductivity values to depths of approximately 16 mbgs on the east side of the EMS, although the origin of this (i.e., salinity impacts or other) is unknown. Elevated terrain conductivity values observed north of the EMS and building may be due to impacts to the shallow groundwater originating from the EMS. However, due to the lack of intrusive information north and east of the EMS, this interpretation cannot be confirmed.

4.4.2 Future Work

The following activities are planned at the CFOs:

- Conduct hydraulic conductivity testing on representative wells at each CFO.
- Conduct groundwater sampling and analysis four times during the year.
- Collect manure samples from the EMS at each dairy operation and the catch basins at the two feedlots.
- Continue to explore options for monitoring liquid levels at the EMS sites.
- Collect data from the PVP instrumentation at CFO-1 and -2.
- Conduct a water balance at each EMS.
- Determine whether additional instrumentation is required at CFO-3, -4, and -5 to further assess the impacts these facilities on groundwater quality.
- Identify areas around the existing CFOs in central Alberta and initiate instrumentation for an assessment of manure spreading activities in central Alberta.
- Carry out geophysical measurements at CFO-3 and CFO-5.
- Continue to collect surrounding land use and management data to assist in interpretation.