5 BATTERSEA DRAIN FIELD

5.1 Introduction and Hypotheses

The Battersea Drain Field (BDF) site was an irrigated field in the Battersea Drain Watershed, which is an area with a high density of confined feeding operations and irrigated crop production. The BDF site had a long history of cattle manure application and this resulted in high nutrient concentrations in the soil. Previous studies have found high concentrations of soil-test phosphorus (STP) with values ranging from 646 to 1476 kg ha^{-1} (about 323 to 738 mg kg^{-1}) in the top 15 cm of soil in 2002 (Riemersma et al. 2004).

The main concerns for this site were the elevated STP concentration, and the high concentrations of phosphorus (P), nitrogen (N), sediment, and bacteria in the edge-of-field runoff. Soil and water quality were monitored for 2 yr (2007 and 2008) prior to the implementation of the beneficial management practices (BMPs) in 2009. The BMPs were designed to address (1) the source of nutrients and (2) the transportation of nutrients from land to surface water. To reduce the source of nutrients, the BMPs that were implemented included (1) the cessation of P application including manure and (2) a nutrient management plan for N. Irrigation management BMPs were implemented to address the transportation of nutrients, and these included (1) a modification of the pivot irrigation system and (2) the utilization of the Alberta Irrigation Management Model (AIMM) to schedule irrigation events. Water was monitored at this site with six stations: two stations on the Battersea Drain, which passed through the field, and four edge-of-field stations.

The underlying assumption was that the over-application of manure caused excessive nutrients in the soil, making these nutrients, as well as fecal bacteria, more susceptible to loss in rainfall, snowmelt, and irrigation runoff at this site. The hypotheses were:

- The cessation of manure application BMP would reduce STP, soil nitrate nitrogen (NO_3-N), and soil ammonium (NH_4-N) concentrations, and subsequently reduce dissolved P and N

concentrations in runoff. Reductions in *Escherichia coli* (*E. coli*) concentrations were also expected.

- The irrigation management BMPs would reduce the amount of irrigation runoff and nutrient load loss.

5.2 Methods

5.2.1 Site Description and Management

The BDF site was located on a quarter section of land in the Battersea Drain Watershed, and was about 30 km northeast from Lethbridge (Figure 5.1). The site was in an area of high agricultural intensity including confine feeding operations and irrigated crop production. The field (65 ha) was bisected by the Battersea Drain from the southwest to the northeast corners (Figure 5.2). A dugout for the landowner's feedlot was in the southwest corner of the field, and a smaller dugout for the pivot irrigation system was in the northwest corner. Both dugouts were filled from a small lateral irrigation canal just before the irrigation flow discharged in the Battersea Drain at the southwest corner upstream from the BDF site.

The soil at most of the site was an Orthic Dark Brown Chernozem in the LET13/U1h soil landscape models with well drained characteristics, as described by the Agricultural Region of Alberta Soil Inventory Database (AGRASID) (Alberta Soil Information Centre 2013). For this soil landscape model, the dominant (60% or more) soil series is Lethbridge with significant (10 to 30%) Kessler and Miscellaneous Saline-ZDB series. Landform is described as undulating, high relief, with a limiting slope of 4%. Parent material consists of medium-textured and very coarse sediments deposited by wind and water, as well as some undifferentiated material. The surface soil had a sandy-loam texture (57.3% sand, 14.8% clay), pH of 7.2, electrical conductivity of 1.2 dS m^{-1}, 1900 mg kg^{-1} TN, 1026 mg kg^{-1} TP, and 4.0% organic matter (Appendix 4).

During the study, the 4-yr crop rotation used was barley silage (*Hordeum vulgare*), potato (*Solanum tuberosum*), corn silage (*Zea mays*), and canola (*Brassica napus*) (Table 5.1). The landowner rented the field to a different producer in years when potatoes were grown. Irrigation water was applied using a low-pressure, drop-tube, centre pivot irrigation system. The irrigation system consisted of six spans plus a corner-arm span, which moved into position when in the corners of the field (Figure 5.3). Prior to the implementation of the BMP plan in fall 2008, the field regularly received applications of beef cattle manure.

Runoff water from the field drained into the Battersea Drain almost exclusively through four drainage points where the edge-of-field monitoring stations were installed (Figure 5.2). There were existing grassed buffer areas at the four edge-of-field drainage points. These buffers, originally composed of a salt tolerant mixture of tall fescue (*Festuca arundinacea*), tall wheatgrass (*Thinopyrum ponticum*), slender wheatgrass (*Agropyron trachycaulum*), smooth bromegrass (*Bromus inermis*), and alfalfa (*Medicago sativa*), were established in June 2002 as part of another study (Riemersma et al. 2002 unpublished). A berm was constructed in the spring 2007 at southwest edge of the field to ensure that runoff flowed to the drainage point where the monitoring station (Station 206) was installed. The grass buffer was reseeded after the berm was constructed.

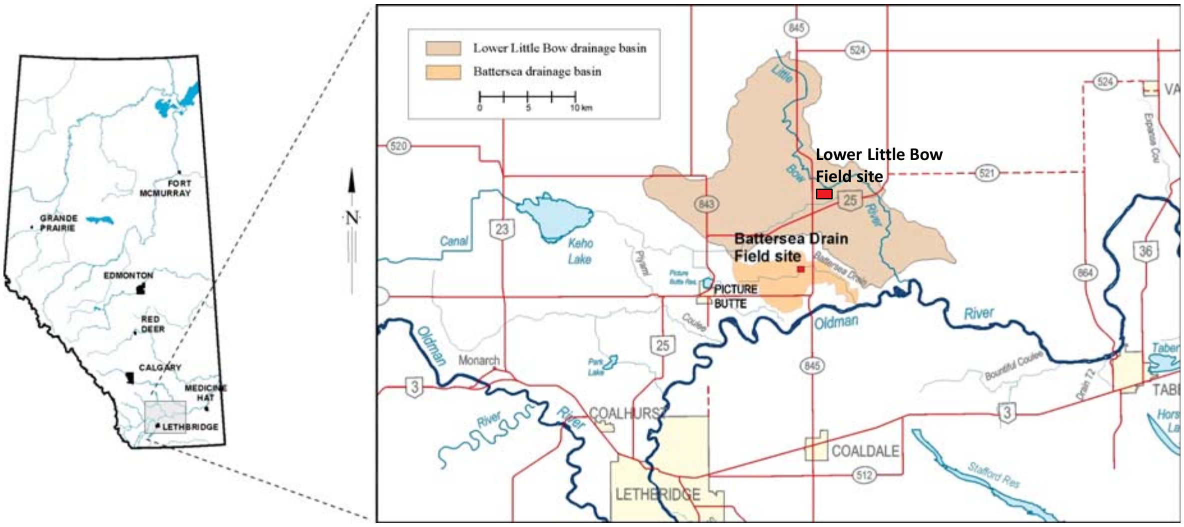

Figure 5.1. Location of Battersea Drain Field and Lower Little Bow Field sites.

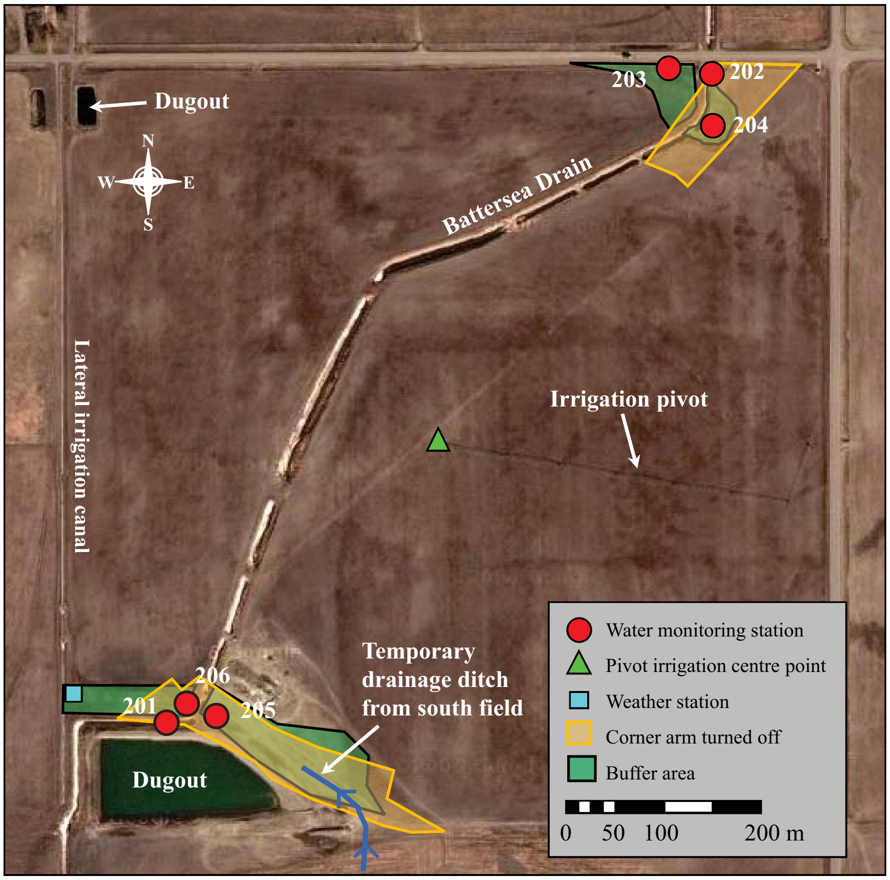

Figure 5.2. Battersea Drain Field showing the Battersea Drain, the upstream (Station 201), downstream (Station 202), and four edge-of-field (Stations 203, 204, 205, and 206) water monitoring stations as well as the grassed buffers and the areas where irrigation was controlled by the pivot irrigation system modification BMP.

Table 5.1. Annual crop rotation and yield at the Battersea Drain Field from 2007 to 2008 (pre-BMP period) and from 2009 to 2012 (post-BMP period).

Year	Crops	Seeding date	Harvest date	Yield (Mg ha^{-1})
2006	Barley silage	na[z]	na	na
2007[y]	Potato	May 3	Oct. 2	na
2008[x]	Corn silage	mid-May	Oct. 10-11	36[w]
2009[x]	Canola	May 5	Sep. 16	1.1
2010[x]	Barley silage	Apr. 23	Aug. 6	25.9[v]
2011[u,t]	Potato	May 3-6	Sep. 19-21	54
2012[s]	Corn silage	May 10	Sep. 21	38.3[w]

[z] na = not available.
[y] Cattle manure was applied on October 12, 2007 at a rate of 135 Mg ha^{-1} (wet weight).
[x] No manure or commercial fertilizers were applied as part of the beneficial management practices (BMP) plan.
[w] Dry weight.
[v] Wet weight.
[u] Nitrogen fertilizer was applied (112 kg ha^{-1}) as part of the BMP plan. Calcium was also applied to the field.
[t] Cattle manure was applied (228 Mg ha^{-1} wet weight) on the west side of the Battersea Drain on September 21, 2011 and on the east side of the Battersea Drain in mid-October after October 13, 2011.
[s] From a nutrient-source perspective, the post-BMP period ended when manure was applied in fall 2011.

Figure 5.3. The centre pivot irrigation system showing the main system of six spans (left) and the corner-arm span (right) at the Battersea Drain Field.

5.2.2 Implementation of Beneficial Management Practices

5.2.2.1 Nutrient Source Management

The nutrient source BMPs consisted of (1) the cessation of P application, including manure, because of the high STP concentration and (2) an annual crop nutrient management plan to determine optimum soil N for crop growth.

Prior to the implementation of the BMP plan, manure was last applied and incorporated with double discs in the fall 2007 (October 12) during the pre-BMP period at a rate of 135 Mg ha^{-1} (wet weight). The cessation of manure application began in fall 2008. No manure, or any form of P, was to be applied for the duration of the study. Unfortunately, manure was applied in fall 2011 at a rate of approximately 228 Mg ha^{-1}(wet weight), which ended the post-BMP period from a nutrient source perspective 4 yr after the previous manure application. The manure was applied first on the west of the Battersea Drain immediately after harvest on September 21, 2011. The east side of the drain received manure between October 13 and 20, 2011. In the 3 yr manure was not applied, manure was hauled to alternate fields. The alternate field in 2008 was the same distance from feedlot as the BDF site, but in 2009 and 2010, the alternate fields were at a greater distance. Net increase in manure hauling costs in 2009 and 2010 were estimated based on Toma and Bouma Management Consultants (2006).

The crop nutrient management plan consisted of annual fertilizer recommendation in the fall for the subsequent crop year, and this started in fall 2008. In each fall from 2008 to 2010, soil samples were collected and analyzed, and the soil-test results were used in the Alberta Farm Fertilizer Information and Recommendation Manager (AFFIRM; AFRD 2005b) program to determine nutrient recommendations for the following crop year. When manure was applied in fall 2011, no soil-test samples were collected and no nutrient management plan was developed for 2012. Phosphorus was not required and no P fertilizer was applied prior to the 2009 to 2011 crop seasons (Table 5.1). Nitrogen was also not recommended for the 2009 and 2010 crop seasons, and no N fertilizer was applied. However, N was recommended for the 2011 potato crop and 112 kg ha^{-1} of N fertilizer was applied.

5.2.2.2 Irrigation Transport Management

The irrigation management BMP consisted of two parts: (1) the pivot irrigation system modification and (2) the utilization of AIMM to schedule irrigation.

Pivot irrigation system modification. The pivot irrigation system generated runoff at the northeast (Station 204) and southwest (Stations 205 and 206) edge-of-field monitoring stations each time the pivot passed over these areas in the field. Station 203 was never affected by irrigation runoff. In order to reduce the volume of irrigation runoff, the pivot irrigation system was modified so some of the nozzles were turned off when the pivot was over the runoff sensitive areas (Figure 5.2). These areas were identified as the main source of runoff entering the Battersea Drain during irrigation events.

In the spring 2009, solenoid switches were installed on the corner arm (Figure 5.3) to switch the nozzles off and on over the runoff sensitive areas (Figure 5.2). In order to operate the new solenoid switches, the irrigation control panel was upgraded to a Reinke RPM preferred model (Reinke Manufacturing Company, Inc., Deshler, Nebraska, United States) (Figure 5.4). The control panel was programmed by the landowner to turn sprinklers off and on as required by the BMP. A global positioning system (GPS) mounted on the pivot communicated with the control panel to activate the solenoid switches.

Observations in 2009 showed that even with these modifications to the irrigation pivot system, runoff still occurred in the southwest corner of the field. Therefore, further modifications to the pivot irrigation system were done in spring 2010. Half of the nozzles on the last span of the main pivot system before the corner arm (Figure 5.3) were also instrumented with solenoid switches. The control panel was programmed so that these nozzles were turned off in the southwest corner but not in the northeast corner of the field.

The flow of water through the pivot irrigation system was measured using a McCrometer propeller flow meter (model RE100; McCrometer, Hemet, California, United States) at the pivot centre. The flow data were recorded by a datalogger (model CP-X; Lakewood Systems Ltd., Edmonton, Alberta, Canada) every 15 min.

Alberta Irrigation Management Model. The AIMM program is a decision support tool used to assist producers to plan irrigation to maximize crop production (ARD 2013a). In the current study, the model was used to forecast soil moisture and to schedule irrigation events to prevent plant water deficit and over irrigation.

The required input information for the model included crop type, seeding date, weather data, soil texture, initial soil moisture content, root-zone depth, allowed depletion of total available water (TAW), and daily irrigation amounts. The model used the American Society of Civil Engineers ASCE standardized evapotranspiration equation (modified Penman-Monteith equation) for calculating reference evapotranspiration (ARD 2013a).

Soil hydrologic properties used in the model include field capacity (FC), wilting point (WP), and TAW. These properties were based on soil texture and were calculated using Soil Pro, a program developed for use with the AIMM software. Total available water is the difference between WP and FC and is considered the amount of water available for crop use. Soil moisture values less than 50% TAW will generally result in crop water stress.

Figure 5.4. Control panel installed on the pivot irrigation system at the Battersea Drain Field in August 2012.

The model output showed FC, 50% TAW, site rainfall (mm), effective irrigation (mm), and the predicted moisture content of the soil prior to the run date of the model, i.e., left side of the prediction line in Figure 5.5. The model also predicted the amount of moisture the crop will use as well as the soil moisture during a set number of days into the future, i.e., right side of the prediction line in Figure 5.5. If the predicted soil moisture should intersect the irrigation threshold (50% TAW) within the model prediction period, then the output will indicate the date irrigation should begin in order to maintain soil moisture greater than 50% TAW.

Initial soil moisture content used for the AIMM model was determined by collecting soil samples from one representative location under the irrigation system. Samples were collected after the crop was seeded and a few weeks prior to the first irrigation event (Table 5.2). In 2010 and 2012, another soil moisture sample was taken in the middle of the irrigation season to verify the accuracy of the model output and to readjust the soil moisture content if required. The soil

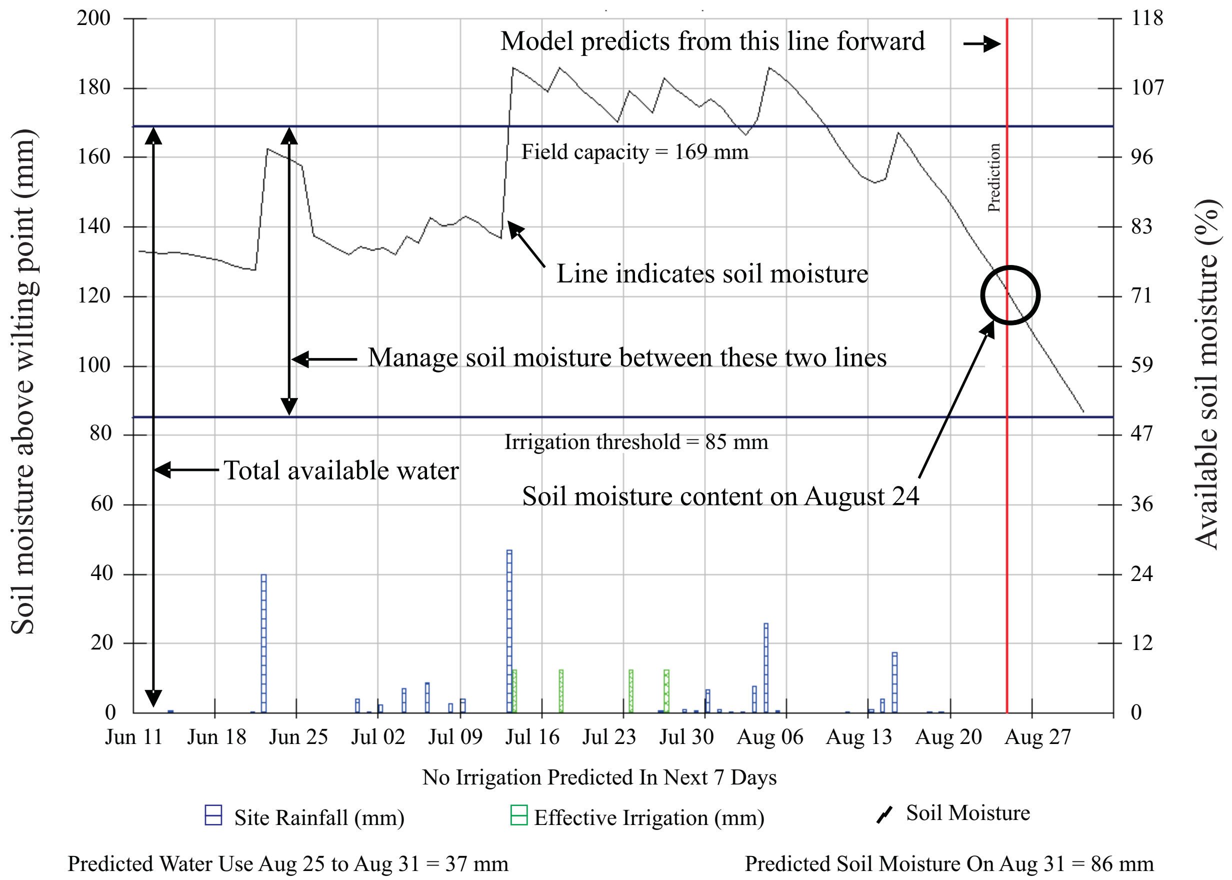

Figure 5.5. Example of output from the Alberta Irrigation Management Model with annotations. Note, in original output, the left y-axis was labeled as soil moisture (mm) and the right y-axis was labeled as soil moisture (%). These titles were replaced with more accurate descriptors.

moisture samples were taken in 25-cm increments to a depth of 1 m. The samples were analyzed for gravimetric moisture content and soil texture. Soil texture was determined by particle size analysis using the Bouyoucos 2-h method with a conversion to a 24-h reading (Karkanis et al. 1991). Soil moisture was determined by oven drying the samples at 105°C for 24 h. The available moisture content and particular size distribution for each 25-cm soil layer was calculated and used for the AIMM input data. Soil bulk density values were used to convert gravimetric moisture values to volumetric moisture values.

The initial measured TAW was used as the starting point for the model. The weather data used in the model were obtained from the Iron Springs weather station (Environment Canada 2013). Up to five rain gauges outside and inside the irrigated area were monitored twice weekly. The irrigation threshold was set at 50% of TAW and a 7-d prediction period was used. The model was run once per week and the AIMM output and irrigation recommendations were shared with the producer on a weekly basis.

5.2.3 Weather

An automated weather station (BWS1) was installed at the site in June 2008 (Figure 5.2), and the station recorded air temperature, precipitation, and relative humidity from June 2008 to September 2012 (Sub-section 2.4.2).

For comparison, the nearest Irrigation Management Climate Information Network (IMCIN) weather station from BWS1 was 5.6 km west near Iron Springs, Alberta. Data from Iron Springs (IMCIN) were downloaded through AgroClimatic Information Services (ARD 2013b). Lethbridge CDA (Canada Department of Agriculture) weather station provided the nearest 30-yr average values from historical data (1971 to 2000) (Environment Canada 2013), which were not available from the Iron Springs station.

5.2.4 Soil Sampling

Soil characterization samples (Sub-section 2.9) were collected from six sites within the field on September 8, 2010 (Figure 5.6). Soil samples collected annually at this site included 0- to 15-cm

Table 5.2. Soil moisture sampling dates and measured total available water from 2009 to 2012 at the Battersea Drain Field.

Year	Initiation sampling date	Initial measured total available water (mm)	Adjustment sampling date	Adjusted measured total available water (mm)
2009	June 12	142	-	-
2010	April 27	143	July 13	70
2011	June 1	138	-	-
2012	May 28	109	Jul 10	112

agronomic samples from 2007 to 2012 (Figure 5.7) and 0- to 60-cm soil-test samples for the AFFIRM program from 2008 to 2010 (Figure 5.6) (Sub-section 2.9). Other soil samples collected included (1) 0- to 2.5-cm surface samplings in 2011; (2) deep-core samples in 2009, 2011, and 2012; and (3) buffer area samples in 2012.

Soil-test samples were generally sampled using transects based on field topography (Sub-section 2.9); however, there was an exception in 2010. Due to time constraints, soil-test samples were collected in conjunction with the agronomic samples using the 200-m grid (Figure 5.7). It was assumed that due to the relatively low topographic relief of the field the grid captured variations within the field and provided representative samples comparable to the transect method.

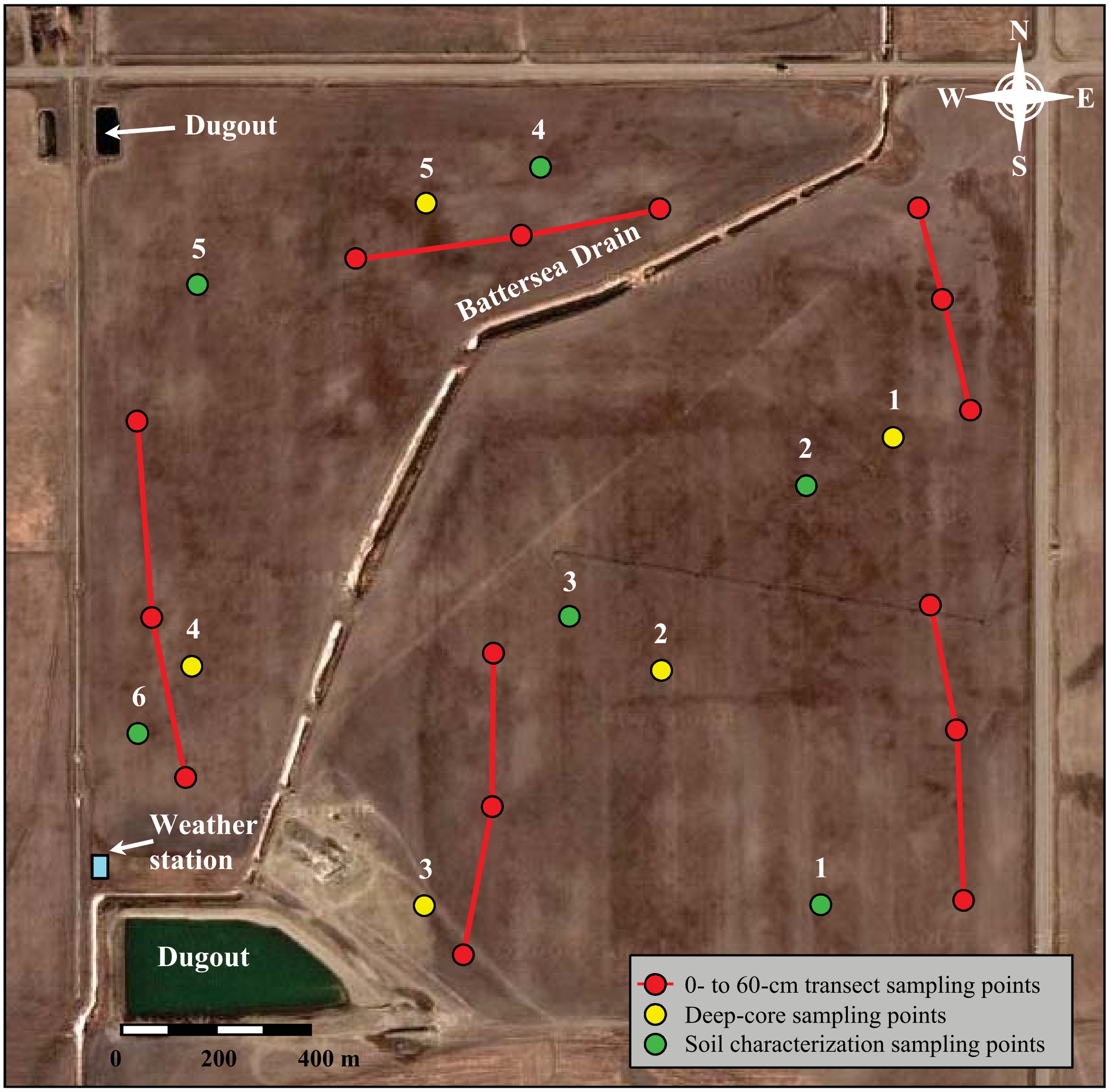

Figure 5.6. Soil sampling points at the Battersea Drain Field.

In fall 2011, manure was applied to the site after 4 yr without manure application. To determine the effect of this manure application on extractable N and P in soil, the 0- to 15-cm agronomic samples were collected twice in fall 2011: pre- (September 30) and post-manure (November 28) application. In addition to the 0- to 15-cm samples, 0- to 2.5-cm surface samples were collected in fall 2011 using the frame-excavation method described by Nolan et al. (2006, 2007). A 11- by 60-cm steel frame was driven into the ground until the top of the frame was at ground level. The soil sample was collected from within the frame with a 2.5-cm deep shovel. Manure was applied to the west side of the drain before the pre-manure sampling, and as a result, only the 10 sampling points

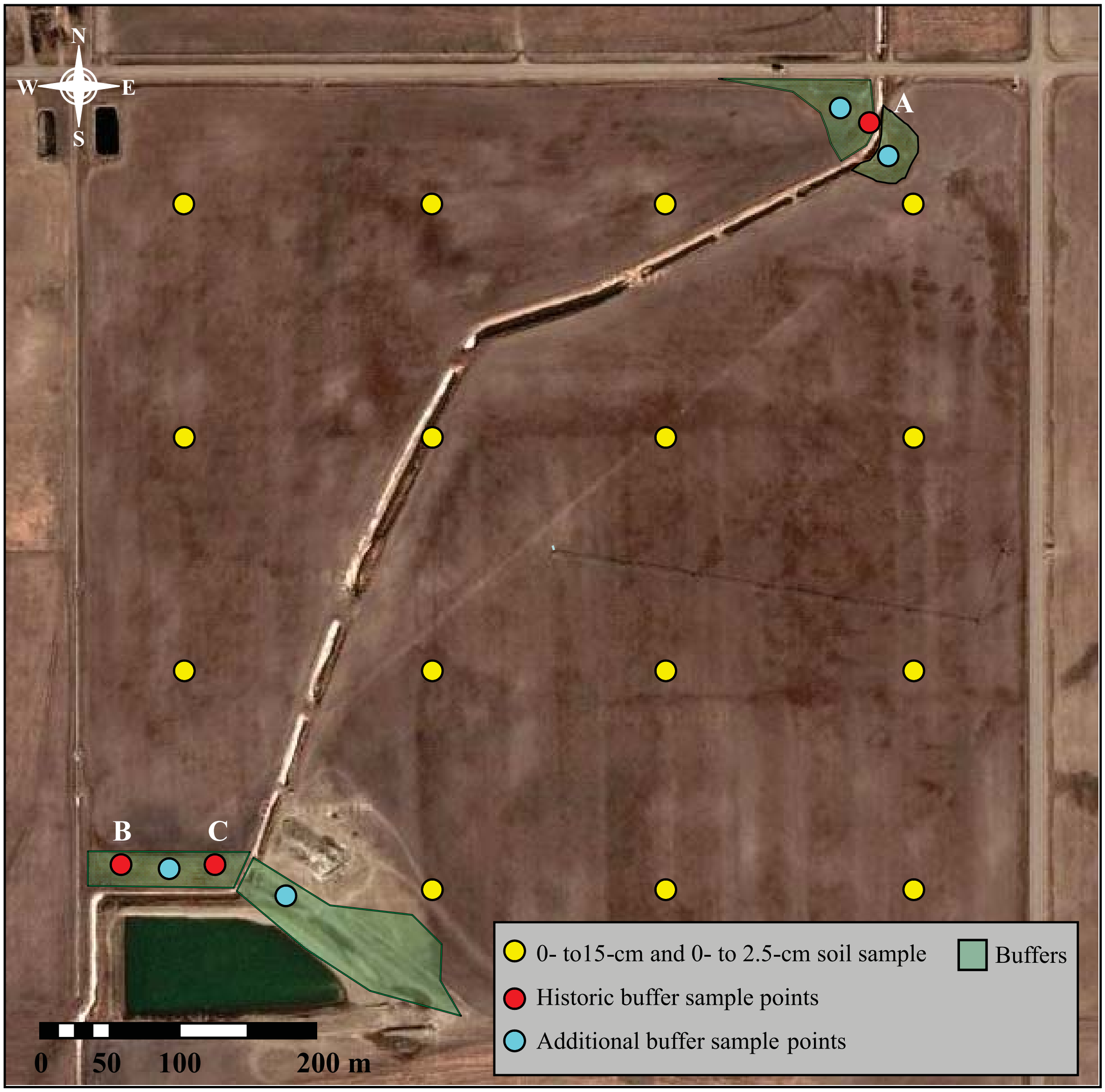

Figure 5.7. Agronomic and grass buffer soil sampling locations at the Battersea Drain Field.

on the east side of the drain were used for the 0- to 15-cm and 0- to 2.5-cm samples (Figure 5.7). All 15 sampling points were used after manure application. Data from only the 10 sampling points on the east side of the drain were used to compare the pre- and post-manure nutrient concentrations in soil. The application of manure in 2011 ended the post-BMP period. Therefore, the pre-manure soil data from the 10 sampling points on the east side of the drain were used as part of post-BMP dataset.

In September 2012, soil samples were collected from the four grass buffers in order to compare nutrient concentrations between the buffers and the field. One location was selected per buffer, and at each sampling point, a Dutch auger was used to collect five core samples (0 to 15 cm), which were mixed into a composite sample. During a previous study at this site, prior to the establishment of the forage buffers in 2002, baseline soil samples were collected in 2001 by Riemersma et al. (2004). Three of those baseline sampling locations were within the buffer areas and they were resampled in September 2012 (Figure 5.7; sample points A, B, and C). Data from sample point A was discarded due to its close proximity to the Battersea Drain.

5.2.5 Manure Sampling

Solid beef manure samples were collected on October 15, 2007 and September 21, 2011. In 2007, nine samples were collected from the manure stockpile at the producer's feedlot. The samples were collected from various areas of the stockpile. Sampling points were approximately 200 m apart. At each sample location, three grab samples were collected, mixed in a bucket, and sub-sampled (0.5 kg) for moisture and chemical analysis (Sub-section 2.10). In 2011, manure samples were collected in a similar manner from six locations in stockpiled manure in the field prior to spreading.

5.2.6 Water Flow and Quality

Six water monitoring stations were established at the BDF site. Two were instream stations, upstream (Station 201) and downstream (Station 202) in the Battersea Drain (Figure 5.2). The other four stations were edge-of-field stations: two on either side of the Battersea Drain near the northeast corner of the site (Stations 203 and 204) and two on either side of the drain near the southwest corner of the site (Stations 205 and 206). Most of the runoff at the BDF site drained through these four edge-of-field stations and directly into Battersea Drain. The drainage area for each edge-of-field station was within the field, and these four drainage areas combined was 32 ha in size and represented about 50% of the area of the field (Jedrych et al. 2013). About 5% of the field did not drain towards the Battersea Drain. Each edge-of-field station was equipped with a circular flume and an Isco water sampler. The upstream Station 201 and downstream Station 202 were each equipped with a staff gauge and an Isco sampler. Station 202 was also equipped with an Acoustic Doppler Current Profiler (ADCP) for direct flow measurements (Sub-section 2.7). Data collection began in late June 2007. Flow data from an existing monitoring station, which was about 20 m upstream from Station 202, were used to supplement the hydrograph for Station 202 from early May to late June 2007. Flow was not measured at the upstream station because it was assumed that differences in flow between the two instream stations, separated by about 950 m, were less than the flow measurement error. Outside of the irrigation season, the flow in the drain was too low to be measured by the ADCP. Low flow was estimated based on previous long-term monitoring data at this site (unpublished data).

The system was designed so that the four edge-of-field stations were masters to the two instream stations. Water sub-samples were collected every 15 min by the Isco samplers during all runoff events detected at an edge-of-field station, which simultaneously triggered both instream water monitoring stations to sample. Furthermore, grab samples were also taken from the two instream stations bi-weekly during the irrigation season (May to October) and monthly during the rest of the year, unless runoff was observed during the scheduled sampling day.

Runoff events were characterized as snowmelt, rainfall, irrigation, or combined irrigation and rainfall. The last category was defined as a runoff event that occurred when a minimum of 25 mm of rainfall occurred during irrigation. Combination events with less than 25 mm of rainfall were classified as irrigation. There were combined irrigation and rainfall runoff events in 2009 (post-BMP year), but these events were deemed to be more similar to rainfall runoff and were analyzed statistically as such since there were no other comparable events in the pre-BMP period (2007 and 2008).

A channel was trenched by the landowner from the quarter section south of Station 205 in spring 2010 (Figures 5.2 and 5.8). The channel was constructed to drain pooled runoff water, which was caused by rainfall in May. Samples collected at Station 205 that were affected by runoff from the south field were not included in the data analysis.

Periodically, high flow in the Battersea Drain backed up into the circular flumes, and this was particularly problematic for Stations 204 and 205. Flow measurements under these conditions were omitted from annual flow and load calculations. Any time there was back-up water from the drain, water samples were not collected or the data were not included in descriptive statistics and testing for significant differences.

Figure 5.8. Drainage channel from the quarter section to the south of Battersea Drain Field in 2010.

Due to the larger variation in water quality parameter concentrations caused by flow conditions rather than event types (snowmelt, rainfall, and irrigation), the water quality data at the in-stream stations (Stations 201 and 202) were grouped by flow conditions. High-flow events in the Battersea Drain occurred when irrigation source water flowed in the drain during the irrigation season from about mid-May to mid-October. Low-flow events in the Battersea Drain occurred outside of the irrigation season when the irrigation source water was turned off from about mid-October to mid-May. The pre-BMP period included water quality data from March 14, 2007 to October 8, 2008. The post-BMP period started in mid-October 2008 when manure was not applied to the field as part of the BMP plan.

For water quality comparisons, the pre-BMP period was 2007 and 2008 and the post-BMP period was from 2009 to 2011. The 2012 water quality data were not included in the post-BMP period because manure was applied at this site in fall 2011. Loads were also calculated (Sub-section 2.8.4). The concentration of water quality parameters were compared between the pre- and post-BMP periods for the upstream and downstream stations and the edge-of-field stations. A description of statistical analysis for upstream-downstream stations and for edge-of-field stations is provided in Sub-section 2.8.4.

5.3 Results and Discussion

5.3.1 Weather

Annual average daily temperature was generally less than the 30-yr average, except for 2007 (Table 5.3). Overall, 2009 had the coolest average temperature compared to the other years. Nine months in 2009, 2010, and 2011 had average temperatures less than the 30-yr averages. The growing season (May to September) average temperatures were less than the 30-yr average from 2008 to 2011 and greater than the 30-yr averages in 2007 and 2012.

Total annual precipitation was 6 to 24% higher than the 30-yr average from 2008 to 2011 (Table 5.4). Precipitation was 27% less than the 30-yr average in 2007 and very similar to the 30-yr average in 2012. In 2007, nine months were well below the monthly 30-yr averages, and this was consistent during the second half of the year. July 2007 was particularly dry. During the study period, April to July often had monthly precipitation above average. This was also true for October and November during the fall period. The largest total monthly precipitation occurred in June 2012, and was more than double the 30-yr average for that month. The months that exceeded average values the most was in October 2009 and 2011, with total amounts three and four times the 30-yr monthly average.

Table 5.3. Monthly, annual, and growing season average daily temperature for the Iron Springs weather station from 2007 to 2012 (ARD 2011). The 30-yr (1971 to 2000) average values are from the Lethbridge CDA weather station.

Time period	2007	2008	2009	2010	2011	2012	2007-2012 average	30-yr average
	----------	----------	----------	----------	(^{o}C)	----------	----------	----------
January	-3.4	-7.6	-7.6	-6.3	-9.5	-3.7	-6.4	-7.8
February	-7.1	-5.6	-6.7	-5.2	-9.1	-3.8	-6.3	-4.6
March	3.5	0.6	-2.5	3.7	-4.5	2.4	0.6	-0.2
April	4.5	3.0	4.8	5.2	3.0	6.9	4.6	6.0
May	11.7	11.6	10.7	8.2	10.0	10.7	10.5	11.3
June	15.6	14.3	13.8	14.3	13.8	14.6	14.4	15.5
July	21.4	16.8	16.6	16.8	17.3	19.4	18.0	18.0
August	16.5	16.8	16.3	15.3	17.3	18.2	16.7	17.7
September	11.1	11.4	15.4	10.5	15.2	14.2	13.0	12.6
October	7.6	6.9	2.8	8.3	6.9	3.5	6.0	7.0
November	-0.4	3.2	2.9	-3.9	-0.6	-2.0	-0.2	-1.5
December	-7.3	-10.6	-12.3	-8.3	-1.1	-8.5	-8.0	-6.1
Annual (Jan to Dec)	6.2	5.1	4.6	4.9	5.0	6.0	5.2	5.7
Growing season (May to Sep)	15.3	14.2	14.5	13.0	14.7	15.4	14.5	15.0

Table 5.4. Total precipitation for the Iron Springs weather station from 2007 to 2012 (ARD 2011). The 30-yr (1971 to 2000) average values are from the Lethbridge CDA weather station.

Time period	2007	2008	2009	2010	2011	2012	2007-2012 average	30-yr average
	----------	----------	----------	----------	(mm)	----------	----------	----------
January	5.0	7.1	9.9	12.6	21.3	4.0	10.0	20.1
February	24.6	6.3	11.9	5.5	9.9	9.5	11.3	12.2
March	13.0	9.0	9.3	6.6	19.2	7.6	10.8	27.5
April	51.6	14.4	28.6	95.0	53.8	39.5	47.2	32.5
May	78.9	77.2	29.7	101.4	80.5	47.4	69.2	48.3
June	23.2	101.9	62.7	72.2	59.3	110.0	71.5	53.0
July	0.5	55.0	82.9	34.7	49.1	41.4	43.9	37.2
August	5.1	30.2	58.7	49.6	17.4	30.9	32.0	47.4
September	28.5	57.4	5.7	33.7	5.3	9.1	23.3	38.3
October	9.6	4.8	53.9	5.2	63.6	36.1	28.9	15.1
November	4.1	20.8	14.1	27.3	4.2	21.7	15.4	14.8
December	10.8	24.8	19.1	7.1	6.9	10.6	13.2	18.6
Annual (Jan to Dec)	254.9	408.9	386.5	450.9	390.5	367.8	376.6	365.0
Growing season (May to Sep)	136.2	321.7	239.7	291.6	211.6	238.8	239.9	224.2

The end of May and early June in 2008 was a particularly wet period with about 165 mm of rainfall (Figure 5.9). Other major precipitation events of note included 40 mm on May 22, 2009, 47 mm on July 13, 2009, 64 mm on May 27, 2010, 40 mm on July 12, 2011, and 57 mm on October 6, 2011. Even though June 2012 had the largest amount of precipitation in a single month during the study, the total amount was distributed throughout the month with 31% (34 mm) of the total amount falling on June 5.

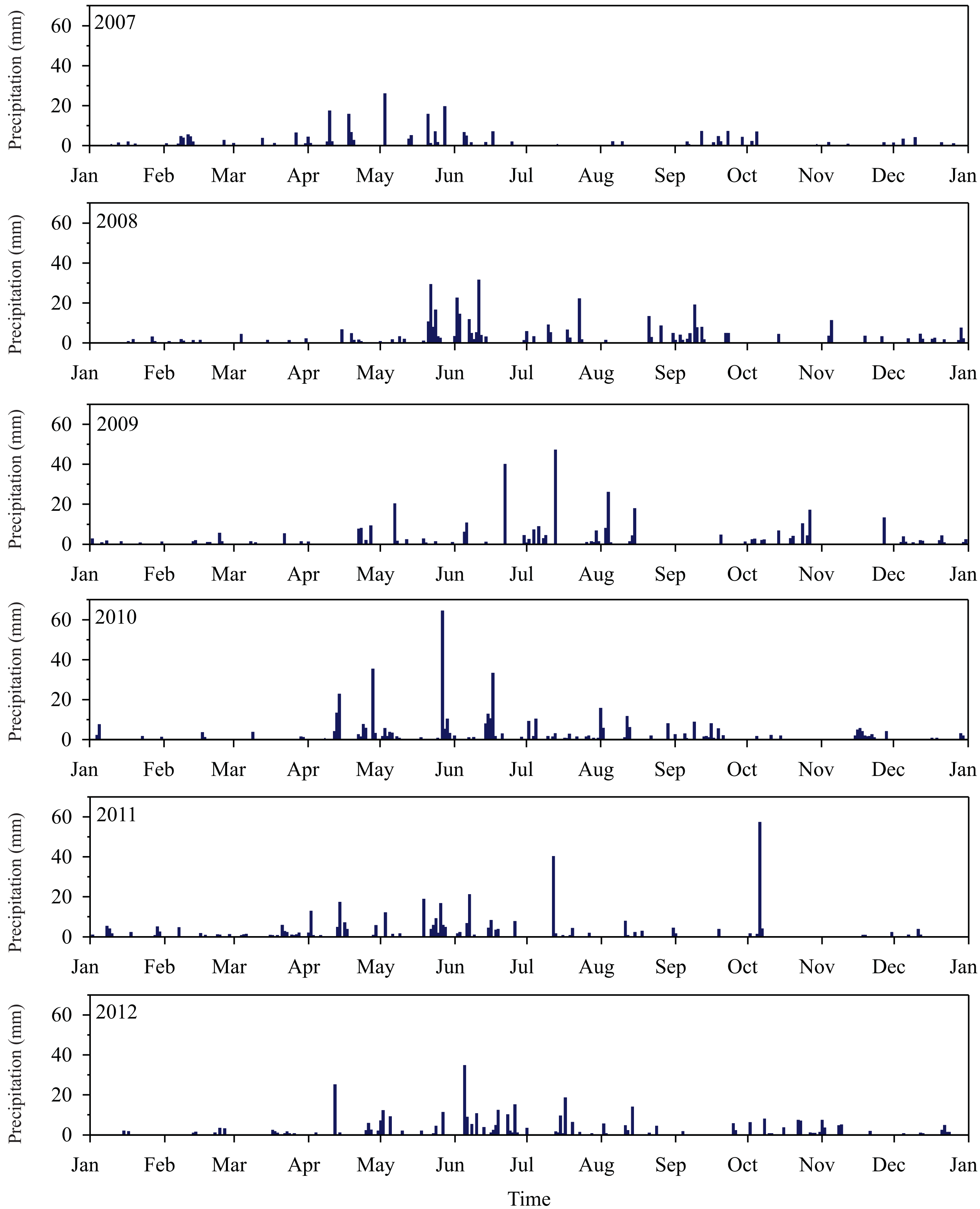

Figure 5.9. Total daily precipitation at the Iron Springs weather station from 2007 to 2012.

The pre-BMP years (2007 and 2008) were generally warmer and drier than the post-BMP years (2009 to 2012). The average temperature was 5.7 °C for the pre-BMP years and 5.1 °C for the post-BMP years. The average annual precipitation was 332 mm for the pre-BMP years and 399 mm for the post-BMP years.

Annual total precipitation at the BDF weather station was similar to the Environment Canada Iron Spring station (Figure 5.10) in 2009 and 2010. The difference was greatest in 2011 when about 20% more precipitation was recorded at the BDF weather station compared to the Iron Springs weather station.

5.3.2 Manure

The water content of the manure applied in 2011 was higher compared to the manure used in 2007 (Table 5.5). This may reflect the wetter conditions in 2011 compared to 2007. The dry-weight nutrient content of the manure in 2011 was similar to 33% less than then compared to the manure in 2007. Ammonium-N and total sulphur (TS) contents were similar between the two years; whereas, TN had the greatest difference. Nutrient content was higher (NH_4-N), lower (TN, TP, total potassium), or similar (TS) to values previously reported by Olson et al. (2003, 2010) and Olson and Papworth (2006) for feedlot beef manure in southern Alberta.

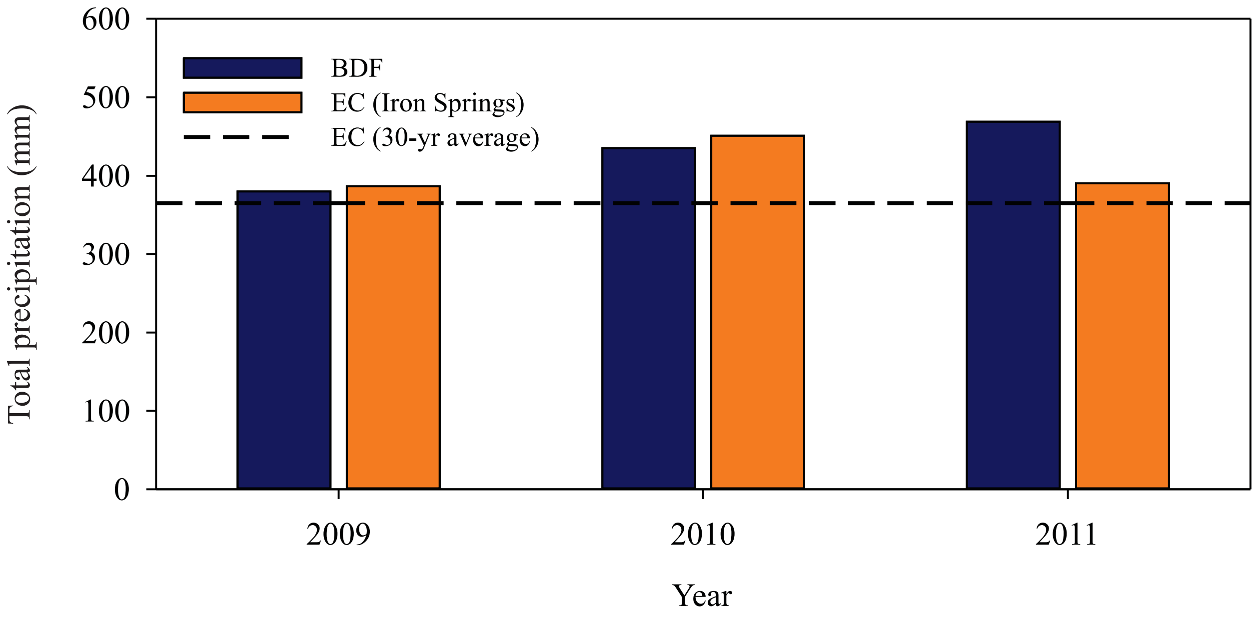

Figure 5.10. Total precipitation at the Battersea Drain Field (BDF) weather station compared to the Environment Canada (EC) Iron Springs weather station from 2009 to 2011. Note that no weather data were collected in 2007 and weather data were only collected for a portion of 2008 and 2012 at the site.

Table 5.5. Average water and nutrient content of manure applied to the Battersea Drain Field in 2007 and 2011.

Sampling date	Number of samples	Water	NH_4-N[z]	TN	TP	TK	TS
		----------------------------	----------	(kg Mg^{-1})	----------	----------------------------	
Oct 15, 2007[y]	9	321	5.10	20.4	5.63	14.4	4.25
Sept 21, 2011[y]	6	1012	5.14	13.7	4.85	13.8	4.19

[z] NH_4-N = ammonium-nitrogen, TN = total nitrogen, TP = total phosphorus, TK = total potassium, TS = total sulphur.
[y] Average values are expressed on a dry -weight basis.

5.3.3 Soil

5.3.3.1 Agronomic Samples

Extractable NO_3-N concentration in the 0- to 15-cm agronomic samples was generally higher in the spring compared to the fall, and the highest values were observed in the springs following manure application (Table 5.6). Manure was applied in fall 2007 and fall 2011, and the concentration of NO_3-N was greater than 70 mg kg^{-1} in the following springs and significantly different compared to the other years (Table 5.6). Extractable NH_4-N concentrations were generally less than 9 mg kg^{-1} in spring and fall. The high concentration of 49 mg kg^{-1} observed in fall 2007 was significantly higher than in the other years in the fall. This high concentration was the result of manure application, which occurred 2 wk prior to soil sampling in late October. With cooler soil temperature in October, the nitrification process was likely limited within the 2-wk period, and little NH_4-N in the applied manure was converted to NO_3-N. This was supported by NO_3-N concentration value, which was not particularly high in fall 2007.

Based on two samplings per year, the 6-yr average (n = 12) concentration of STP was 405 mg kg^{-1}. Average concentration for individual sampling times ranged from 328 to 509 mg kg^{-1} (Table 5.6). The 6-yr average STP was nearly seven times higher than the agronomic threshold of 60 mg kg^{-1}, above which crops will generally not respond to added P (Howard 2006). Average STP concentration was typically higher in the fall by 6 to 33% compared to the spring, except in 2010, when STP concentration was 17% higher in the spring. The application of manure in fall 2007 had no noticeable effect on STP since the increase in STP from spring to fall 2007 was no greater than compared to most other years.

The average STP concentration was particularly high in spring 2010 at 509 mg kg^{-1} (Table 5.6). The reason for this higher average is unknown. This average may simply reflect the variability in a manured field. For the 189 agronomic samples collected during the 6 yr, STP concentration ranged widely from 42 to 1300 mg kg^{-1}. It is interesting that in a heavily manured field with a high average STP concentration, such as at BDF, two soil samples had relatively low STP concentrations (<100 mg kg^{-1}). One sampling point in the field was particularly high in STP, with an average concentration of 1074 mg kg^{-1}. This sampling point was in the extreme northeast part of the field and about 50 m southeast from Station 204 (Figures 5.2 and 5.6). According to the landowner, crop growth was often poor in this area of the field due to excessive soil wetness. Therefore, with continued manure application for many years and limited crop removal of P because of poor growth, the accumulation of STP was particularly high in this part of the field.

Table 5.6. Average concentrations of nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and soil-test phosphorus (STP) in the agronomic soil samples collected from 2007 to 2012 at the Battersea Drain Field.

			NO_3-N		NH_4-N		STP	
	Sampling dates		Spring	Fall	Spring	Fall	Spring	Fall
Year	Spring	Fall	---------------------------- (mg kg^{-1}) ----------------------------					
2007	May 16	Oct. 26[z]	36*b*[y]	24*bc*	5.2*a*	49.2*a*	328*b*	349*a*
2008	May 30	Oct. 16	73*a*	38*a*	8.9*a*	4.3*b*	356*b*	475*a*
2009	May 22	Oct. 5	38*b*	40*a*	3.3*b*	3.7*b*	347*b*	432*a*
2010	May 26	Oct. 5	14*c*	17*cd*	5.1*a*	3.8*b*	509*a*	436*a*
2011	June 6	Sep. 30[x]	17*c*	11*d*	2.0*c*	2.4*b*	354*b*	428*a*
2012	May 16	Sep. 25	71*a*	27*b*	6.3*a*	3.1*b*	403*ab*	446*a*

[z] Soil nutrient concentrations after manure application.
[y] Average concentrations per parameter and season followed by different letters are significantly different at $P < 0.1$.
[x] Soil nutrient concentrations prior to manure application.

It appeared that the higher concentration of STP in fall 2008 may have been the result of the manure application in the previous fall. Then without additional manure application, fall STP concentration decreased slightly until fall 2011 and then increased in fall 2012 because of the application of manure in 2011. Despite what appears to be a manure effect, the average STP concentrations in the fall were not significantly different among the years (Table 5.6). The STP concentration in spring 2008 was slightly elevated compared to the previous fall and this may have been caused by the manure application. However, there was no downward trend in spring STP concentrations from 2008 to 2011. As discussed above, average concentration was much higher in 2010 and may have be the result of field variability. The variability associated with measuring STP concentration in this field with high average STP concentration was likely greater than the effects of a single application of manure.

The cessation of manure application as part of the BMP plan resulted in a significant reduction in the concentrations of spring NO_3-N and spring and fall NH_4-N from the pre-BMP period to the post-BMP period (Table 5.7). The average concentration of fall NO_3-N was less in the post-BMP period compared to the pre-BMP period, but difference was not statically significant.

In contrast, average STP concentration was not significantly different between the pre- and post-BMP periods (Table 5.7). In fact, STP concentration was slightly higher during the post-BMP period compared to the pre-BMP period. By grouping the data into the two BMP periods, any trend in the post-BMP may be obscured by averaging. However, comparing the last year of the pre-BMP period (2008) to the last year of the post-BMP period (2011) still showed no significant difference in STP concentration (Table 5.6).

Table 5.7. Pre-BMP (2007 and 2008) and post-BMP (2009 to 2011) period comparison of average nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and soil-test phosphorus (STP) concentrations in the agronomic soil samples from the Battersea Drain Field.

Season/BMP period	NO_3-N	NH_4-N	STP
	------------------------------	(mg kg^{-1})	------------------------------
Spring pre-BMP	54*a*[z]	7*a*	342
Spring post-BMP	23*b*	4*b*	403
Fall pre-BMP	31	27*a*	412
Fall post-BMP	23	3*b*	432

[z] Average concentrations per parameter and season followed by different letters are significantly different at P <0.1.

The amount of TP in the manure applied to the field in fall 2007 was estimated at 574 kg ha^{-1} based on an application rate of 135 Mg ha^{-1} (wet weight) and analysis of manure samples (Table 5.5). The amount of TP removed by the crops grown from 2008 to 2011 (i.e., prior to the next manure application in fall 2011) was 95 kg ha^{-1}. This estimate was based on actual yields (Table 5.1) and average TP removal for the crops report by the Canadian Fertilizer Institute (2001). Total P removal average values used in the estimate were 2.77 kg Mg^{-1} for corn silage (dry weight), 9.18 kg Mg^{-1} for canola, 2.60 kg Mg^{-1} for barley silage (dry weight), and 0.40 kg Mg^{-1} for potato (Canadian Fertilizer Institute 2001). The amount of TP added was six-fold greater than the amount removed in the four crop years before the manure application in late 2011. Therefore, it is not surprising that STP concentration was not significantly reduced during the BMP period of no manure application.

The lack of STP reduction after 4 yr without manure P application also reflects the residual capacity of P in the soil at this site with a high degree of P saturation to maintain high STP levels. As crops remove P from the pool of readily available P, which is measured as STP, the residual accumulation of organic P from manure application replenishes the available P through mineralization. After P accumulates to a high concentration, the time required to reduce STP by crop removal can take many years if not decades. Whalen and Chang (2001) reported 452 mg kg^{-1} STP in the top 15 cm of soil after the application of 60 Mg ha^{-1} yr^{-1} beef cattle manure for 16 yr under irrigation. In the same study for selected plots, manure was applied for 14 yr followed by no manure for another 14 yr (Hao et al. 2004). They found that for the same treatment (60 Mg ha^{-1} yr^{-1} manure under irrigation), STP was only reduced to 346 mg kg^{-1}. However, Olson et al. (2010a) found that after 6 yr of beef manure application at 120 Mg ha^{-1} yr^{-1} under irrigation, STP was reduced from 386 to 284 mg kg^{-1} in a coarse-textured soil and from 431 to 336 mg kg^{-1} in a medium-textured soil after only 2 yr of no manure application. At the BDF site, in order to reduce high STP concentration in the top soil layer, and therefore reduced the risk of P loss in runoff, the application of no P, including manure, needs to continue for many more years (i.e., two decades or more).

For N, the amount of TN added to soil in fall 2007 was estimated at 2081 kg ha^{-1}. The amount of TN removed by the crops grown from 2008 to 2011 was estimated at 570 kg ha^{-1}. This estimate was based on actual yields (Table 5.1) and average TN removal for the crops report by the Canadian Fertilizer Institute (2001) of 15.6 kg Mg^{-1} for corn silage (dry weight), 38.8 kg Mg^{-1} for canola, 3.2 kg Mg^{-1} for potato, and 17.4 kg Mg^{-1} for barley silage (dry weight). The amount of TN added was 3.7-fold greater than the amount removed in the four crop years before the manure application in late 2011. However, unlike STP, extractable N was significantly reduced in the top 15 cm of soil during the post-BMP (Table 5.7), despite that more TN was added than was removed. Compared to P, much larger quantities of TN were removed and the ratio between added and removed TN was smaller. The other important difference between N and P is that nitrate is very soluble and mobile in soil; whereas, the vast majority added P from the manure applied in 2007 remained in the top layer of soil. The observed reduction in NO_3-N during the post-BMP period may have been the result of leaching and denitrification. Also, exchangeable ammonium would have been in equilibrium with the soil solution and subject to crop uptake and to nitrification and subsequent leaching and denitrification. Without the regular addition of fresh manure, extractable N was reduced in the top 15 cm of soil due to a combination of processes (e.g., crop removal, leaching, and denitrification).

5.3.3.2 AFFIRM Samples

The concentrations of NO_3-N, NH_4-N, and STP in the 0- to 15-cm soil-test samples (Table 5.8) were comparable to the values for fall agronomic soil samples (Table 5.6) from 2008 to 2010. Generally the concentration of the extractable nutrients decreased with depth (Table 5.8). High concentration of STP was also measured in the 15- to 30-cm soil layer. Phosphorus is relatively immobile in soil and when applied in excess of crop removal, P will accumulate and remain near the soil surface (Chang et al. 2005; Olson et al. 2010a). However, as the surface soil become saturated with accumulated P, some P can leach into lower depths in the soil profile (Whalen and Chang 2001; Casson et al. 2006; Olson et al. 2010a).

Based on the AFFIRM program, nutrient management plans for the crop years 2009 and 2010 recommended no application of N. In 2011, potatoes were grown and the application of 168 to 179 kg ha^{-1} N was recommended for optimal crop yield. The actual amount of commercial fertilizer N applied in 2011 was 112 kg ha^{-1} (Table 5.1). Due to high concentration of STP, the application of P was not recommended and will not be recommended for the foreseeable future. Though, it is interesting that STP concentration in the 0- to 15-cm layer decreased from 2008 to 2010 (Table 5.8).

Converting the NO_3-N values in Table 5.8 to kilograms per hectare by multiplying by two (15-cm layer) or by four (30-cm layer) showed the NO_3-N content in the 0- to 60-cm layer ranged from 50 to 164 kg ha^{-1} among the 3 yr. The NO_3-N limit in the AOPA regulations for the BDF site is 180 kg ha^{-1} (i.e., irrigated, coarse textured soil, and water table <4 m). Based on the AOPA NO_3-N limit, manure application would not be restricted at this site other than not applying within 30 m from the Battersea Drain.

Table 5.8. Soil-test results for nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and soil-test phosphorus (STP) for samples collected at the Battersea Drain Field.

Year	Soil layer (cm)	NO_3-N	NH_4-N	STP
		(mg kg^{-1})		
2008	0 to 15	31	3.1	478
	15 to 30	18	1.9	165
	30 to 60	15	1.5	50
2009	0 to 15	30	3.6	449
	15 to 30	16	2.2	139
	30 to 60	18	7.2	24
2010	0 to 15	13	5.3	401
	15 to 30	6	1.5	161
	30 to 60	3	1.1	26

5.3.3.3 Effect of Manure Application in 2011

The differences between pre- and post-manure application soil samples were inconsistent between the two sampling layers for NO_3-N and STP. For NO_3-N, concentration was lower after manure application in the 0- to 2.5-cm layer; whereas, concentration was higher after manure application in the 0- to 15-cm layer (Table 5.9). This was also true for STP but in reverse order in terms of soil layer. In any event, average concentrations of NO_3-N and STP after manure application were not significantly different to pre-manure application for either soil layer. In contrast, the concentration of NH_4-N was significantly increased in the 0- to 2.5-cm soil layer by the application of manure in 2011. The concentration of NH_4-N was also higher in the 0- to 15-cm post-manure soil samples, but was not significantly different from the pre-manure application samples.

Table 5.9. Average concentration of nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and soil-test phosphorus (STP) in soil samples collected pre- and post-manure application in fall 2011 at the Battersea Drain Field.

Soil layer (cm)	Application phase	Sampling date[z]	NO_3-N	NH_4-N	STP
			(mg kg^{-1})		
0 to 2.5	Pre-manure	Sep. 30	37*a*[y]	7.5*a*	462*a*
	Post-manure	Nov. 28	19*a*	91*b*	492*a*
0 to 15	Pre-manure	Sep. 30	11*a*	2.4*a*	428*a*
	Post-manure	Nov. 28	25*a*	6.7*a*	398*a*

[z] Cattle manure was applied (228 Mg ha^{-1} wet weight) on the west side of the Battersea Drain on September 21, 2011 and on the east side of the Battersea Drain in mid-October after October 13, 2011.
[y] For each soil layer and parameter, averages followed by the same letter are not significantly different (*P* <0.1)

Typically, NO_3-N represents only a small portion of the TN in manure, and most of the mineral N is in the form of NH_4-N. Olson et al. (2010b) found NO_3-N accounted for ≤ 0.1% of TN, and that NH_4-N accounted for 11 to 12% of TN in beef manure sampled in the same geographical area as the BDF site. In the current study, NH_4-N accounted for about 38% of TN in the manure applied in fall 2011 (Table 5.5).Therefore, NO_3-N in the manure would have contributed little to soil NO_3-N, at least during the short time between application of manure and the post-application soil sampleing. Based on a manure application rate of 228 kg ha^{-1} (wet weight) and analyzed nutrient content (Table 5.5), the amount of NH_4-N applied was 581 kg ha^{-1}. Assuming a soil bulk density of 1330 kg m^3, and the added NH_4-N remained within the 0- to 15-cm layer, the increase in NH_4-N concentration would been about 291 mg kg^{-1}. The change in NH_4-N concentration from pre- to post-manure application in the 0- to 15-cm layer was much less than this calculated value (Table 5.9). Also the significant increase in NH_4-N concentration in the 0- to 2.5-cm layer accounted for about 28 kg ha^{-1} of added NH_4-N, again assuming a soil bulk density of 1330 kg m^{-3}. Even though NH_4-N concentration responded to manure application, this represented only a small portion of the NH_4-N in the manure at the time of application. This may suggest a large portion of NH_4-N was lost by volatilization and some may have been nitrified.

In a similar calculation, the amount of TP in manure applied in fall 2011 was estimated at 548 kg ha^{-1}. Typically, only a small portion of TP in manure is in plant available form at the time of application. Olson et al. (2010a) reported that 37% of TP in beef manure was in extractable form, which can contribute directly to STP shortly after application. Using this factor, the amount of plant-available P in the manure added to the field was estimated at about 203 kg ha^{-1}. Assuming a soil bulk density of 1330 kg m^{-3}, this would be equivalent to an increase in STP of 101 mg kg^{-1} in the top 15 cm of soil. As shown in Table 5.9, STP concentration was actually less in the post-manure application soil samples. Possibly, the previously mentioned high variability in STP at this site may have obscured the ability to measure the effects of a single manure application.

5.3.3.4 Deep Soil Cores

Extractable NO_3-N concentration was relatively consistent throughout the 3-m soil profile and among the 3 yr at the BDF site, with values that ranged from 8 to 29 mg kg^{-1} (Table 5.10). There were no obvious accumulation of NO_3-N, even below the root zone (>150 cm). Because this site had coarse-textured soil (loamy sand to loam), leaching potential was high, particularly under irrigation. Olson et al. (2010b) found less NO_3-N in an irrigated, coarse-textured soil compared to an irrigated, medium-textured soil, even though both soil types received the same amount of beef manure. They concluded the difference was due to greater leaching in the coarse-textured soil. Irrigation can also increase leaching potential compared to rain-fed conditions (Chang and Entz 2006).

Extractable NH_4-N concentration was low (<3 mg kg^{-1}) throughout the soil profile and remained relatively unchanged among the 3 yr (Table 5.10).

The highest STP concentration was in the top 30-cm soil layer and most of the accumulated STP remained in this soil layer (Table 5.10). The 30- to 60-cm layer had the second highest STP concentration and was a magnitude or more less than the surface soil layer. This suggests that some

Table 5.10. Average nitrate nitrogen, (NO_3-N), ammonium nitrogen (NH_4-N), soil-test phosphorus (STP), and chloride (Cl) concentrations in deep soil cores at the Battersea Drain Field site in 2009, 2011, and 2012. [z]

	NO_3-N			NH_4-N			STP			Cl		
Soil layer	2009	2011	2012	2009	2011	2012	2009	2011	2012	2009	2011	2012
(cm)	(mg kg^{-1})											
0-30	29	15	19	2.3	2.3	1.7	349	221	271	16	8	25
30-60	20	10	15	1.7	1.4	0.7	39	52	28	10	3	40
60-90	20	14	18	1.8	1.2	0.9	13	12	8	18	8	24
90-120	20	13	14	2.2	1.2	0.6	12	11	8	29	7	8
120-150	17	15	17	1.9	1.2	0.6	8[y]	5	6	29	11	10
150-180	15[y]	15	16	1.6[y]	1.2	0.5	4[y]	18	9	25[y]	16	13
180-210	11[w]	17	16	1.0[w]	1.3	0.5	1[w]	7[y]	5	27[w]	24	14
210-240	15[w]	16	19	1.0[w]	1.5	0.6	20[w]	5	15	30[w]	31	22
240-270	8[v]	12	24[x]	0.9[v]	2.0	1.2[x]	1[v]	4	1[x]	15[v]	25	32[x]
270-300	11[v]	14	19[w]	0.4[v]	2.4	1.5[w]	1[v]	6	1[w]	18[v]	26	44[w]

[z] Averages are for n = 5, unless footnoted otherwise.
[y] n = 4
[x] n = 3
[w] n = 2
[v] n = 1

P leached further into the soil profile. When surface soil becomes saturated with accumulated P, the risk of P leaching can increase (Olson et al. 2010a). In soil layers deeper than 60 cm, the STP concentration ranged from 1 to 20 mg kg^{-1}, with some indication of even smaller amount of P leaching to greater depths.

In 2009, there were higher concentrations of Cl in the 90- to 240-cm soil layers compared to the other layers. The higher Cl concentrations in these layers may have been the result of Cl in the manure applied in fall 2007 and leached into the soil profile. In 2011, the concentration of Cl was reduced in the 0- to 180-cm soil layer, suggesting the Cl from manure leached further into the soil profile. In 2012, this Cl was moved even further down the soil profile, while Cl from the manure application in fall 2011 caused an increase in Cl concentration in the 0- to 90-cm soil layers. Chloride is not biologically or chemically active in the soil and can be used as a tracer for the measurement of net leaching in soil (Chang et al. 1991). The deep core results showed that Cl, and likely other soluble constituents, such as nitrate, readily leached from applied manure under the conditions at this site.

5.3.3.5 Grass Buffer Soil

In fall 2012, NO_3-N and STP concentrations in the 0- to 15-cm soil layer were less in the buffer area than in the cultivated field area (Table 5.11). After the grass buffers were established in 2002 (Riemersma et al. 2002, 2004), manure was no longer applied on these areas; whereas, manure application continued on the rest of field from 2002 to 2007, until the BMP plan was implemented in 2008. The forage in the buffer areas was rarely harvested. Therefore, crop removal was not a mechanism for P decrease in the buffers. Possibly, a small amount of P may have been lost due to leaching and surface runoff. The difference between the grass buffer soil and the field soil was more likely caused by increased STP concentration in the field with continued manure application.

Table 5.11. Average concentration of nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), soil-test phosphorus (STP) in soil (0 to 15 cm) samples from the grass buffer areas and field at the Battersea Drain Field in fall 2012.

	n	NO_3-N	NH_4-N	STP
		-------------------	(mg kg^{-1})	-------------------
Field	15	27	3	446
Buffer	4	2	3	338

Prior to the establishment of the grass buffers, the average STP concentration in 2001 for the whole field was 308 mg kg^{-1} (Riemersma, unpublished data), which was less than any average value measured during the current study from 2007 to 2012 (Table 5.6). However, the average STP concentration in 2001 was only slightly less than the spring and fall averages in 2007. Therefore, continued manure application from 2002 to 2007 at least maintained high STP concentrations and likely caused some further increase in concentration.

The concentration of STP at two sampling points in the southwest corner grass buffer in 2001 (Figure 5.7) differed by 201 mg kg^{-1} (Table 5.12). This supports the similar in-field variability observed during the current study. Sampling these same two sampling points in 2012 showed that concentrations of NO_3-N and STP had decreased during the 11-yr period. Unfortunately, a statistical comparison could not be carried out, as only two sampling points in 2001 where in the buffer areas that could be re-sampled in 2012. As indicated above, crop removal was not a mechanism for reducing the nutrient concentration in the surface soils in the buffer areas. Without the addition of manure for 11 yr, leaching may have reduced the concentrations of NO_3-N and STP in the surface soil. On the other hand, the average field concentration of STP in 2001 (308 mg kg^{-1}) was similar to the concentration measured in the buffer areas in fall 2012 (Table 5.11). Caution needs to be taken when interpreting results based on limited samples from a field with high variability.

Regardless, STP concentration in the grass buffers was still very high, even after 11 yr without manure application. This clearly demonstrates the long-term residual effect of accumulated P from the over application of manure prior to the establishment of the grass buffers. The buffers may provide some benefit in terms of slowing runoff water and trapping sediment. However, the grass buffers at this site are likely still a source of nutrient loss, particularly dissolved P.

Table 5.12. Comparing historical and current buffer nutrient concentrations of soil samples at the Battersea Drain Field.

Year	Sample point[z]	NO_3-N	NH_4-N	STP
		-------------------	(mg kg^{-1})	-------------------
Fall 2001[y]	B	25	2	423
Fall 2012	B	1	5	297
Fall 2001[y]	C	6	2	222
Fall 2012	C	3	4	125

[z] Refer to Figure 5.7.
[y] From Riemersma, unpublished data.

5.3.4 Water Flow

Annual flow of water measured at the downstream Station 202 ranged from 4.9 million m^3 yr^{-1} in 2009 to 6.5 million m^3 yr^{-1} in 2012 (Figure 5.11). More than 90% of the annual flow occurred from late-April/early-May to mid-October. The initial increase in flow each spring was caused by snow and ice melting in the drain. High flow in the drain during the growing season was sustained by water released from the Picture Butte Reservoir for irrigation and field runoff. The annual flow distribution in the drain was similar among years with some variations. For example, in 2010, less irrigation source water was released from the Picture Butte Reservoir in May and June (on average, 0.48 m^3 s^{-1} in May and 0.42 m^3 s^{-1} in June) compare to previous years (Ryan Chogi, Water Master with the Lethbridge Northern Irrigation District, personal communication). After water release from the reservoir was ceased in early October, the flow quickly decreased in the drain in all 6 yr and remained low until the following spring. Low flows during the non-irrigation season (i.e., from mid-October to late-April/early-May) was caused mainly by shallow groundwater discharge into the drain. Flow was intermittent at Station 201 but sustained at Station 202 during the non-irrigation season. Some flow during this period was caused by snowmelt and rainfall runoff. During these low-flow periods, flow typically ranged from 0.01 to 0.02 m s^{-1}, except when runoff events occurred. During a 6-mo period, low flow represented about 150,000 to 300,000 m^3 yr^{-1}.

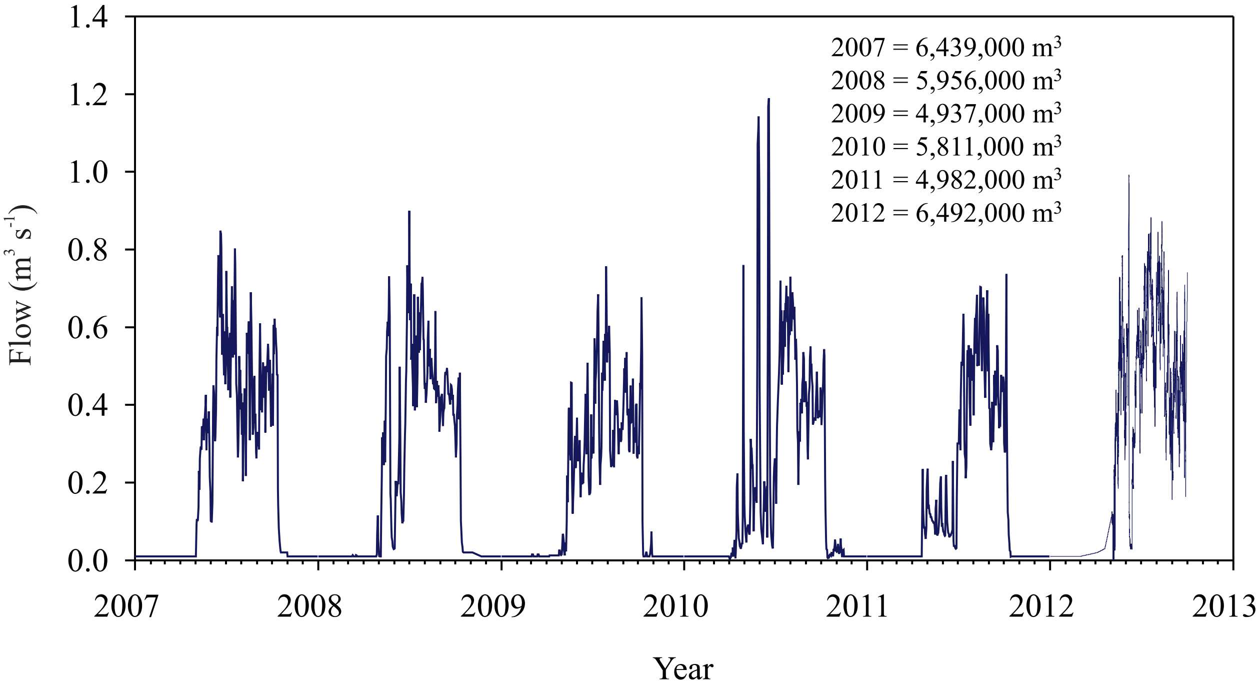

Figure 5.11. Annual hydrographs for the downstream Station 202 at the Battersea Drain Field from 2007 to 2012. Note that flow in 2012 is only from January 1 to September 30.

Annual flow at the four edge-of field stations ranged from 0 to 9030 m^3 yr^{-1} during 6 yr of monitoring (Table 5.13). The 6-yr average was 848 m^3 yr^{-1} for Station 203, 2348 m^3 yr^{-1} for Station 204, 4591 m^3 yr^{-1} for Station 205, and 1382 m^3 yr^{-1} for Station 206. Total edge-of-field runoff flow ranged from 1569 m^3 in 2012 to 18,574 m^3 in 2010 (Table 5.13). The annual runoff flow through the edge-off-field stations was small compared to the flow in the drain, representing less than 0.4% of the annual flow at Station 202.

The measured flows at the edge-of-field stations were underestimated because there were periods when water from the drain backed up into the flumes and prevented flow measurement at Stations 204, 205, and 206 in every year. The annual flow in 2007 was also underestimated because flow measurements were not taken prior to late June because of a delay in the installation of the instrumentation. There may have also been runoff not within the monitoring station drainage areas that entered the drain, and therefore, not recorded. Even considering the runoff flow not measured, the amount of runoff from the field along the reach between the upstream and downstream stations was still small compared to the annual flow in the drain.

On average among the four edge-of-field stations from 2008 to 2012, 21% of annual runoff flow was caused by snowmelt, 42% by rainfall, and 31% by irrigation. Results from 2007 were not included in these averages because snowmelt and rainfall runoff was not measured due to a delay in installing the instrumentation. Snowmelt runoff typically occurred from January to April, rainfall runoff typically occurred in May and June, and irrigation runoff was more dominant in July and August (Figure 5.12). The distribution of runoff among the three event types varied greatly depending on the station and year. For example, very little to no snowmelt runoff occurred in 2009 and in 2012; whereas, 37 to 85% of the runoff was caused by snowmelt in 2011 (Table 5.13). Generally, no irrigation runoff occurred at Station 203, except in 2008. Irrigation runoff was observed at Stations 204, 205, and 206 in regular cycles as the pivot irrigation system passed over these edge-of-field sites during the pre-BMP period.

In the pre-BMP year 2008, irrigation contributed relatively large proportions to total runoff (Table 5.13). Irrigation runoff occurred in 2007, but the relative contributions could not be determined because snowmelt and rainfall runoff were not recorded. In the post-BMP years from 2009 to 2011, relatively low to no runoff was caused by irrigation at most of the stations. This may suggest that the modifications to the pivot system reduced the amount of runoff caused by irrigation at this site. Further discussion on the effects of the pivot modification BMP are in Sub-section 5.3.6.

Table 5.13. Edge-of-field station annual flow and proportions of flow caused by snowmelt, rainfall, irrigation, and irrigation/rainfall runoff at the Battersea Drain Field.

Station	Year	Flow (m^3 yr^{-1})	Snowmelt	Rainfall	Irrigation	Irrigation/rainfall
			(%)			
203	2007	0	nm[z]	nm	0	0
204	2007	953	nm	nm	nd[y]	0
205	2007	907	nm	nm	nd	0
206	2007	376	nm	nm	nd	0
	2007 total	*2,236*				
203	2008	556	9	48	43	0
204	2008	2,701	0	30	70	0
205	2008	4,102	0	19	81	0
206	2008	1,459	15	19	66	0
	2008 total	*8,818*				
203	2009	487	47	27	0	26
204	2009	1,209	7	10	34	49
205	2009	4,688	8	43	8	41
206	2009	411	19	64	14	3
	2009 total	*6,795*				
203	2010	2,413	13	87	0	0
204	2010	4,356	8	92	0	0
205	2010	9,030	9	91[x]	0	0
206	2010	2,775	58	42	0	0
	2010 total	*18,574*				
203	2011	1,627	37	63	0	0
204	2011	4,225	52	44	4	0
205	2011	8,066	59[x]	27	14	0
206	2011	3,101	85	15	0	0
	2011 total	*17,019*				
203	2012	5	0	100	0	0
204	2012	644	0	0	100	0
205	2012	751	0	11	89	0
206	2012	169	0	0	100	0
	2012 total	*1,569*				

[z] nm = not measured. No snowmelt or rainfall runoff flow data were collected in 2007 because the flow instrumentation was not installed until late June 2007. The annual flow values are for runoff generated by irrigation.
[y] nd = not determined.
[x] A trench was observed on June 3 from the quarter section south of the Battersea Drain Field and this affected runoff at Station 205 from the first week of June 2010 to the summer of 2011. This runoff was not included in the water quality analyses. Approximately 75% of the total rainfall runoff in 2010 and 100% of the snowmelt in 2011 was affected by the trench water from the quarter section south of the Battersea Drain Field.

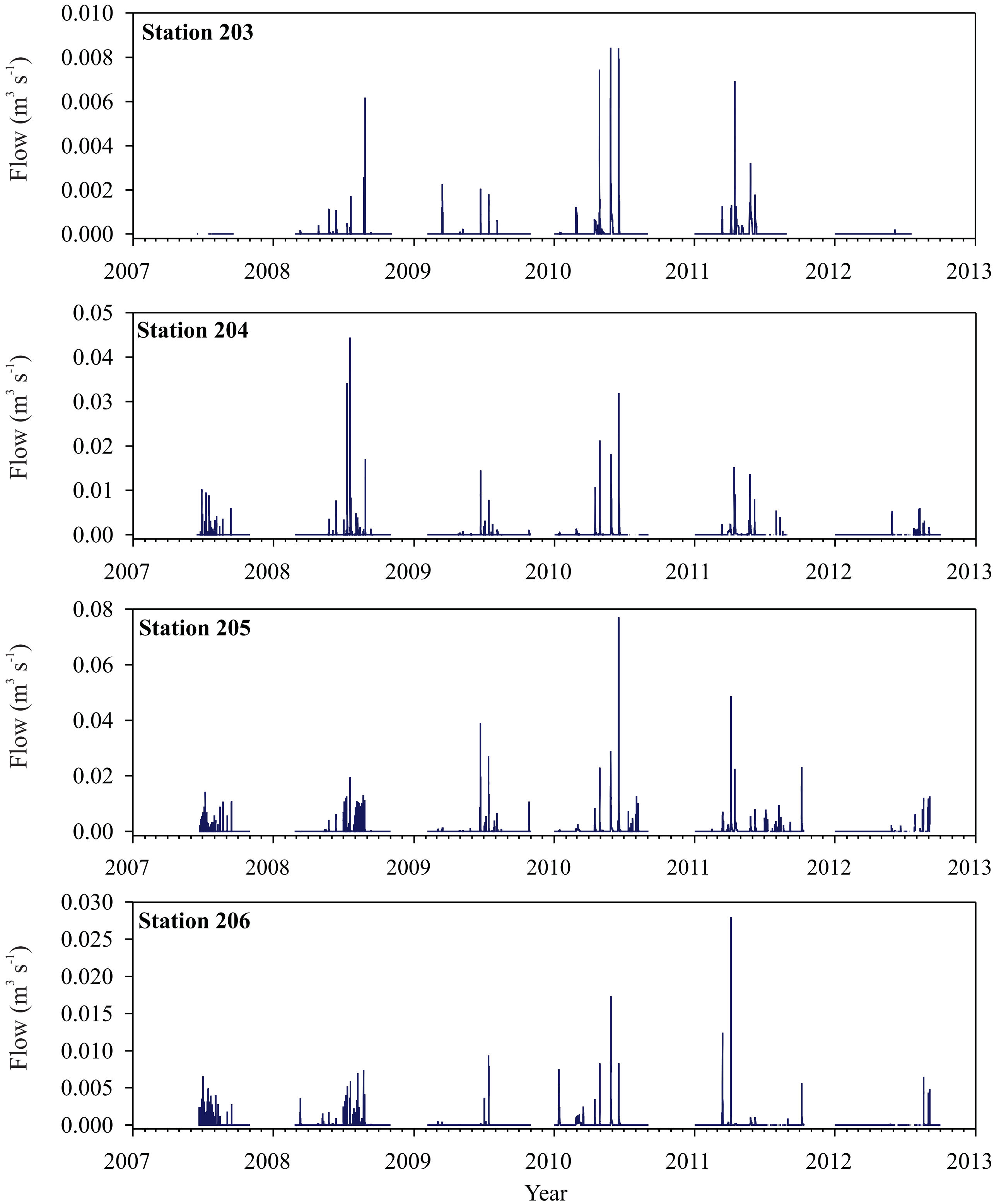

Figure 5.12. Annual hydrographs for the edge-of-field water monitoring stations at the Battersea Drain Field from 2007 to 2012. Note no flow was measured prior to late June 2007 because the instrumentation was not installed.

5.3.5 Alberta Irrigation Management Model BMP

Results from the utilization of AIMM to schedule the irrigation as part of the BMP plan varied annually based on weather conditions and producer management.

In 2009, the soil moisture measurement for the model initiation was taken on June 12; however, the first model output was delayed to July 20. Irrigation was stopped on August 4 to allow the field to dry in preparation for harvest (Table 5.14). The AIMM output showed that the soil moisture remained well above the irrigation threshold level of 71 mm for the entire growing season (Figure 5.13). The rainfalls that followed irrigation events in early July and August resulted in soil moisture above FC, and this caused some water loss through deep percolation and runoff. Therefore, the model was successful in predicting soil moisture content, but model output results could have possibly been more effectively used to control some runoff in 2009. The onset of irrigation could have been delayed in order to maintain soil moisture content at a lower level, which may have reduced the risk of runoff. However, greater than expected rainfall occurred just after some irrigation events, and this caused runoff. Without these rainfall events, likely little to no runoff would have occurred.

In 2010, the soil moisture content was high when the model was initiated on April 27 and remained greater than FC until the end of June, because of the above average precipitation received during this period (Table 5.4). On July 8, it was recommended to start irrigating on July 12 based on the AIMM simulation results. The pivot system was started on July 12 and a soil moisture sample was taken on July 13 to measure the actual moisture content. The measured available soil moisture content of 70 mm was slightly lower than the AIMM output of 76 mm, and as a result, a correction was applied to the model (Figure 5.14). The five continuous irrigation circles applied 98 mm of total irrigation water and increased the soil available moisture to 112 mm. Rain in early August maintained the soil moisture above the irrigation threshold of 77 mm until harvest.

Table 5.14. Annual timing and volume of irrigation water applied to the Battersea Drain Field from 2007 to 2008 (pre-BMP period) and from 2009 to 2012 (post-BMP period).

Year	Crop	First application date	Last application date	Irrigation volume (m^3 yr^{-1})	Irrigation amount[z] (mm yr^{-1})
2007	Potato	Jun.	Sep. 14	280,499	469
2008	Corn silage	Jun. 30	Aug. 27	216,655	362
2009	Canola	May 24	Aug. 4	87,265	146
2010	Barley silage	Jul. 12	Jul. 25	46,863	78
2011	Potato	Jul. 1	Sep. 16	156,986	263
2012	Corn silage	May 25	Sep. 4	179,381	300

[z] Irrigated area was estimated at 59.8 ha.

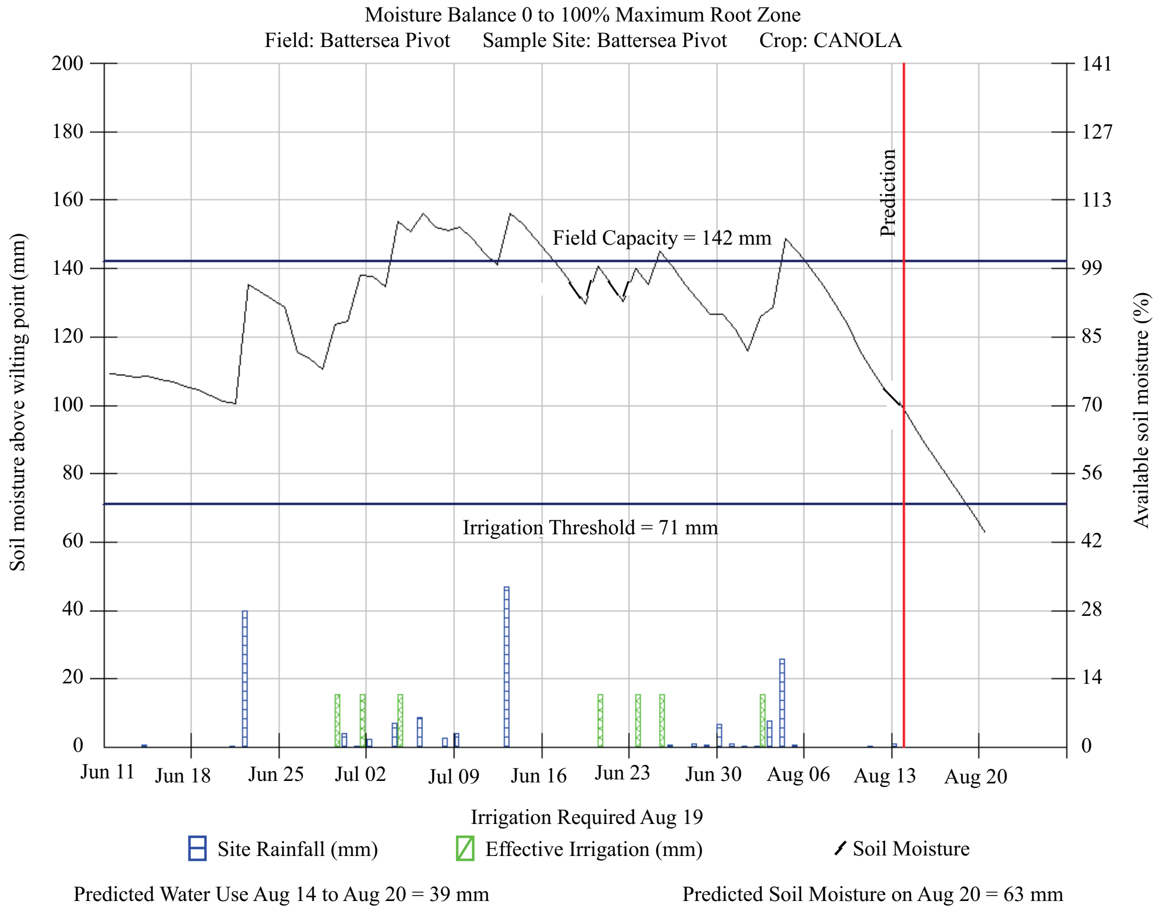

Figure 5.13. Alberta Irrigation Management Model output for the Battersea Drain Field on August 14, 2009.

The AIMM program successfully predicted the change in soil moisture at the BDF site in 2010. Irrigation was initiated when the TAW reached 50% and the timing and volume of irrigation water applied in 2010 was appropriate for the crop and to control irrigation runoff since soil moisture was maintained well below FC. No irrigation runoff occurred at the water monitoring stations in 2010 (Table 5.13).

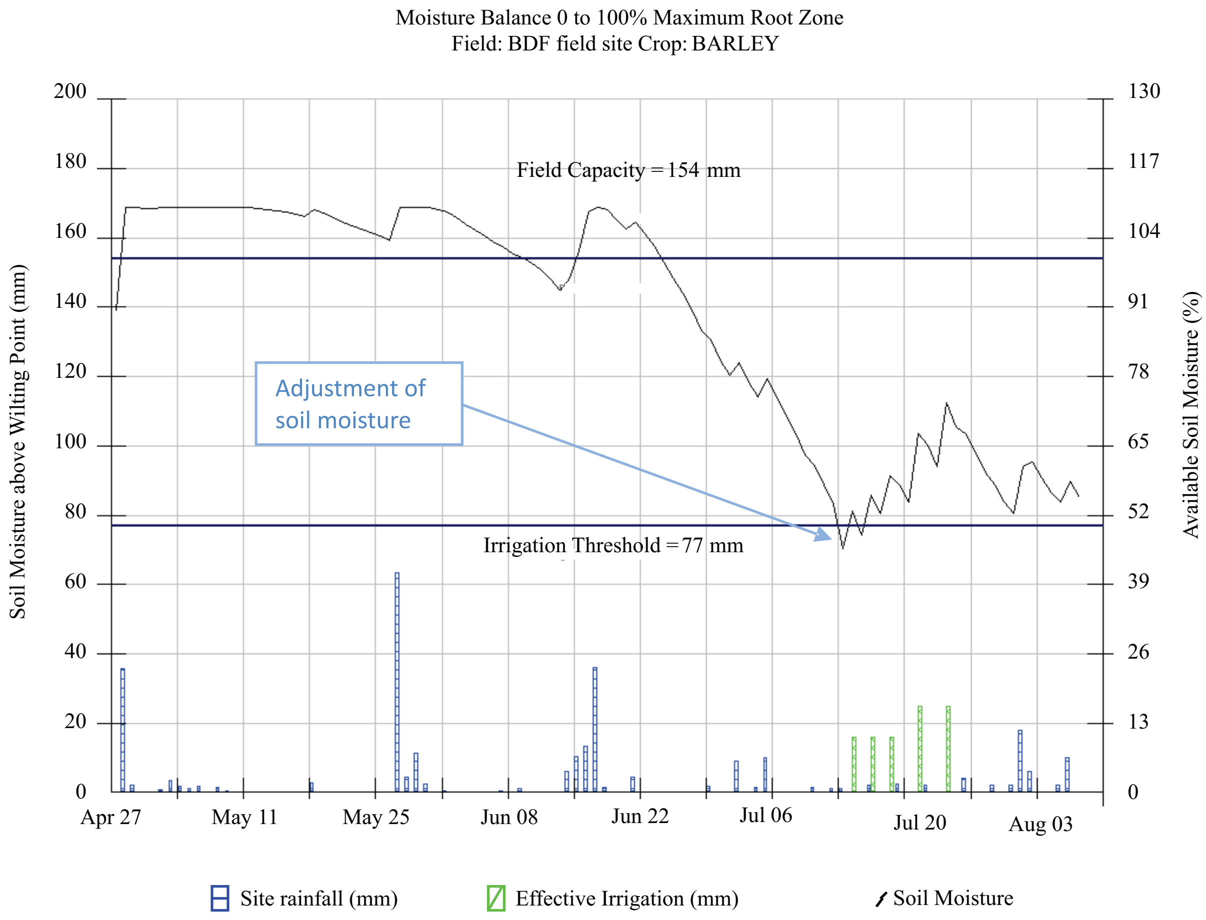

Figure 5.14. Alberta Irrigation Management Model output for the Battersea Drain Field in 2010.

In 2011, the AIMM simulation was initiated on May 29. Soil moisture content was high at the beginning of the season with above average precipitation in April and May and near average precipitation in June (Table 5.4). Irrigation was initiated in early July as soil moisture started to decrease (Figure 5.15). The site was well irrigated from July to mid-August, and this kept soil moisture well above the irrigation threshold. Despite the AIMM recommendations, the producer preferred to keep soil moisture high to ensure that the potato crop was not stressed, as available soil moisture depletion of 35% was used for the potato crop. The field was allowed to dry in September in preparation for harvest. The AIMM program successfully predicted the change in soil moisture at the BDF site in 2011, but failed to convince the producer to reduce irrigation volume or frequency. In 2011, the land was leased and managed by a different producer.

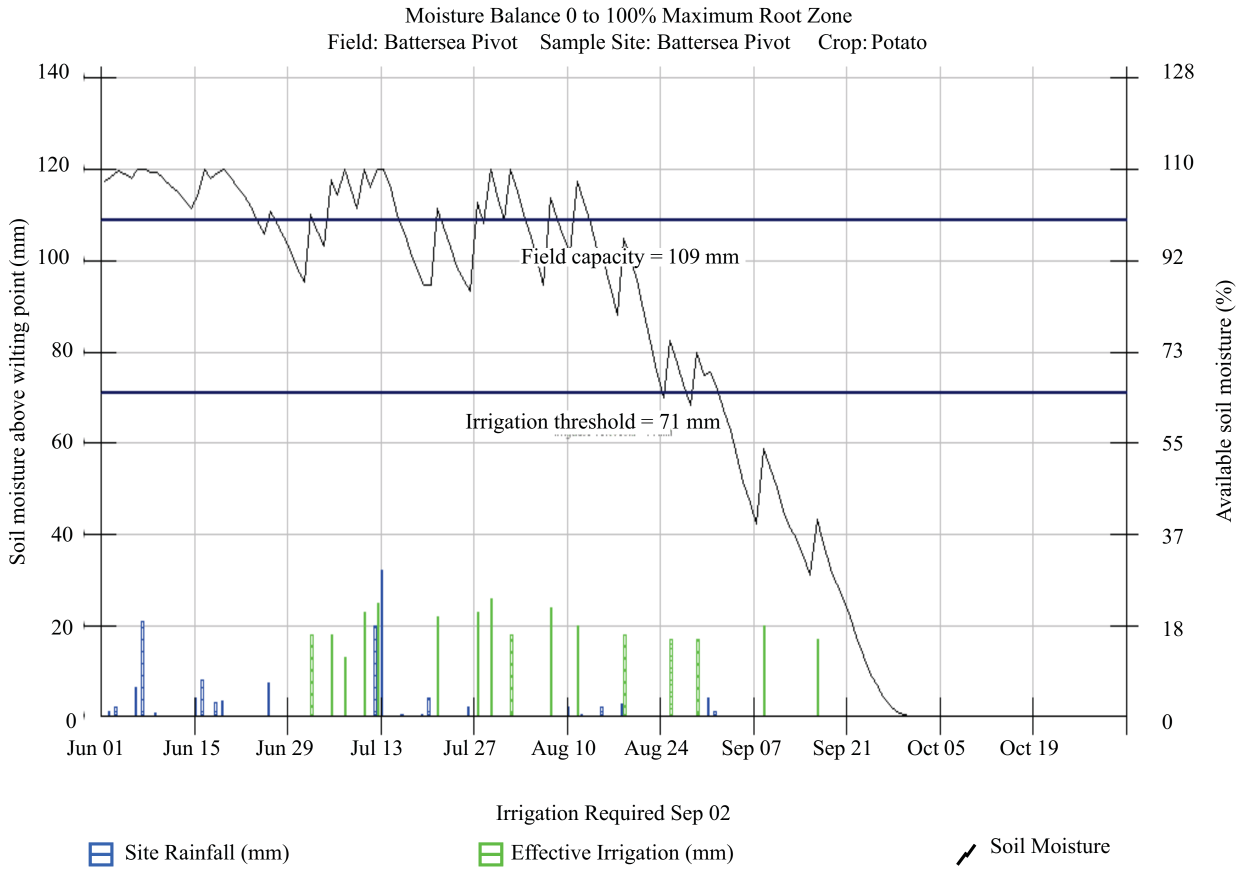

Figure 5.15. Alberta Irrigation Management Model output for the Battersea Drain Field in 2011.

In 2012, the AIMM simulation was initiated on May 28, which was when the first irrigation circle was completed for seed germination. The corn crop was seeded on May 10 (Table 5.1). Precipitation in April and May was averaged; whereas, the precipitation in June was twice the 30-yr average (Table 5.4) and resulted in predicted soil moisture content above FC (Figure 5.16). Essentially no irrigation occurred in June. The two irrigation circles applied on July 11 and 14 were followed by rain and the soil moisture exceeded FC and generated runoff (Table 5.13). For the remaining of the season, irrigation and rain maintained the TAW in the appropriate zone to meet crop needs and minimized the risk of runoff.

The above results showed that AIMM was able to reasonably predict soil moisture at the BDF site. When soil was near or at FC, runoff risk was greater when water was applied by irrigation or rainfall under these soil conditions. Forecasting no irrigation when soil is wet will likely reduce runoff risk. However, it was not established whether or not excessive irrigation was practiced during the pre-BMP period at this site. Ideally, the AIMM model should have been applied during the pre-BMP period to determine if over irrigation had occurred and whether there would have

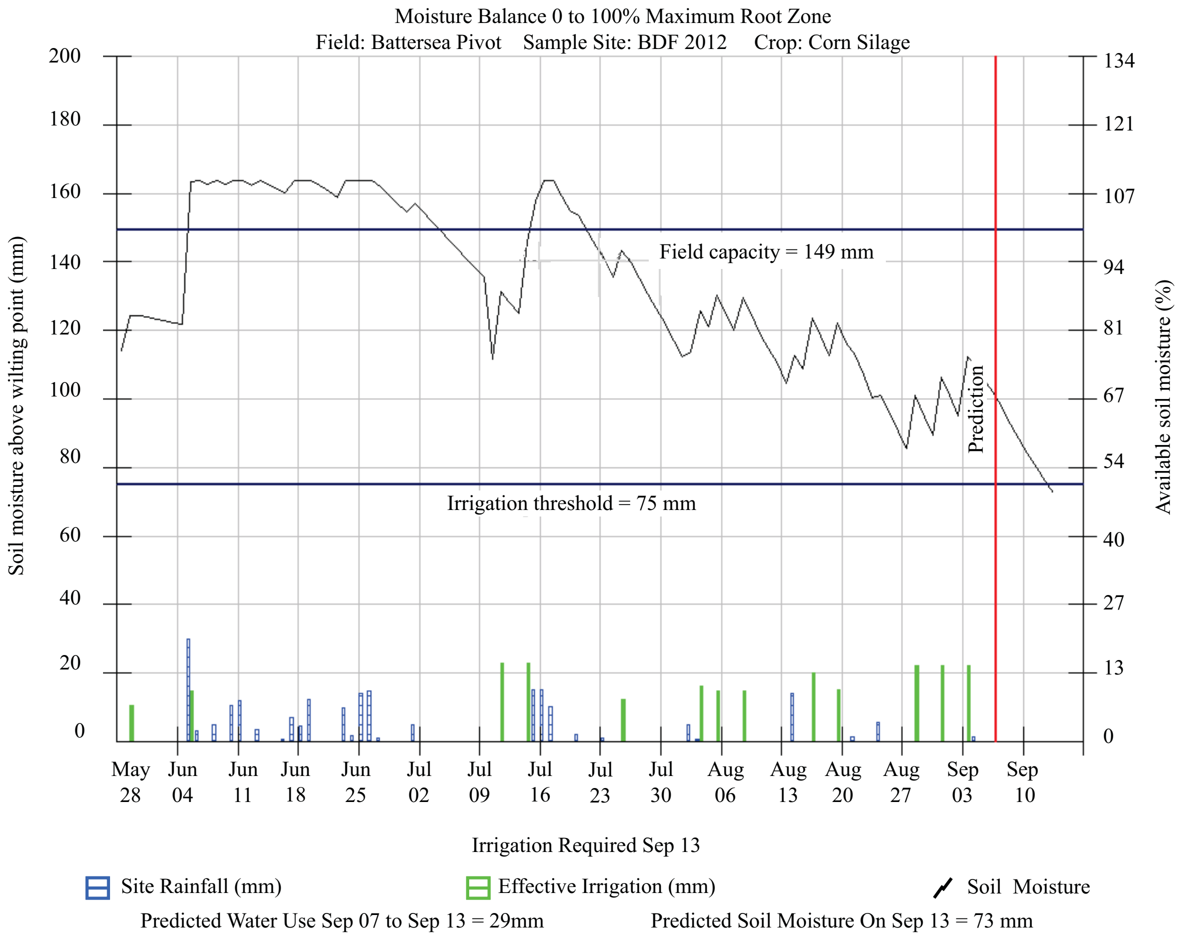

Figure 5.16. Alberta Irrigation Management Model output for the Battersea Drain Field in 2012.

been opportunities to have recommended no irrigation. It should not be assumed that over irrigation would occur if AIMM is not used, as was the case for this site. Nitschelm et al. (2011) showed that irrigators using low-pressure pivots met about 90% of optimum water use, and that 90% of fields in their study were irrigated to or below optimum crop water use. The AIMM program was designed to achieve optimum crop production under irrigation, and irrigation will be recommended when soil water content becomes too low. Using the model to prevent unnecessary irrigation is more for efficiency and conservation management of water, and reduction of runoff at a runoff-prone site would be a secondary benefit. Rainfall shorty after a major irrigation event increases the risk of runoff, and this cannot be prevented by using AIMM. The increased risk of runoff after irrigation will depend on the amount and intensity of rainfall.

5.3.6 Pivot Irrigation System Modification BMP

From 2007 to 2012, annual quantity of irrigation water applied to the field ranged from 78 to 469 mm depending on the crop, climatic variables, and irrigation management (Table 5.14). The year with the most irrigation (2007) also had least amount of precipitation compared to the other years, and was well below the 30-yr average (Table 5.4). Conversely, the least amount of irrigation was in 2010, which also had the most precipitation compared to the other years.

The irrigation rate over the irrigation runoff sensitive area was reduced in the post-BMP period (Figures 5.17 and 5.18). In the northeast area of the field, the irrigation rate was reduced from approximately 60 L s^{-1} in the pre-BMP period to about 35 L s^{-1} during the post-BMP period. In the southwest area, the corner arm never fully extended because of the large dugout in the corner of the field. In the pre-BMP period, the irrigation rate was of 45 L s^{-1} for the short period of time required for the corner arm to move over the drain in the southwest area. In the post-BMP period, the reduced irrigation rate of 45 L s^{-1} was extended to a longer period while the corner arm moved over the runoff sensitive area. After 2009, nozzles on the last span of the main pivot system were modified and should have resulted in a further reduction in the irrigation rate when the system was moved over the runoff sensitive areas. Unfortunately, this further modification was generally not operational (Figures 5.17 and 5.19).

The producer reported difficulty in programming the new irrigation control panel, and the pivot modification did not always work as expected (Figure 5.20). The landowner of the Lower Little Bow BMP site also reported that the design of the irrigation control panel program was not user friendly and was difficult to program (Section 6). Perhaps different or improved precision irrigation technology may overcome some of the difficulties encountered with the system used in the current study.

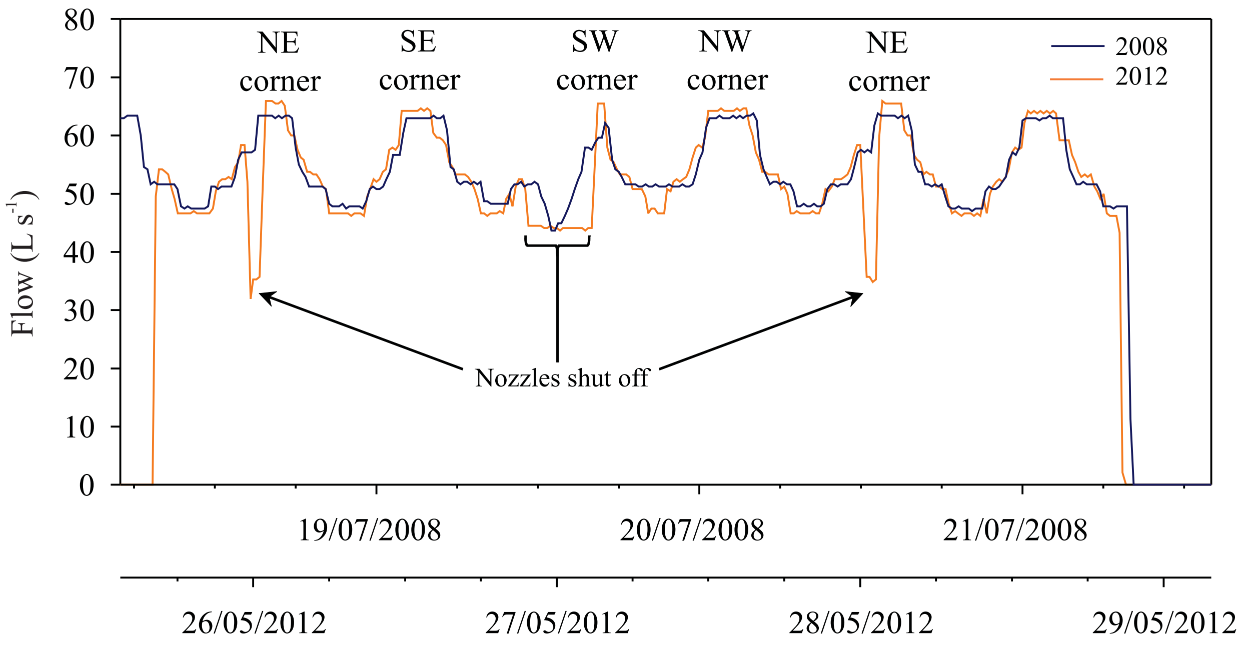

Figure 5.17. Pre (2008) and post (2012) BMP irrigation flow rate at the Battersea Drain Field. The four ordinal directions indicate when the corner arm was active within one circle of the pivot.

Figure 5.18. Pivot irrigation system at the Battersea Drain Field showing the corner arm nozzles turned off as the pivot passed over the runoff sensitive area of the northeast corner on July 16, 2010.

Figure 5.19. Irrigation system with only the corner arm nozzles turned off (right from the wheels) while moving over the southwest area of Battersea Drain Field on July 12, 2011.

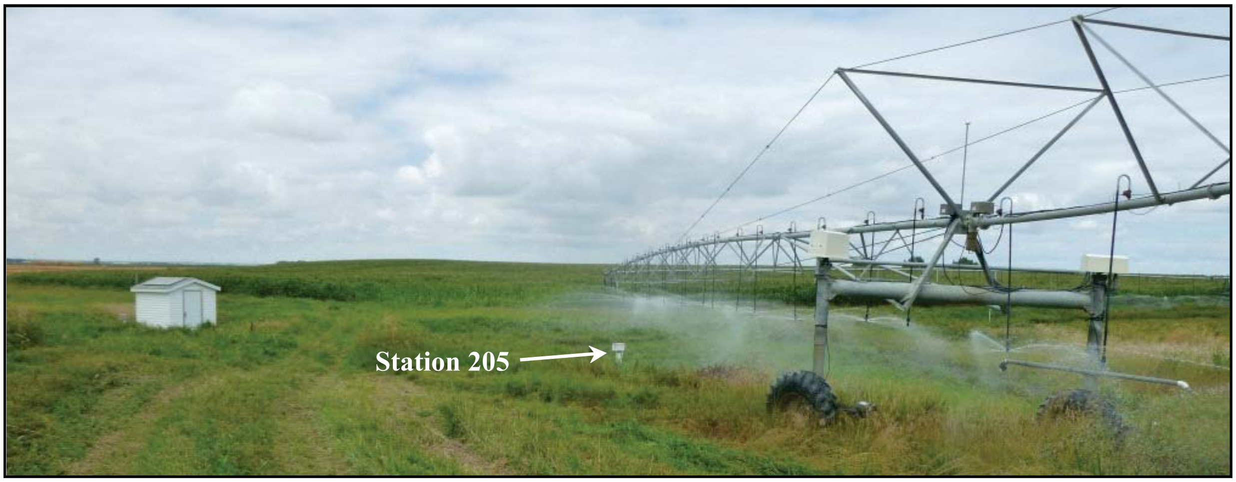

Figure 5.20. Irrigation water being applied from the corner arm over the southwest corner of Battersea Drain Field on August 15, 2012.

The evaluation of the effectiveness of the BMP was challenging for a variety of reasons including the inconsistency in the reduced application rate over the runoff sensitive areas (i.e., control panel programming issues), the irrigation flow datalogger malfunction, and the inability to measure runoff flow for extended periods when water from the drain was backed up into the circular flumes (Figure 5.21). Furthermore, a low area in front of Station 205 remained saturated for extensive periods of time (Figure 5.22) because of the drain back-up, runoff directed from the quarter section south of BDF (Figure 5.23a), or pivot system malfunction (Figure 5.23b). Therefore, Station 205 was prone to runoff from any additional water, irrigation or rain, to the runoff sensitive area. Furthermore, the pivot system wheel tracks created preferential flow channels for runoff towards the runoff sensitive areas (Figure 5.24). Finally, the average annual total irrigation water applied was about two-fold greater in the pre-BMP period compared to the post-BMP period (Table 5.14).

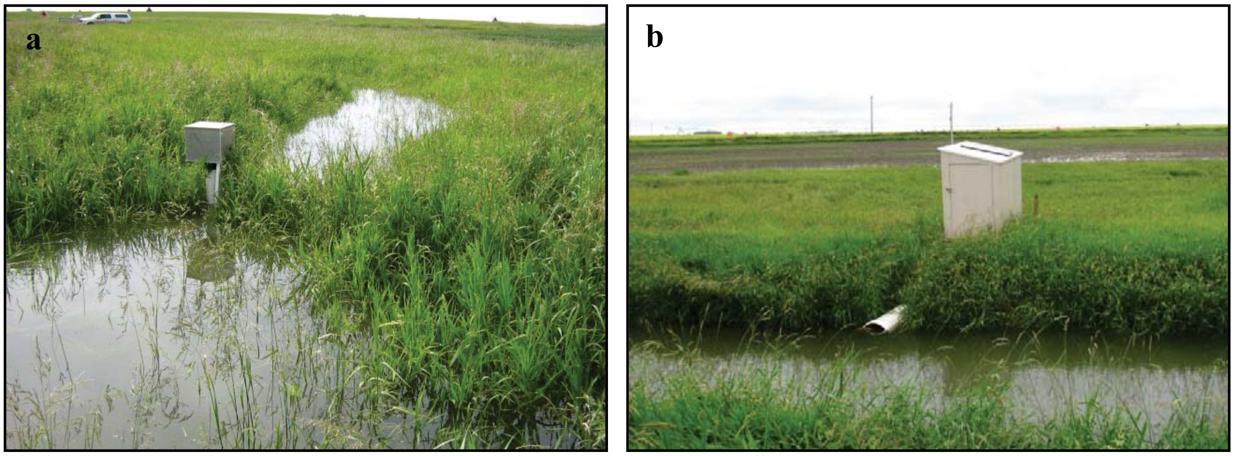

Figure 5.21. Battersea Drain water level backed up into (a) Stations 206 and (b) 204.

Figure 5.22. Extended period of water accumulation in the runoff sensitive area of Station 205 on July 12, 2011 at the Battersea Field Drain.

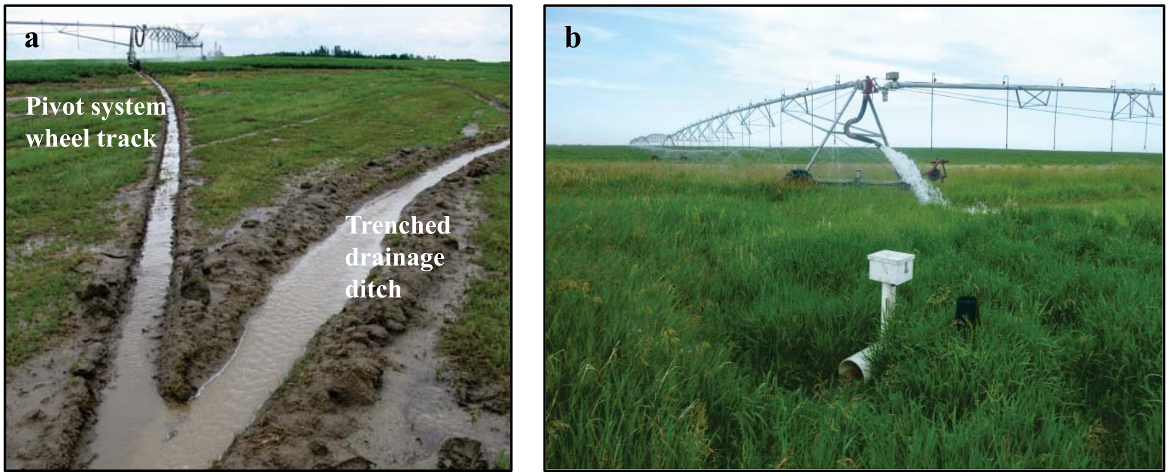

Figure 5.23. Images showing (a) a trenched drainage channel directing water from the quarter section south of Battersea Drain Field towards Station 205 on July 12, 2011, and (b) an irrigation pivot malfunction at Station 205 on July 9, 2012.

Irrigation runoff was observed every time the pivot irrigation system passed over Station 204, 205, and 206 during the pre-BMP period. From all the irrigation events that occurred in the post-BMP period, only a few pivot circles could be used to evaluate the effectiveness of the reduced irrigation rate over the runoff sensitive areas. There was large variability in irrigation runoff volume, peak flow, and duration among irrigation events at Stations 204, 205, and 206. During some irrigation events, the pivot modification BMP completely eliminated irrigation runoff. For example, no irrigation runoff was recorded at Station 206 in 2010. However, in general, irrigation runoff still occurred at these three stations in the post-BMP period, though irrigation runoff volume, duration, and peak flow were all reduced or irrigation runoff was eliminated per irrigation event for the events when the reduced irrigation flow BMP worked properly and irrigation runoff was measured (Table 5.15). On an annual basis, about 0.8 and 3% of total irrigation water applied was lost as runoff in 2007 and 2008 (pre-BMP period), respectively, compared to less than 1% or no runoff in the post-BMP period (Tables 5.13 and 5.14). In addition, the producer expressed that higher crop yield occurred in the runoff sensitive areas. This was attributed to the reduction in the amount of irrigation water applied, which in turn caused these areas to be less saturated with water, and this had a positive effect on crop growth.

5.3.7. Cost of Beneficial Management Practices

The cost of the BMPs implemented at the BDF site was mostly associated with transportation of manure to alternate fields and with the modification to the pivot irrigation system (Table 5.16). From 2008 to 2011, the producer agreed not to apply manure at the BDF site. As a result, the manure that would have been applied to the BDF site was transported to alternate sites, which involved greater transportation distances from the feedlot in two of the three years. In 2008, the

Figure 5.24. Preferential flow channel created by the irrigation pivot system wheel tracks at the Battersea Drain Field. Images taken July 12, 2011 (left) and June 5, 2012 (right).

Table 5.15. Average runoff volume, duration, and peak flow per irrigation event at the edge-of-field runoff monitoring stations during the pre-BMP (2007 to 2008) and post-BMP (2009 to 2012) periods.

Station	BMP period	Water volume (m^3)	Duration (hr)	Peak flow ($m^3\ s^{-1}$)
204	Pre	57.3	24.1	2.7
	Post	50.9	18.3	2.4
205	Pre	110.8	31.0	7.2
	Post	54.5	19.4	3.1
206	Pre	24.3	19.0	2.6
	Post	13.3	5.0	1.1

alternate field was the same distance from the feedlot as the BDF, resulting in no net increase in hauling cost of manure. In 2009 and 2010, the alternate field was 6.5 km further away and resulted in a net increase in manure hauling costs, which accounted for 69% of the total cost of the BMPs. The modification to the pivot irrigation system in 2009 and 2010 accounted for nearly all (30%) of the remaining BMP costs.

Table 5.16. Cost of the beneficial management practices implemented at the Battersea Drain Field.

Year	Item	Cost ($)	Labour (h)
2008	Soil testing[z]	103	2
	Manure hauling[y]	0	
	Sub-total	**103**	**2**
2009	Soil testing	103	
	Rain gauges	15	
	Control panel for pivot	8,445	3
	Control panel installation	720	
	Manure hauling	14,840	
	BMP maintenance and management	-	2
	Sub-total	**24,123**	**7**
2010	Pivot modifications - equipment	1,500	
	Pivot modifications - installation	2,220	
	Soil testing	103	2
	Manure hauling	15,370	
	BMP maintenance and management[x]	-	6
	Sub-total	**19,193**	**8**
2011	Soil testing	103	2
	BMP maintenance and management[x]	-	6
	Sub-total	**103**	**8**
2012	Soil testing	103	2
	BMP maintenance and management[x]	-	6
	Sub-total	**103**	**8**
	Grand total	**43,625**	**33**

[z] Three samples (0 to15, 15 to 30, and 30 to 60 cm) per year, and the cost of analysis was $34.25 per sample.
[y] The 2008 alternative manure application site was located nearby and did not generate additional transportation cost. The 2009 and 2010 cost was based on Toma and Bouma Management Consultants (2006) with an application rate of 87.5 Mg ha^{-1}, 7 km of additional transportation distance, and an annual 4% increase in price.
[x] Includes running AIMM and developing a nutrient management plan.

5.3.8 Water Quality

5.3.8.1 Instream Water Quality

During high-flow conditions in the drain, when irrigation water was released from the Picture Butte Reservoir, the average annual concentrations of all N and P parameters, TSS, and EC were the highest in 2010 and 2011 and the lowest in 2007 at the upstream and downstream monitoring stations (Table 5.17). Total precipitation was the highest and well above average in 2010; whereas, the lowest amount of precipitation was in 2007 (Table 5.4). Precipitation was also above the 30-yr average in 2011. As indicated above, the most amount of irrigation water applied to the BDF sites was in 2007 and least amount applied was in 2010 (Table 5.14). Perhaps in dry years (e.g., 2007), more water was released into the drain from the Picture Butte Reservoir for irrigation and there were less contributions from runoff into the drain. Conversely, in wet years, less water may have been released from the reservoir and there were more contributions from runoff into the drain. For example, in spring 2010, there was less irrigation source water in the drain because of extensive rainfall (Ryan Chogi, Water Master with the Lethbridge Northern Irrigation District, personal communication). We hypothesize the latter scenario would result in higher nutrient concentrations in water in the drain compared to the former scenario.

In our study, the Picture Butte Reservoir was 9.5 km upstream from Station 201, which in turn was 1 km upstream from Station 202. In a separate study, water immediately downstream from the reservoir was sampled four times per year for 5 yr from 2007 to 2013 (Little et al. 2010; Charest et al. 2014). Water exiting the reservoir contained on average (n = 20) 0.47 mg $L^{-1}$of TN, 0.03 mg L^{-1} of TP, and EC was 280 µS cm^{-1}. In the drier years (2007, 2009, and 2012), the concentrations of TN, TP, and EC at Station 201 were more similar to the water exiting the reservoir compared to the wetter years (2008, 2010, and 2011) when the concentrations of TN, TP, and EC were higher. This suggests that years of high precipitation may have resulted in more runoff contributions to the drain and a greater degree of water quality degradation during high-flow conditions, supporting the above hypothesis.

During the low-flow periods, the high and low concentrations of water quality parameters in the drain were not dominant in any particular year (Table 5.17). This may reflect the difference in source water between the two flow periods. During the low-flow periods, water in the drain was from shallow groundwater discharge and snowmelt and rainfall runoff early in the spring. This is in contrast to the high-flow periods, which were mainly regulated by irrigation water released from the Picture Butte Reservoir.

Generally, the average concentrations of most water quality parameters were comparable between high- and low-flow periods at the upstream Station 201 (Table 5.17). The exceptions were for TSS, *E. coli*, and EC. The concentration of *E. coli* was 20-fold greater during high flow and this was likely due to greater microbial activity during the warmer conditions of the high-flow periods. Electrical conductivity was two-fold greater and TSS concentration was 1.8-fold greater during low-flow compared to high-flow. At the downstream Station 202, there were similar observations for average concentrations for TSS, *E. coli*, and EC between the high- and low-flow periods (Table 5.17). The average concentrations of TP and particulate phosphorus (PP) were similar between the two periods and TDP was slightly less during low-flow. In contrast, the average concentrations of TN and NO_3-N were four-fold and 10-fold greater, respectively, during low flow compared to high flow at Station 202.

Table 5.17. Average concentration of water quality parameters at Stations 201 (upstream) and 202 (downstream) during high flow (irrigation season) and low flow (outside of irrigation season) at the Battersea Drain Field site from 2007 to 2012.[z,y]

	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli*	EC	
Year[x]	------------------------------- (mg L^{-1}) -------------------------------									(mpn 100 mL^{-1})	($\mu S\ cm^{-1}$)	pH
					High flow - Station 201							
2007 (25)	0.47	0.40	0.03	0.03	0.05	0.02	0.03	20	na[w]	284	313	7.73
2008 (37)	1.32	1.14	0.09	0.06	0.21	0.09	0.13	44	2.58[v]	2258	494	8.13
2009 (30)	0.78	0.61	0.11	0.03	0.10	0.06	0.03	12	3.79	935	377	8.30
2010 (32)	5.39	1.85	2.59	0.84	0.99	0.75	0.24	35	46.5	2520	1228	8.26
2011 (32)	5.66	2.95	0.93	1.72	1.16	0.76	0.40	81	33.2	1366	945	8.08
2012 (7)	0.65	0.55	0.09	0.03	0.11	0.04	0.08	24	2.34	274	349	8.15
Average (163)	*2.71*	*1.40*	*0.74*	*0.53*	*0.50*	*0.33*	*0.17*	*39*	*24.4*	*1503*	*671*	*8.12*
					High flow - Station 202							
2007 (25)	0.49	0.40	0.04	0.03	0.06	0.02	0.02	10	na	291	325	8.10
2008 (37)	1.15	0.92	0.16	0.04	0.16	0.11	0.07	10	3.00[v]	1820	485	8.12
2009 (30)	0.86	0.65	0.15	0.03	0.10	0.07	0.03	10	4.05	768	396	8.31
2010 (32)	5.90	1.83	3.14	0.84	0.97	0.72	0.26	41	49.8	834	1284	8.24
2011 (32)	6.40	3.03	1.46	1.84	1.15	0.82	0.33	25	34.5	1497	969	8.11
2012 (7)	0.63	0.49	0.11	0.03	0.12	0.04	0.08	22	2.65	310	354	8.24
Average (163)	*2.94*	*1.36*	*0.98*	*0.55*	*0.49*	*0.34*	*0.14*	*20*	*25.9*	*1070*	*690*	*8.18*
					Low flow - Station 201							
2007 (7)	1.84	0.94	0.51	0.38	0.18	0.08	0.10	25	na	27	1244	7.99
2008 (9)	1.86	1.34	0.13	0.36	0.53	0.11	0.43	151	19.8[v]	13	1340	8.04
2009 (13)	3.28	1.61	1.11	0.52	0.42	0.23	0.19	49	32.8	276	1508	8.14
2010 (23)	3.50	1.55	0.60	1.31	0.85	0.48	0.37	69	19.3	20	1026	7.78
2011 (3)[u]	5.61	0.78	3.50	0.96	0.24	0.05	0.19	76	42.6	39	2287	7.89
2012 (5)[u]	3.68	1.07	1.74	0.83	0.24	0.08	0.16	31	47.6	3	2232	8.02
Average (60)	*3.13*	*1.38*	*0.87*	*0.83*	*0.55*	*0.27*	*0.28*	*69*	*27.6*	*75*	*1367*	*7.95*
					Low flow - Station 202							
2007 (7)	13.0	1.45	11.0	0.51	0.15	0.08	0.07	17	na	15	1630	8.10
2008 (9)	13.4	1.67	11.0	0.53	0.29	0.03	0.26	179	52.8[v]	34	1588	8.01
2009 (13)	9.96	1.56	7.78	0.48	0.28	0.18	0.10	20	45.8	224	1624	8.11
2010 (23)	9.70	1.53	6.59	1.42	0.71	0.49	0.21	25	32.0	15	1187	7.80
2011 (3)[u]	25.6	0.65	24.1	0.63	0.08	0.03	0.06	35	77.0	29	2310	7.94
2012 (5)[u]	26.9	5.42	20.7	0.67	0.12	0.03	0.09	18	72.0	5	2438	8.07
Average (60)	*12.9*	*1.83*	*10.1*	*0.87*	*0.41*	*0.24*	*0.16*	*46*	*44.3*	*63*	*1554*	*7.96*

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, *E. coli* = *Escherichia coli*, EC = electrical conductivity.
[y] High flow corresponded to when irrigation water was diverted from the Picture Butte Reservoir into the Battersea Drain (early May to early October). Low flow was outside of the irrigation season when irrigation water was diverted.
[x] Number of samples are shown in parenthesis.
[w] na = not analyzed.
[v] Chloride was added in late July 2008; n = 13 for high flow and n = 3 for low flow.
[u] The low-flow samples in 2011 and all samples in 2012 were collected after the manure application on September 21, 2011.

During the high-flow periods, the average concentration of ON, NH_3-N, TP, TDP, Cl, and EC were similar between the upstream and downstream stations (i.e., within 5% of each other) (Table 5.17). Total N increased 8% and NO_3-N increased 32% from upstream to downstream; whereas, the concentrations of PP, TSS, and *E. coli* decreased from upstream to downstream. During low-flow periods, the average concentration of TN increased by more than 4-fold and NO_3-N increased by more than 11-fold from upstream to downstream (Table 5.17). The average concentrations of ON and Cl also increased but not to the same extent, and the average concentration of NH_3-N was similar between the two stations. In contrast to the N parameters, the average concentrations of the P parameters, TSS, and *E. coli* decreased from upstream to downstream during low flow.

The discussion above and the results in Table 5.17 clearly show a substantial increase in TN and NO_3-N concentrations during low flow from upstream to downstream, resulting in an annual cycle of changing TN and NO_3-N concentrations in the drain (Figure 5.25a,c). The fact that the average concentrations were relatively similar between high- and low-flow periods at Station 201, suggests that most of the increase in TN and NO_3-N concentrations occurred within the reach between the two stations. During the low-flow periods (fall to spring), water in the drain was maintained by discharge from shallow groundwater. The water table throughout the area is typically less than 3.5 m below ground surface (Rodvang et al. 2004). Olson et al. (2009) measured 8-yr average water table depths of 2.1 and 2.5 m at two nearby sites in the Battersea area. The presences of shallow groundwater in the area suggest the increase in N concentration in the drain was caused by groundwater discharge with high N concentration. The increase in TN concentration was primarily caused by NO_3-N, as ON concentration increased by only 32% from upstream to downstream and NH_3-N concentration was similar between the two stations (Table 5.17). The portion of TN as dissolved inorganic N (NO_3-N plus NH_3-N) increased from 54% at Station 201 to 85% at Station 202 during low flow; whereas, percent dissolved inorganic N was similar (47% at Station 201 vs. 52% at Station 202) between the two stations during high flow.

The high application rates of manure for many years at the BDF site was likely the source of NO_3-N, as well as commercial fertilizer N that may have been applied in some years. The combination of a course-textured soil and irrigation water, along with excess nutrients from manure, created a high-risk potential for NO_3-N leaching at this site. From an 8-yr manure application small-plot study in the Battersea area, Olson et al. (2009) reported NO_3-N concentrations in groundwater for the control treatment (i.e., no manure) ranged from 10 to 95 mg L^{-1} under a coarse-textured soil and 1 to 13 mg L^{-1} under a medium-texture soil. They found even higher concentrations of NO_3-N in groundwater under manure application treatments at the coarse-textured site. Furthermore, the observed increase in Cl concentration from upstream to downstream during low flow in the current study suggests manure applied to the field was the likely source. Chloride in manure can be used as a tracer or indicator for the movement of soluble constituents from applied manure.

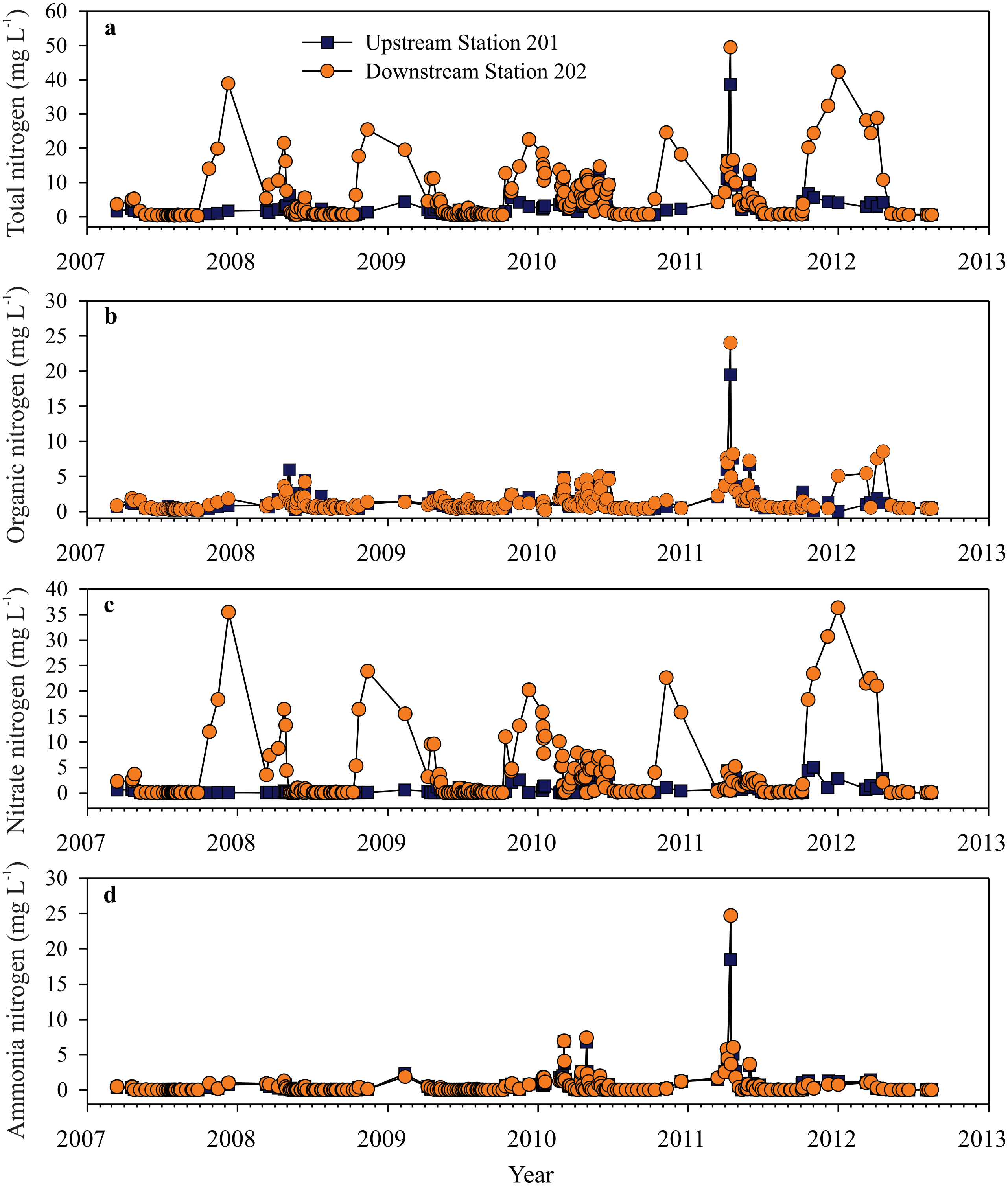

Figure 5.25. Concentrations of (a) total nitrogen, (b) organic nitrogen, (c) nitrate nitrogen, and (d) ammonia nitrogen at the upstream Station 201 and downstream Station 202 at the Battersea Drain Field from 2007 to 2012.

During higher flow periods, water in the drain was largely influenced by water released from the reservoir, and this water contained relatively low N concentrations, as indicated above. The greater volume of water in the drain likely recharged into the local groundwater, and thus, groundwater with high N concentration may not have entered the drain during this this period. Zilkey (2001) found at a site about 5 km further downstream from the BDF site that when water levels in the drain were high, seepage rates and mass fluxes of NO_3-N and TP into the drain were low to negative; whereas, when water levels dropped in the drain, the hydraulic gradient reversed and seepage rate and mass flux of NO_3-N and TP dramatically increased into the drain.

Peak concentration of NO_3-N (and TN) during the low-flow periods was measured in November or December (Figure 5.25c). The concentration of NO_3-N then dramatically decreased towards spring. Perhaps frozen conditions in the soil profile reduced the leaching rate of NO_3-N. In April of most years, there was an increase in NO_3-N concentration prior to the start of the high-flow period. This increase in spring may have been caused by an increase in NO_3-N leaching rate as the soil profile thawed.

Total P and TDP did not behave as dramatically as N in the Battersea Drain water. In fact, average concentrations of TP and TDP were similar between the two stations and between the high- and low-flow periods. There was actually a 25% decrease in TP concentration and an 11% decrease in TDP concentration from upstream to downstream during low flow (Table 5.17). In contrast to N, groundwater discharge into the drain may have caused a slight dilution effect on TP and TDP concentration in water that entered this reach of the drain at Station 201. During high flow, 66% of TP was in the form of TDP on average at Station 201 and increased slightly to 71% at Station 202. During low flow, there was about equal proportions of TDP and PP at Station 201 and TP was 60% TDP at Station 202. The increase in the portion of TP as TDP from upstream to downstream was mainly due to a reduction in PP concentration, which was accompanied by a reduction in TSS concentration. The TP and TDP peak concentrations generally corresponded to the snowmelt events in January, February, and March 2010 and especially to the rainfall events from mid-April to mid-June (Figure 5.26a,b). In 2011, TP and TDP peak concentrations corresponded to rainfall runoff events in May and June and especially to the snowmelt events in March and April. Particulate P and TSS concentrations were highest on April 29, 2008, February 22, 2010, and in October 2011 at the upstream station (Figure 5.26c,d). The high values in February 2010 may have been caused by sediment disturbance when the surface ice was broken in order to sample the water.

Concentration of *E. coli* in all 6 yr ranged from 0.5 to 59,540 mpn 100 mL^{-1} at the upstream station and from 0.5 to 28,000 mpn 100 mL^{-1} at the downstream station (Figure 5.27). Generally, peak concentrations occurred from late May to July. The high concentration at the upstream station in late May 2010 was the highest value recorded at the two instream sites during 6 yr of monitoring. A similarly high value of 39,000 mpn 100 mL^{-1} was observed at this station in spring 2008. The high *E. coli* concentrations were linked with heavy rainfall events in 2008, 2009, and 2010; however, there were also peaks in April and October in 2011. In 2007 and 2012, there was a lack of heavy rainfall events throughout the growing season and *E. coli* concentrations ranged from 0.5 to 1000 mpn 100 mL^{-1}.

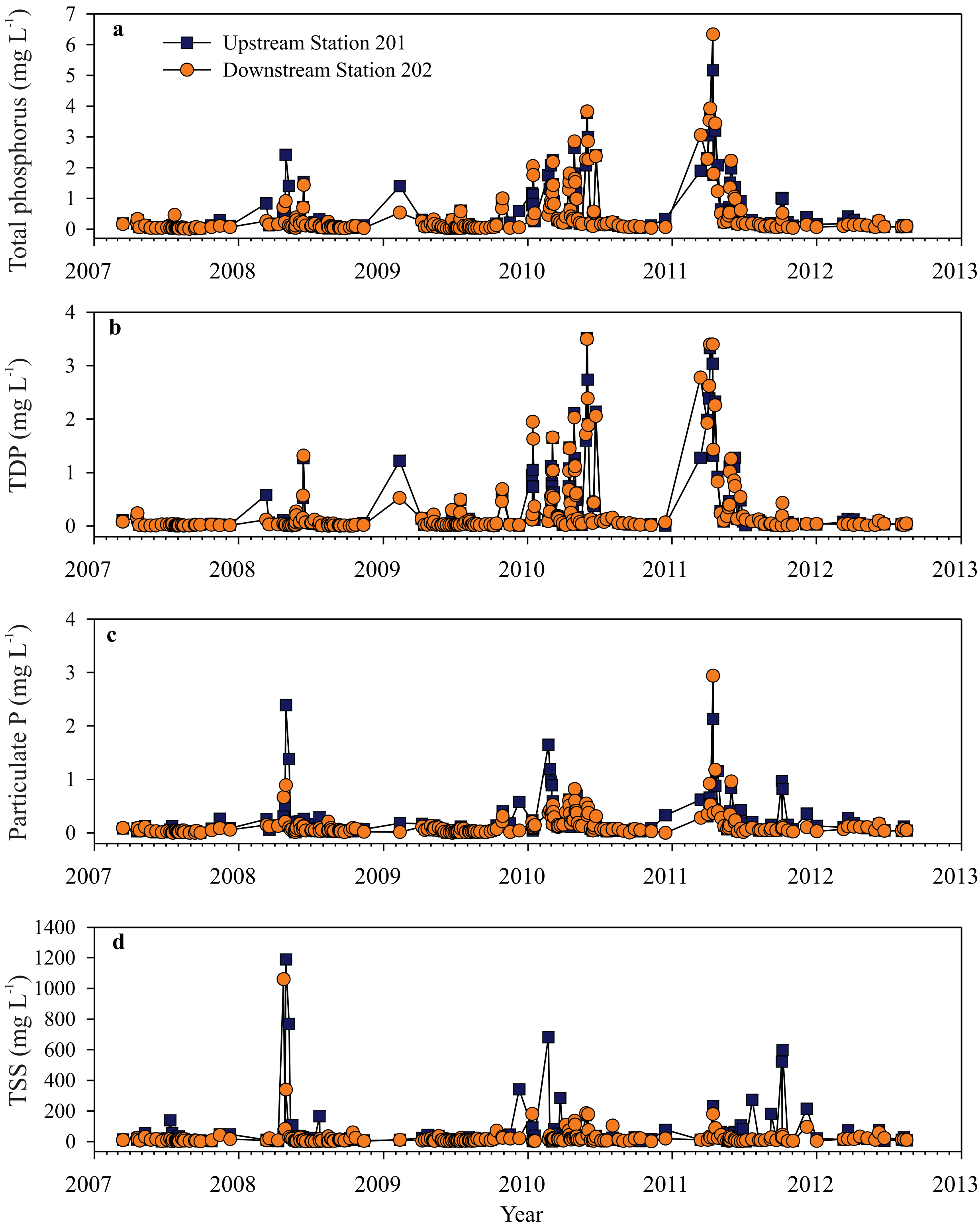

Figure 5.26. Concentrations of (a) total phosphorus, (b) total dissolved phosphorus (TDP), (c) particulate phosphorus, and (d) total suspended solids (TSS) at the upstream Station 201 and downstream Station 202 at the Battersea Drain Field from 2007 to 2012.

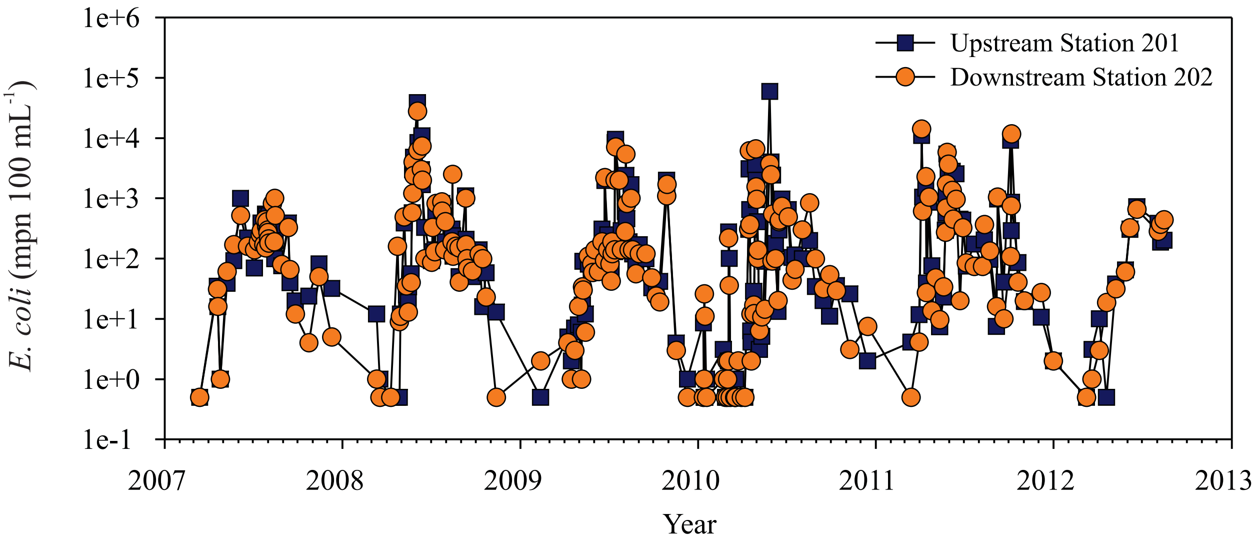

Figure 5.27. Concentration values of *Escherichia coli* (*E. coli*) at the upstream Station 201 and downstream Station 202 at the Battersea Drain Field from 2007 to 2012.

The instream loads of nutrients and TSS were largest in 2010 and generally the smallest in 2007 compared to the other years during high flow and for high flow and low flow combined (Table 5.18). Even though 2007 had the second highest annual flow (Figure 5.11), concentrations were the lowest in 2007, resulting in the smallest loads during the study. Annual flow was not the highest in 2010, but because of high parameter concentrations, the largest loads were observed in 2010. The concentrations of many parameters were higher in 2011, but because the annual flow was 14% less in 2011 compared to 2010, smaller loads occurred in the former year. It is interesting that NO_3-N load was 1.7-fold greater during the low-flow period compared to the high-flow period, even though low-flow was less than 10% of the total annual flow. The load for NH_3-N was also slightly higher during low flow. It would appear that NO_3-N leached from the BDF site and into groundwater contributed a large portion of the N load in the reach between Stations 201 and 202.

Table 5.18. Load values for nutrients and total suspended solids at the downstream water monitoring station (Station 202) at the Battersea Drain Field site from 2007 to 2012.[z]

Year	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS
	----	----	----	(kg yr^{-1})	----	----	----	----
				Low flow				
2007	3,100	623	2314	130	54	14	40	10,337
2008	6,680	816	5610	168	61	12	49	127,534
2009	3,765	307	3283	165	54	32	23	6,637
2010	3,998	839	2234	876	454	307	147	20,056
2011	6,155	2095	2643	1371	950	710	240	22,990
2012	5,008	1700	3183	105	31	8	23	5,820
Average	*4,784*	*1,063*	*3,211*	*469*	*267*	*181*	*87*	*32,229*
				High flow				
2007	2,508	1981	203	174	294	126	97	46,703
2008	4,586	3706	552	182	599	305	311	54,615
2009	3,653	2884	510	142	379	235	144	49,435
2010	14,973	6122	7395	1131	3227	2635	592	193,027
2011	5,616	3322	1773	475	891	548	343	59,752
2012	3,556	2814	582	156	608	256	351	108,543
Average	*5,815*	*3,472*	*1,836*	*377*	*1,000*	*684*	*306*	*85,346*
				Overall				
2007	5,608	2603	2517	304	348	140	136	57,040
2008	11,267	4522	6162	350	660	317	359	182,149
2009	7,418	3191	3793	307	433	266	167	56,072
2010	18,970	6961	9629	2006	3682	2942	739	213,083
2011	11,770	5417	4417	1846	1841	1259	582	82,742
2012[y]	8,564	4514	3765	261	638	264	374	114,363
Average	*10,600*	*4,535*	*5,047*	*846*	*1,267*	*865*	*393*	*117,575*

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids.
[y] Annual flow in 2012 included flow from January 1 to September 30.

5.3.8.2 Edge-of-field Water Quality

The concentration of water quality parameters in surface runoff from the BDF site and into the Battersea Drain varied with year, runoff type, and monitoring station (Tables 5.19 to 5.24). Since the four edge-of-field stations were placed at drainage points from the same field, which was under one management practice, the data from the four stations were combined to simplify comparisons (Table 5.25).

For the most part, no one year had consistently low or high concentrations in runoff for most water quality parameters. The one exception was in 2008 when average concentrations of nearly all of the parameters were the lowest in snowmelt runoff compared to the other 3 yr that had snowmelt runoff samples (Table 5.25). Also in 2008, the highest average concentration of TP and TDP was observed in rainfall and irrigation compared to the other years. These high concentrations may have been caused by the application of manure that occurred in fall 2007. The least amount of precipitation was in 2007 and the most precipitation was in 2010 (Table 5.4). However, the amount

Table 5.19. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2007.[z]

Station[x]	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl[y]	*E. coli*	EC	pH
	($mg\ L^{-1}$)									($mpn\ 100\ mL^{-1}$)	($\mu S\ cm^{-1}$)	
						2007 Rainfall						
203 (1)	2.21	2.00	0.08	0.10	2.32	2.23	0.09	6	ns[w]	0.5	868	8.00
204 (1)	17.9	6.80	10.8	0.12	6.31	6.20	0.11	4	ns	0.5	4140	8.10
205 (2)	11.8	2.74	8.89	0.12	0.69	0.49	0.20	5	ns	2	2115	8.00
206 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
						2007 Irrigation						
203 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
204 (6)	3.54	3.25	0.20	0.07	3.02	2.71	0.31	41	ns	4981	1492	8.23
205 (9)	3.85	3.02	0.59	0.16	1.01	0.43	0.57	281	ns	4471	884	7.94
206 (8)	2.83	2.61	0.10	0.09	2.01	1.83	0.19	35	ns	2234	535	8.20
						2007 All						
203 (1)	2.21	2.00	0.08	0.10	2.32	2.23	0.09	6	ns	1	868	8.00
204 (7)	5.59	3.75	1.71	0.08	3.49	3.20	0.28	36	ns	4270	1870	8.21
205 (11)	5.29	2.97	2.10	0.15	0.95	0.44	0.51	231	ns	3659	1108	7.95
206 (8)	2.83	2.61	0.10	0.09	2.01	1.83	0.19	35	ns	2234	535	8.20

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] This water quality parameter was not added until late July 2008.
[x] Number of sample are shown in parentheses.
[w] ns = not sampled.

of precipitation did not seem to bias low or high concentration of the water quality parameters among the years. Perhaps, in drier years, with the application of supplemental water through irrigation, the potential effects of precipitation amounts on the average concentration in runoff water were negated.

The average concentrations of nearly all parameters in edge-of-field runoff were higher in rainfall compared to snowmelt events (Table 5.25). For example, TN was 1.7-fold higher and TP was 1.3-fold higher in rainfall runoff than in snowmelt runoff. The largest difference was for *E. coli*, which was 84-fold higher in rainfall runoff, and this was attributed to greater microbial activity caused by warmer temperature under rainfall conditions. The concentrations of TN, NO_3-N, NH_3-N, TP, TDP, Cl, and EC were also higher in rainfall compared to irrigation (Table 5.25). The largest differences were for NO_3-N and NH_3-N, which had average concentrations about 5-fold higher in rainfall runoff. For the other parameters (PP, TSS, and *E. coli*), concentrations in rainfall runoff were 47 to 64% of the concentrations in irrigation runoff. The comparison between snowmelt and irrigation runoff was less consistent. Average concentrations were higher (ON, PP, TSS, *E. coli*, and EC), lower (TN, NO_3-N, and NH_3-N), or similar (TP, TDP, Cl) in irrigation runoff

Table 5.20. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2008.[z]

	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl[y]	*E. coli*	EC	
Station[x]	--------------------------------				(mg L^{-1})				--------------------------------	(mpn 100 mL^{-1})	(µS cm^{-1})	pH
						2008 Snowmelt						
203 (3)	2.51	2.08	0.36	0.05	3.28	3.19	0.09	9	na[w]	1	745	8.03
204 (0)	ns[v]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
205 (1)	3.25	3.18	0.03	0.03	0.90	0.61	0.29	200	na	1	1410	8.10
206 (3)	2.62	2.23	0.13	0.24	2.30	2.25	0.05	7	na	2	328	8.03
						2008 Rainfall						
203 (10)	4.53	4.42	0.04	0.04	4.03	3.75	0.29	5	259	321	3428	8.04
204 (14)	8.00	7.14	0.64	0.17	6.05	5.93	0.13	10	137	2,269	3084	8.05
205 (11)	11.6	6.48	4.49	0.35	3.16	2.94	0.21	19	59.4	1,069	1719	7.96
206 (10)	18.3	16.3	0.71	1.28	13.5	12.8	0.68	18	84.5	3,490	1219	7.98
						2008 Irrigation						
203 (3)	5.79	5.25	0.36	0.09	3.71	3.42	0.29	48	223	13,800	4323	8.03
204 (9)	6.19	5.72	0.31	0.12	4.60	4.20	0.40	72	62.8	8,832	2143	8.19
205 (9)	2.96	2.87	0.03	0.04	1.83	1.52	0.31	60	31.5	2,654	1026	7.93
206 (6)	4.25	4.15	0.04	0.04	7.25	6.73	0.52	27	27.9	1,335	701	8.08
						2008 All						
203 (16)	4.39	4.13	0.16	0.05	3.83	3.58	0.25	14	241	2,788	3093	8.04
204 (23)	7.29	6.58	0.51	0.15	5.49	5.25	0.23	34	96	4,655	2716	8.10
205 (21)	7.52	4.77	2.36	0.20	2.48	2.22	0.26	45	45.5	1,649	1407	7.96
206 (19)	11.4	10.2	0.41	0.72	9.75	9.22	0.53	19	50.5	2,310	915	8.02

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] Chloride was added late July 2008. Number of samples analyzed for Cl was 2 (203), 5 (204), 4 (206), 2 (20) for rainfall; 2 (203), 4 (204), 4 (206), 3 (206) for irrigation; and 4 (203), 9 (204), 8 (206), 5 (206) for all.
[x] Number of samples are shown in parentheses.
[w] na = not analyzed.
[v] ns = not sampled.

compare to snowmelt. Of note was that average concentrations of PP and TSS were 1.8-fold and 4.4-fold greater, respectively, in irrigation runoff, and *E. coli* concentration was nearly 180-fold greater in irrigation runoff compared to snowmelt runoff.

The proportion of TN in the form of dissolved inorganic N was 39% in snowmelt and rainfall runoff and 16% in irrigation runoff, with an overall proportion of 16% as dissolved inorganic N (Table 5.25). Therefore, most of the TN was in ON form (Figure 5.28). Even though, on average, TN was dominated by ON, there were several instances when the majority of TN was in the form of NO_3-N, particularly at Station 204 in 2010 and 2011 and at Station 205 in late 2009, 2010, and early 2011 (Figure 5.28). In contrast, most of the TP was in the form of TDP for all three runoff event types, with an overall proportion of 94% (Table 5.25). Particulate P was never a dominant form of TP in runoff water at this site (Figure 5.29).

Table 5.21. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2009.[z]

Station[y]	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli* (mpn 100 mL^{-1})	EC (µS cm^{-1})	pH
	($mg\ L^{-1}$)											
2009 Snowmelt												
203 (4)	2.64	2.12	0.06	0.43	1.56	1.37	0.19	42	9.15	1	498	7.73
204 (1)	8.48	6.89	1.43	0.13	6.88	6.84	0.04	2	270	1	7030	8.24
205 (7)	4.74	2.82	0.49	1.40	0.98	0.90	0.07	11	36.6	17	996	7.86
206 (7)	5.81	4.75	0.34	0.63	6.52	6.09	0.43	12	18.0	20	444	7.83
2009 Rainfall												
203 (5)	4.76	3.99	0.64	0.04	3.06	2.93	0.13	9	76.6	1440	2596	8.03
204 (7)	10.2	6.48	3.62	0.12	5.13	5.03	0.09	9	193	1143	4373	8.12
205 (11)	5.88	2.97	2.75	0.09	2.54	2.17	0.37	282	37.9	1472	996	8.10
206 (3)	5.27	4.62	0.56	0.03	7.07	6.95	0.12	22	23.9	903	642	8.09
2009 Irrigation												
203 (0)	ns[x]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
204 (4)	12.1	7.35	4.44	0.10	4.72	4.44	0.28	12	163	746	4318	8.24
205 (6)	3.23	3.16	0.03	0.03	2.16	2.01	0.15	15	26.8	2048	901	8.30
206 (2)	3.17	3.10	0.03	0.03	5.08	4.97	0.12	19	11.9	7700	567	8.07
2009 All												
203 (9)	3.82	3.16	0.39	0.22	2.39	2.24	0.15	24	46.6	800	1663	7.90
204 (12)	10.7	7.22	3.71	0.11	5.14	4.99	0.15	10	189	916	4576	8.17
205 (24)	4.89	2.97	1.41	0.45	1.99	1.76	0.23	136	34.7	1192	972	8.08
206 (12)	5.24	4.44	0.35	0.38	6.42	6.12	0.30	16	18.5	1521	514	7.94

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] Number of samples are shown in parentheses.
[x] ns = not sampled.

The annual change in the concentration of most N and P parameters varied among years and monitoring stations, with no consistent pattern (Figures 5.28 and 5.29). However, the concentrations of NH_3-N and PP generally remained consistently low with time.

On October 6 and 7, 2011 a rainfall runoff event occurred and caused in relatively high N and P concentrations at Stations 204, 205, and 206 (Figures 5.28 and 5.29). In fact at Stations 205 and 206, the highest concentrations of TN, ON, and NH_3-N during the 6-yr study and the highest concentrations of TP, TDP, and PP in 2011 were measured during the October runoff event. After no manure application in the previous 3 yr as part of the BMP plan, manure was applied in fall 2011. Manure was applied on the west side of the drain on September 21 and on the east side of the drain between October 13 and 21. Therefore, the early October runoff event occurred after the west side received manure, but before the east side received manure. The application of manure on the west could explain the high concentrations at Station 206, but not for Stations 204 and 205, as these two stations were located on the east side of the drain. The application of manure may have

Table 5.22. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2010.[z]

Station[y]	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli*	EC	pH
	($mg\ L^{-1}$)									($mpn\ 100\ mL^{-1}$)	($\mu S\ cm^{-1}$)	
2010 Snowmelt												
203 (2)	3.24	2.57	0.31	0.34	2.88	2.57	0.32	17	9.25	1	334	7.67
204 (5)	9.93	4.81	3.33	1.44	6.28	5.98	0.30	12	74.6	42	2345	7.91
205 (13)	7.53	1.85	4.95	0.52	1.27	1.08	0.19	20	34.8	2	1031	7.80
206 (11)	3.12	2.29	0.49	0.24	3.03	2.88	0.15	10	12.7	91	461	7.85
2010 Rainfall												
203 (19)	2.98	2.61	0.29	0.05	3.39	3.31	0.09	12	55.2	44	2523	8.17
204 (10)	10.8	3.87	6.66	0.21	5.09	4.88	0.21	14	192	26	4180	8.13
205 (8)	11.4	1.09	10.2	0.11	1.12	1.05	0.07	30	107	98	2409	8.06
206 (3)	2.58	2.12	0.34	0.09	3.56	3.31	0.25	28	10.6	39	410	7.98
2010 All												
203 (21)	3.00	2.61	0.29	0.07	3.34	3.24	0.11	12	50.8	40	2315	8.12
204 (15)	10.5	4.18	5.55	0.62	5.49	5.25	0.24	13	153	31	3568	8.06
205 (21)	9.01	1.56	6.94	0.36	1.21	1.07	0.14	24	62	38	1556	7.90
206 (14)	3.01	2.26	0.46	0.21	3.15	2.97	0.17	14	12.3	79	450	7.88

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] Number of sample are shown in parentheses.

contributed, but was likely not the main reason. Another possibility for the cause of the high N and P concentration during the October runoff events was due to the surface conditions of the field. A potato crop was grown in 2011, and the crop was harvested on September 21. Potato harvest leaves the soil surface highly disturbed, exposed, and with little crop residue. These surface conditions existed on both sides of the drain, and this may have contributed to the high N and P concentrations in October 2011.

The average concentrations of TN and NO_3-N were higher in edge-of-field runoff compared to the two instream stations during high flow and Station 201 during low flow (Figure 5.30a,c). In contrast, the average concentrations of TN and NO_3-N were lower in edge-of-field runoff compared to the downstream Station 202 during low flow. As described above, the high concentration of N at Station 202 was believed to be caused by leaching of NO_3-N from the field and into shallow groundwater, which discharged into the drain between Stations 201 and 202. The average

Table 5.23. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2011.[z]

Station[y]	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli* (mpn 100 mL^{-1})	EC ($\mu S\ cm^{-1}$)	pH
	---------------------------------				($mg\ L^{-1}$)				---------------------------------			
						2011 Snowmelt						
203 (5)	2.94	2.77	0.08	0.09	3.51	3.42	0.09	9	76	1	2269	7.80
204 (4)	11.6	8.53	2.23	0.74	5.61	5.41	0.21	6	397	1	6031	7.99
205 (0)	ns[x]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
206 (4)	5.45	3.79	1.08	0.53	5.48	5.30	0.19	6	55.1	1	983	7.73
						2011 Rainfall						
203 (8)	5.10	3.82	1.21	0.07	3.13	3.04	0.08	5	114	135	3493	8.03
204 (6)	17.6	5.50	11.7	0.18	4.45	4.4	0.06	4	400	41	6438	8.03
204 (2)[w]	11.7	3.45	5.97	0.47	3.72	3.45	0.27	17	186	1,255	3290	7.73
205 (7)	7.35	2.54	4.75	0.05	0.89	0.83	0.07	24	95.2	2,602	2714	8.10
205 (2)[w]	25.8	13.4	1.26	9.90	5.17	3.60	1.57	235	200	7,017	1390	7.67
206 (2)	4.69	2.90	1.67	0.04	4.99	4.81	0.18	10	25.4	14	677	7.85
206 (1)[w]	78.4	55.3	0.03	23.1	15.1	14.5	0.6	10	268	110,000	2600	7.37
						2011 Irrigation						
203 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
204 (1)	3.89	3.78	0.03	0.11	3.75	3.32	0.43	48	82.2	2,046	3000	8.23
205 (3)	2.47	2.05	0.36	0.04	1.40	0.82	0.86	96	13.3	1,061	736	8.04
206 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
						2011 All						
203 (13)	4.27	3.42	0.77	0.08	3.27	3.19	0.09	7	99.4	83	3022	7.94
204 (13)	13.8	5.98	7.00	0.39	4.64	4.48	0.16	10	342	370	5564	7.98
205 (12)	9.21	4.23	3.07	1.69	1.73	1.33	0.51	75	81.3	2,953	2114	8.01
206 (7)	15.7	10.9	1.10	3.61	6.71	6.47	0.24	7	77	15,719	1126	7.71

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] Number of samples are shown in parentheses.
[x] ns = not sampled.
[w] These samples were collected after manure was applied on September 21, 2011 and after a rainfall event in early October.

concentrations of TP and TDP were much higher in edge-of-field runoff compared to the instream water at Stations 201 and 202 (Figure 5.30d,e). This reflects the high concentration of STP that had accumulated in the soil surface caused by years of manure application. The average concentration of Cl was also higher at the edge-of-field (Table 5.25) compared to both instream stations (Table 5.17). The concentration of TSS was intermediate between the high-flow and low-flow periods for the instream stations (Figure 5.30f), and the concentrations of *E. coli* and EC were higher in edge-of-field runoff compared to both instream stations (Figure 5.30g,h).

Table 5.24. Average concentration of water quality parameters for the four edge-of-field water monitoring stations at the Battersea Drain Field in 2012.[z]

Station[y]	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli* (mpn 100 mL^{-1})	EC ($\mu S\ cm^{-1}$)	pH
	----	----	----	----	(mg L^{-1})	----	----	----	----			
					2012 Rainfall							
203 (1)	5.22	3.48	1.34	0.10	3.64	3.31	0.33	18	52.4	1414	1820	7.98
204 (0)	ns[x]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
205 (1)	3.74	3.21	0.46	0.07	1.76	1.34	0.42	172	42.6	1223	1420	7.68
206 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
					2012 Irrigation							
203 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
204 (4)	9.48	5.35	3.60	0.36	4.88	4.78	0.11	10	98.9	937	2765	8.13
205 (2)	1.78	1.73	0.03	0.04	1.58	1.34	0.25	35	15.2	278	760	7.83
206 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
					2012 All							
203 (1)	5.22	3.48	1.34	0.10	3.64	3.31	0.33	18	52.4	1414	1820	7.98
204 (4)	9.48	5.35	3.60	0.36	4.88	4.78	0.11	10	98.9	937	2765	8.13
205 (3)	2.43	2.23	0.17	0.05	1.64	1.34	0.30	80	24.3	593	980	7.78
206 (0)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, Cl = chloride, *E. coli* = *Escherichia coli*, EC = electrical conductivity, pH = potential hydrogen.
[y] Number of sample are shown in parentheses.
[w] ns = not sampled.

As indicated previously, edge-of-field runoff flow was less than 0.4% of the flow at Station 202. Therefore, it is unlikely the influence of surface runoff from the BDF site had a measureable effect on water quality from upstream (Station 201) to downstream (Station 202). This was clearly demonstrated by the TP and TDP results, which showed little change in concentration from Station 201 to Station 202, even though edge-of-field concentrations were much higher (Figure 5.30d,e). Furthermore, even though TSS and *E. coli* concentrations were higher in edge-of-field runoff, average concentrations of these two parameters actually decreased from Station 201 to Station 202 (Figure 5.30f,g).

Table 5.25. Average concentration of water quality parameters in edge-of-field runoff (Stations 203, 204, 205, and 206 combined) at the Battersea Drain Field from 2007 to 2012.[z]

Year	n	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	Cl	*E. coli* (mpn 100 mL^{-1})	EC (µS cm^{-1})	pH
		(mg L^{-1})											
						Snowmelt							
2007	0	ns[y]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
2008	7	2.66	2.30	0.21	0.13	2.52	2.42	0.10	36	ns	1	661	8.04
2009	19	4.89	3.60	0.39	0.84	3.45	3.22	0.23	18	36	14	1005	7.84
2010	31	6.08	2.53	2.81	0.56	2.81	2.61	0.20	15	32	40	996	7.83
2011	13	6.37	4.86	1.05	0.43	4.76	4.61	0.16	7	168	1	3031	7.84
2012	0	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Ave.	*70*	*5.47*	*3.23*	*1.57*	*0.57*	*3.32*	*3.13*	*0.19*	*16*	*61*	*22*	*1343*	*7.86*
						Rainfall							
2007	4	10.9	3.56	7.17	0.11	2.50	2.35	0.15	5	ns	1	2310	8.03
2008	45	10.4	8.40	1.46	0.43	6.55	6.24	0.31	13	123	1814	2412	8.01
2009	26	6.77	4.30	2.33	0.08	3.86	3.64	0.22	126	85	1312	2172	8.09
2010	40	6.58	2.58	3.86	0.10	3.38	3.25	0.13	17	96	50	2756	8.12
2011	28	12.9	6.29	4.67	1.64	3.60	3.38	0.22	27	174	5218	3532	7.96
2012	2	4.48	3.35	0.90	0.09	2.70	2.33	0.38	95	48	1318	1620	7.83
Ave.	*145*	*9.11*	*5.45*	*3.05*	*0.50*	*4.46*	*4.24*	*0.22*	*38*	*116*	*1838*	*2666*	*8.05*
						Irrigation							
2007	23	3.42	2.94	0.32	0.11	1.88	1.51	0.37	137	ns	3826	921	8.11
2008	27	4.64	4.37	0.16	0.07	4.17	3.78	0.38	55	69	5832	1693	8.06
2009	12	6.16	4.54	1.50	0.05	3.50	3.31	0.19	14	70	2556	1984	8.24
2010	0	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
2011	4	2.83	2.49	0.28	0.06	1.99	1.65	0.75	80	36	1307	1490	8.10
2012	6	6.91	4.14	2.41	0.26	3.78	3.63	0.15	18	71	717	2097	8.03
Ave.	*72*	*4.59*	*3.82*	*0.63*	*0.10*	*3.17*	*2.84*	*0.35*	*72*	*67*	*3903*	*1507*	*8.11*
						Overall							
2007	27	4.53	3.03	1.33	0.11	1.97	1.63	0.34	117	ns	3259	1127	8.10
2008	79	7.75	6.48	0.91	0.28	5.38	5.06	0.31	29	94	2916	2011	8.03
2009	57	6.01	4.12	1.51	0.33	3.65	3.43	0.22	66	66	1141	1744	8.04
2010	71	6.36	2.56	3.40	0.30	3.13	2.97	0.16	16	68	45	1987	7.99
2011	45	10.1	5.54	3.24	1.15	3.79	3.63	0.25	25	163	3363	3244	7.93
2012	8	6.30	3.94	2.03	0.21	3.51	3.30	0.21	37	65	868	1978	7.98
Ave.	*287*	*7.09*	*4.50*	*2.08*	*0.41*	*3.86*	*3.61*	*0.25*	*41*	*91*	*1913*	*2053*	*8.01*

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TS S = total suspended solids, *E. coli* = *Escherichia coli*, EC = electrical conductivity.
[y] ns = not sampled.

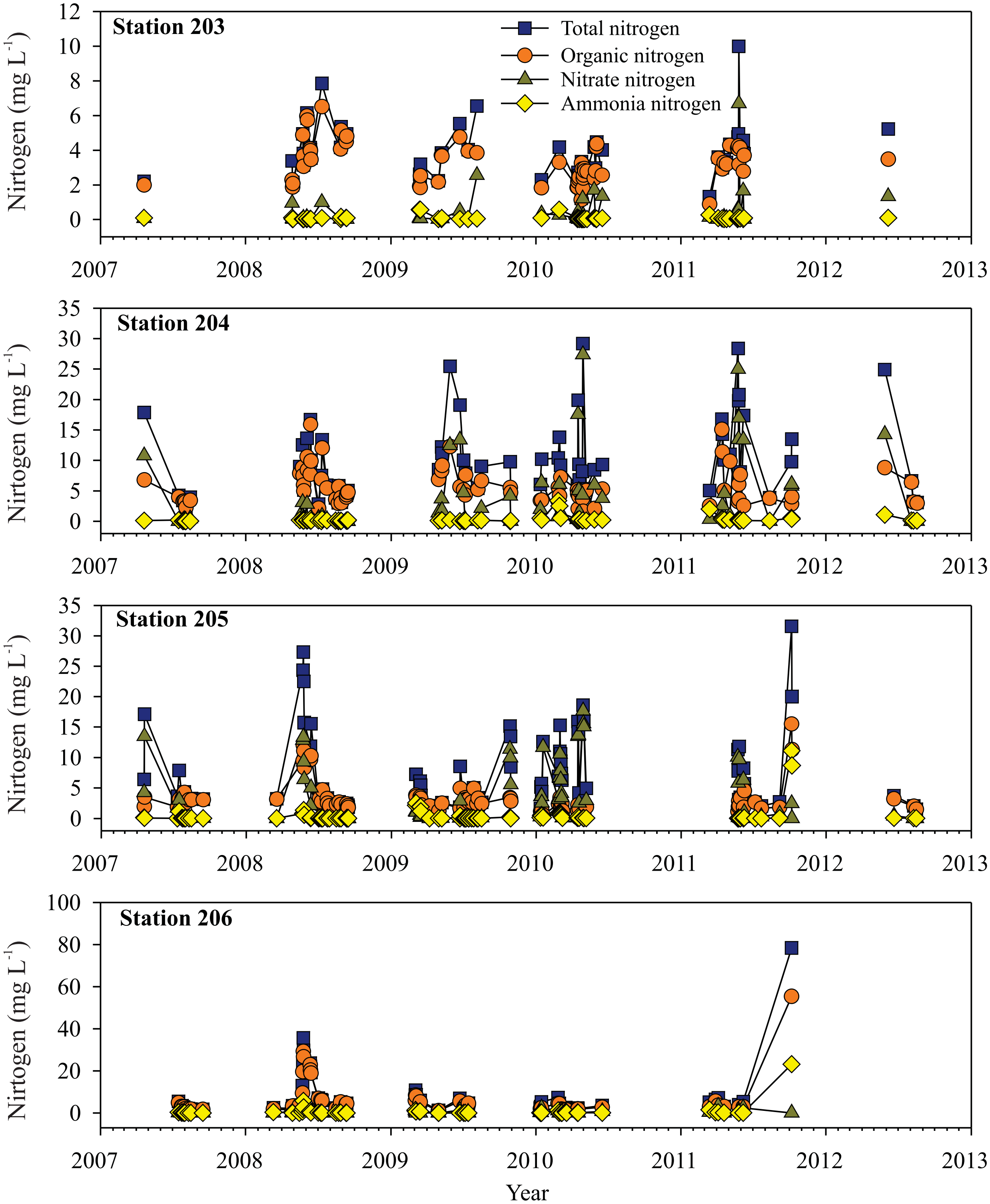

Figure 5.28. Nitrogen concentration in surface runoff at the four edge-of-field stations at the Battersea Drain Field from 2007 to 2012.

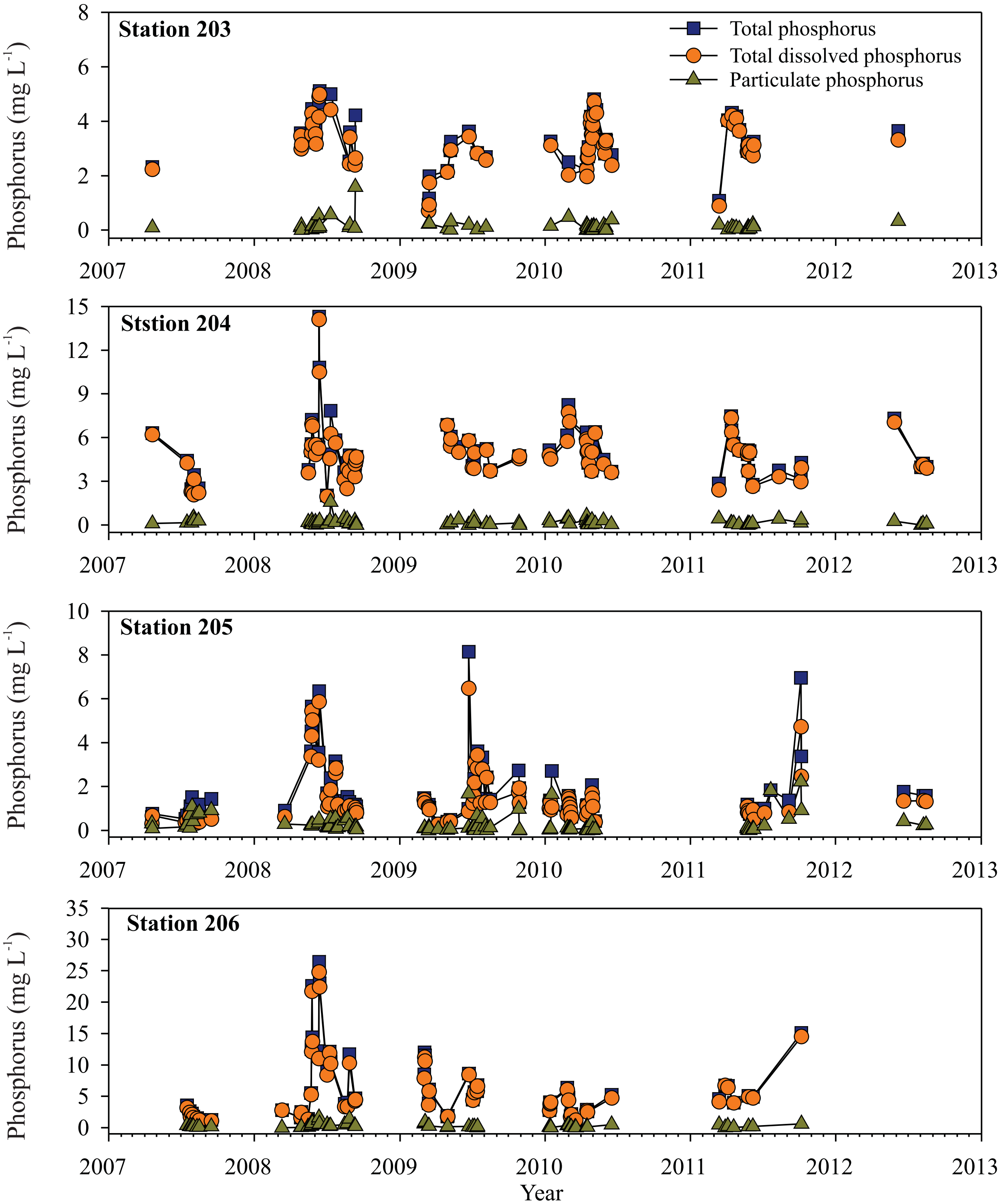

Figure 5.29. Phosphorus concentration in surface runoff at the four edge-of-field stations at the Battersea Drain Field from 2007 to 2012.

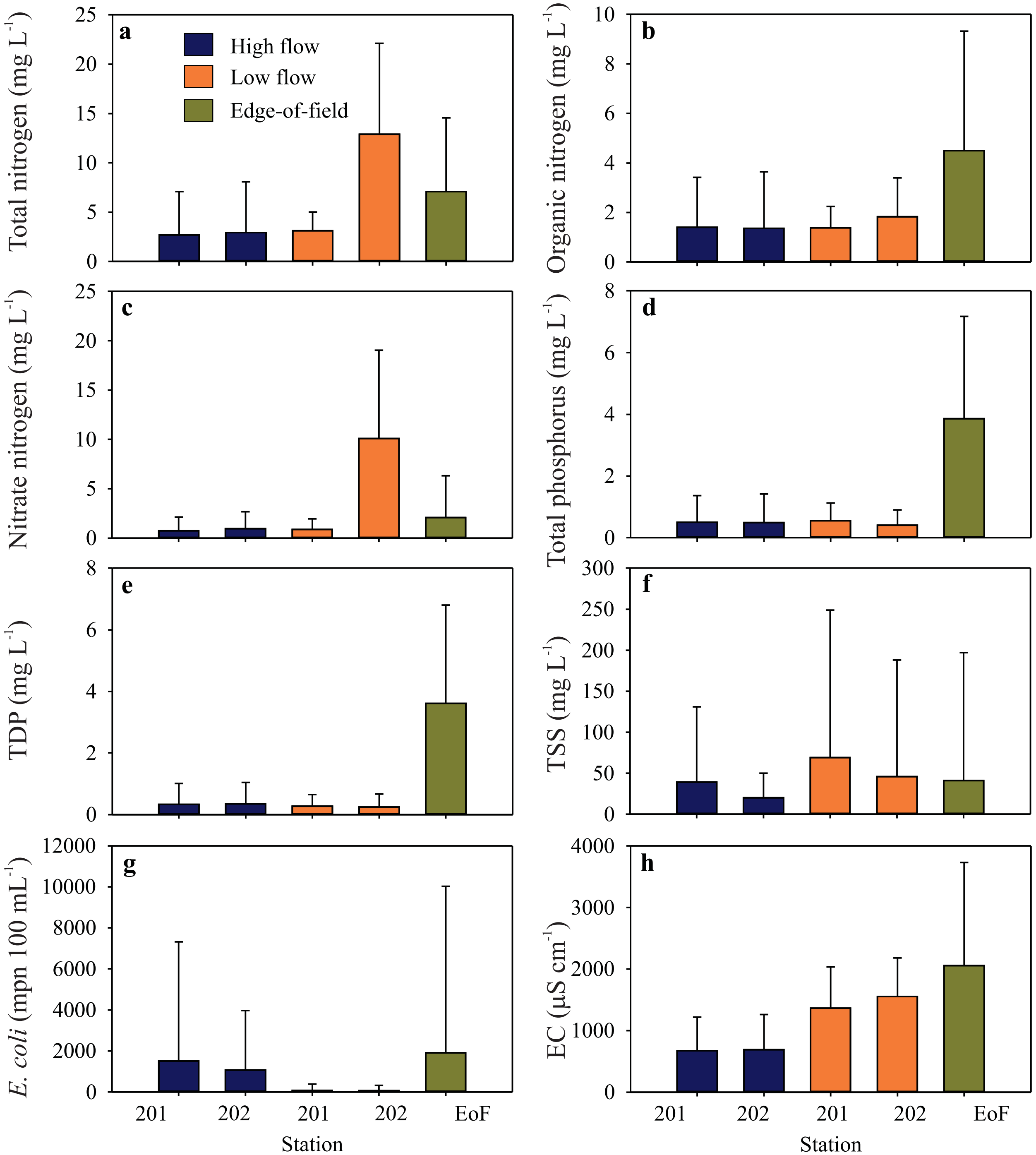

Figure 5.30. Comparison of average concentration of (a) total nitrogen, (b) organic nitrogen, (c) nitrate nitrogen, (d) total phosphorus, (e) total dissolved phosphorus (TDP), (f), total suspended solids (TSS), (g) *Escherichia coli* (*E. coli*), and (h) electrical conductivity (EC) among the water monitoring stations at the Battersea Drain Field from 2007 to 2012. Station 201 was the upstream station and Station 202 was the downstream station in the drain. The edge-of-field (EoF) stations included Stations 203 to 206. The t-bars are standard deviations.

Total annual loads for TN ranged from 8 to 183 kg yr^{-1}, TP ranged from 4 to 63 kg yr^{-1}, and TSS ranged from 58 to 3539 kg yr^{-1} in edge-of-field runoff (Table 5.26). Generally, loads were highest in 2011 followed by 2010. Annual flows were 2- to 12-fold higher during these two years compared to the other years (Table 5.13) and this resulted in the higher loads in 2010 and 2011. Annual flow was slightly higher in 2010, but because of higher concentrations in 2011 (Table 5.25), nutrient and TSS loads were generally higher in 2011. One expectation was for the total load of NO_3-N, which was highest in 2010. Another exception was for TSS, which had the highest load in 2009. This was caused by a 40-mm rainfall event on June 22, 2009 in combination with irrigation, which together, generated 1344 m^3 of flow at Station 205 and the highest TSS concentration (2390 mg L^{-1} on June 23) measured at Station 205.

For most parameters in most years, the nutrient and TSS loads in edge-of-field runoff (Table 5.26) accounted for less than 1% of the total loads determined at the instream Station 202 (Table 5.18). However, edge-of-field TP and TDP loads generally accounted for more of the instream loads compared to the other parameters. In five out of six years, edge-of-field TP loads represented 1 to 7% of the instream loads, and in all six years, edge-of-field TDP loads accounted for 1 to 11% of instream loads. This likely reflects the very high STP concentrations in the surface soil at the BDF site.

5.3.8.3 Beneficial Management Practices Effects on Water Quality

Instream water quality. Average concentrations of many water quality parameters at both instream stations were higher during the post-BMP period compared to the pre-BMP period (Tables 5.27 and 5.28), with *E. coli* and TSS as exceptions for one or both stations. This was particularly true for high-flow and total flow, and less so for low-flow.

The average concentration of most parameters, except for TSS and *E. coli*, were significantly different between the high-flow and low-flow periods (not shown), and therefore, the comparison between the BMP periods were performed by flow period (high and low) and total flow.

Upstream-downstream differences for TN and NO_3-N were significantly larger in the post-BMP period compared with the pre-BMP period for high flow and total flow; whereas, there were no significant differences between pre- and post-BMP periods for the other parameters (Tables 5.27 and 5.28). The reason for the increase in TN and NO_3-N concentration in the post-BMP period is unknown, but was likely not caused by the BMPs. The concentrations of TN and NO_3-N for total flow were three-fold and 10-fold greater, respectively, at Station 201 in the post-BMP period compared to the pre-BMP period. Perhaps the factors that caused higher concentrations in the drain prior to reaching Station 201 during the post-BMP period also increased the contributions along the reach from Station 201 to Station 202.

Table 5.26. Load values for nutrients and total suspended solids at the edge-of-field water monitoring stations at the Battersea Drain Field from 2007 to 2012.[z]

Station	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS
	($kg\ yr^{-1}$)							
				2007				
203	ns[y]	ns	ns	ns	ns	ns	ns	ns
204	3.51	3.28	0.11	0.10	3.21	3.00	0.21	33
205	3.29	2.19	1.01	0.06	0.72	0.35	0.36	183
206	1.55	1.39	0.06	0.08	1.03	0.92	0.11	14
Total	8.35	6.86	1.18	0.24	4.96	4.27	0.68	230
				2008				
203	2.51	2.33	0.13	0.02	2.14	2.03	0.11	16
204	21.0	19.4	1.03	0.48	16.8	15.7	1.16	231
205	18.4	15.0	2.85	0.25	9.03	7.67	1.36	190
206	8.73	8.24	0.13	0.32	11.5	10.8	0.67	39
Total	50.6	45.0	4.14	1.07	39.5	36.2	3.30	476
				2009				
203	1.90	1.54	0.19	0.13	1.10	1.02	0.08	15
204	14.2	7.52	6.54	0.09	6.52	6.40	0.12	13
205	26.7	16.7	8.14	1.39	19.9	16.6	3.36	3495
206	1.94	1.69	0.15	0.08	2.53	2.48	0.05	16
Total	44.8	27.5	15.0	1.69	30.1	26.5	3.61	3539
				2010				
203	8.88	6.47	2.03	0.31	7.29	6.73	0.56	84
204	57.4	19.3	36.1	1.67	18.7	18.1	0.56	64
205	78.0	22.6	53.3	1.56	11.3	9.27	2.05	464
206	8.7	6.76	1.40	0.36	10.9	10.1	0.78	73
Total	152.9	55.1	92.8	3.90	48.2	44.2	3.95	685
				2011				
203	7.28	5.62	1.53	0.13	5.35	5.21	0.14	10
204	63.9	31.0	30.2	1.55	22.0	21.3	0.63	37
205	74.1	29.4	28.7	13.7	15.3	11.7	3.62	648
206	37.8	23.9	5.89	7.84	20.3	19.3	1.03	25
Total	183.1	89.9	66.3	23.2	63.0	57.5	5.42	720
				2012				
203	0.03	0.02	0.01	0.00	0.02	0.02	0.00	0.09
204	4.83	3.04	1.53	0.18	2.96	2.90	0.06	6.65
205	1.36	1.29	0.06	0.03	1.20	1.00	0.21	51.3
206	ns	ns	ns	ns	ns	ns	ns	ns
Total	6.22	4.35	1.60	0.21	4.18	3.92	0.27	58.0

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids.
[y] ns = not sampled.

Table 5.27. Average concentration of nitrogen parameters and *Escherichia coli* for the upstream (Station 201) and downstream (Station 202) stations in the pre- (2007 and 2008) and post-BMP (2009 and 2011) periods, and the differences (= downstream – upstream) between the two stations in the pre- and post-BMP periods.[z]

	TN		ON		NO_3-N		NH_3-N		*E. coli*	
	Pre	Post[y]	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Station	(mg L^{-1})								(mpn 100 mL^{-1})	
					High flow (n = 61 pre, 91 post)					
Upstream	0.97	4.05	0.84	1.83	0.06	1.27	0.05	0.89	1470	1561
Downstream	0.89	4.54	0.71	1.89	0.11	1.65	0.04	0.95	1200	935
Difference[x]	*-0.08b*	*0.49a*	*-0.13*	*0.06*	*0.05b*	*0.38a*	*-0.01*	*0.06*	*-270*	*-626*
					Low flow (n = 13 pre, 39 post)					
Upstream	2.06	3.23	1.28	1.50	0.34	0.73	0.41	0.96	17	106
Downstream	12.46	10.31	1.69	1.50	10.03	7.65	0.60	1.01	22	87
Difference	*10.40*	*7.08*	*0.41a*	*0b*	*9.69*	*6.92*	*0.21*	*0.05*	*5*	*-19*
					Total flow (n = 74 pre, 130 post)					
Upstream	1.16	3.81	0.91	1.73	0.11	1.11	0.11	0.91	1211	1124
Downstream	2.92	6.27	0.88	1.77	1.86	3.45	0.14	0.97	987	680
Difference	*1.76b*	*2.46a*	*-0.03*	*0.04*	*1.75b*	*2.34a*	*0.03*	*0.06*	*-224*	*-444*

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonium nitrogen, *E. coli* = *Escherichia coli*.
[y] The 2012 water data were not included in the post-BMP period because manure was applied in fall 2011.
[x] Average differences for pre- and post-BMP periods per parameter and event type followed by letters are significantly different at P <0.1.

Table 5.28. Average concentrations of phosphorus parameters, total suspended solids, and electrical conductivity for the upstream (Station 201) and downstream (Station 202) stations in the pre- (2007 and 2008) and post-BMP (2009 and 2011) periods, and the differences (= downstream – upstream) between the two stations in the pre- and post-BMP periods.[z]

	TP		TDP		PP		TSS		EC		pH	
	Pre	Post[y]	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Station	(mg L^{-1})								(µS cm^{-1})			
					High flow (n = 61 pre, 91 post)							
Upstream	0.15	0.76	0.06	0.55	0.09	0.22	35	24	421	872	7.96	8.22
Downstream	0.12	0.77	0.07	0.55	0.05	0.21	10	26	417	905	8.11	8.22
Difference[x]	*-0.03*	*0.01*	*0.01*	*0*	*-0.04*	*-0.01*	*-25*	*2*	*-4*	*23*	*0.15a*	*0b*
					Low flow (n = 13 pre, 39 post)							
Upstream	0.45	0.65	0.11	0.36	0.33	0.28	116	58	1301	1207	7.95	7.93
Downstream	0.26	0.52	0.06	0.35	0.20	0.16	126	24	1593	1369	8.04	7.93
Difference	*-0.19*	*-0.13*	*-0.05*	*-0.01*	*-0.13*	*-0.12*	*10*	*-34*	*292a*	*162b*	*0.05*	*0*
					Total flow (n = 74 pre, 130 post)							
Upstream	0.20	0.73	0.07	0.49	0.13	0.24	50	40	583	1124	7.97	8.13
Downstream	0.15	0.69	0.07	0.49	0.08	0.20	32	25	636	680	8.10	8.13
Difference	*-0.05*	*-0.04*	*0*	*0*	*-0.05*	*-0.04*	*-18*	*-15*	*53*	*-444*	*0.13*	*0*

[z] TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, EC = electrical conductivity, pH = potential hydrogen.
[y] The 2012 water data were not included in the post-BMP period because manure was applied in fall 2011.
[y] Average differences for pre- and post-BMP periods per parameter and event type followed by letters are significantly different at P <0.1.

During low flow, the relative differences between upstream and downstream for ON and EC were significantly less in the post-BMP period, suggesting a positive effect caused by the BMPs (Tables 5.27 and 5.28). These were the only parameters that showed a potential positive BMP effect for instream water quality, and only during low flow. There were no significant differences between the pre- and post-BMP periods for the other parameters during low flow. However, for TN and NO_3-N, the concentrations were higher during the post-BMP period compared to the pre-BMP period at Station 201; whereas, the opposite was true at Station 202. Even though the downstream-upstream differences between the pre- and post-BMP periods were not significantly different (Table 5.27), the trend suggests that the cessation of manure application may have reduced the source of NO_3-N for leaching during the low-flow period. *Escherichia coli* for high flow and total flow and EC for total flow showed similar non-significant trends. In comparison, the P parameters showed no trends to indicate a BMP effect in the drain.

Overall, the implemented BMPs at the BDF site showed little positive effect on water quality parameters in the drain, with the exception of significantly reduced ON and EC concentrations and a trend toward reduced TN, NO_3-N, and NH_3-N concentrations during low flow. This suggests that manure cessation may have reduced the leaching potential of N and salts into the shallow groundwater, which discharged into the drain during the low-flow periods.

Edge-of-field water quality. The concentration of nearly all water quality parameters was significantly different between rainfall and irrigation runoff events at Stations 204 and 205, except for ON (data not shown). Also, the hydrological characteristics differed among the monitoring stations. Therefore, the comparisons between the BMP periods were performed by event type and for the whole growing season for each edge-of-field monitoring station (rainfall plus irrigation).

Organic N, TP, and *E. coli* concentrations were significantly less in rainfall runoff during the post-BMP period compared with the pre-BMP period at Station 203 (Table 5.29). During rainfall events, ON concentration was also significantly improved at the other three edge-of-field stations during the post-BMP period compared to the pre-BMP period. The concentration of *E. coli* was significantly reduced at all of the edge-of-field stations in the post-BMP period compared the pre-BMP period either for rainfall and/or the growing season runoff. The concentration of PP was also significantly reduced in the post-BMP period at Stations 205 and 206, as well as the concentration of TSS at Station 204.

In contrast to the above significant improvements in water quality from the pre-BMP period to post-BMP period for edge-of-field runoff, there were many parameters that had concentrations that were either not significantly different between two BMP periods or were significantly higher in the post-BMP period. The concentrations of TN and NO_3-N at Stations 203 and 204 and EC at Station 204 were significantly higher in the post-BMP period compared to the pre-BMP period (Table 5.29). This was also the case for TDP at Station 205 in irrigation runoff and for TSS in growing season runoff.

Station 206 showed the most improvement among the four edge-of-field stations, as nearly all water quality parameter concentrations, except for NO_3-N and TSS, were significantly improved in post-BMP period rainfall runoff compared to pre-BMP rainfall runoff. Station 204 showed the least amount of significant improvement from the pre-BMP period to the post-BMP period. Reasons for differences among the edge-of-field stations were unclear since runoff at the four stations drained from the same field under the same management practices in a given year. Perhaps, some variation in surface topography, in-field flow paths, and soil nutrient distribution may have contributed to these differences.

Table 5.29. Pre- (2007 to 2008) and post- (2009 to 2011) BMP period comparison of average concentrations of water quality parameters for the edge-of-field monitoring stations at the Battersea Drain Field.[z,y]

BMP period	TN	ON	NO_3-N	NH_3-N	TP	TDP	PP	TSS	*E. coli* (mpn 100 mL^{-1})	EC (µS cm^{-1})	pH
	(mg L^{-1})										
Station 203 rainfall (n = 11 pre, 32 post)											
Pre-BMP	4.32	4.20*a*[x]	0.04*b*	0.05	3.88*a*	3.61	0.27	5	292*a*	3195	8.04
Post-BMP	3.78	3.13*b*	0.58*a*	0.05	3.27*b*	3.18	0.09	10	285*b*	2777	8.11
Station 204 rainfall (n = 15 pre, 23 post)											
Pre-BMP	8.65*b*	7.12*a*	1.32*b*	0.16	6.07	5.94	0.13	9	2118*a*	3155*b*	8.05
Post-BMP	12.4*a*	5.09*b*	7.05*a*	0.17	4.93	4.80	0.13	10	370*b*	4828*a*	8.10
Station 204 irrigation (n =15 pre, 5 post)											
Pre-BMP	5.13*b*	4.73	0.27	0.10	3.97	3.60	0.37	59*a*	7181	1883*b*	8.21
Post-BMP	10.4*a*	6.64	3.55	0.11	4.53	4.22	0.31	19*b*	1006	4054*a*	8.24
Station 204 growing season (n =30 pre, 28 post)[w]											
Pre-BMP	6.89*b*	5.92	0.79*b*	0.13	5.02	4.77	0.25	34*a*	4562*a*	2519*b*	8.13
Post-BMP	12.0*a*	5.36	6.42*a*	0.16	4.86	4.70	0.17	12*b*	483*b*	4690*a*	8.12
Station 205 rainfall (n = 13 pre, 26 post)											
Pre-BMP	11.7	5.90*a*	5.16	0.31	2.78	2.56	0.21*a*	17	904	1780	7.97*b*
Post-BMP	7.97	2.28*b*	5.57	0.08	1.66	1.46	0.20*b*	135	1354	1893	8.09*a*
Station 205 irrigation (n = 18 pre, 9 post)											
Pre-BMP	3.40	2.94	0.31	0.10	1.42	0.98*b*	0.44	171*a*	3616	955	7.94
Post-BMP	2.98	2.79	0.14	0.03	1.91	1.71*a*	0.38	35*b*	1719	860	8.24
Station 205 growing season (n = 31 pre, 35 post)[w]											
Pre-BMP	6.87	4.19*a*	2.35	0.19	1.99	1.64	0.35*a*	106*b*	2441*a*	1301	7.95*b*
Post-BMP	6.69	2.41*b*	4.17	0.07	1.72	1.52	0.24*b*	112*a*	1448*b*	1650	8.12*a*
Station 206 rainfall (n = 10 pre, 8 post)											
Pre-BMP	18.3*a*	16.3*a*	0.71	1.28*a*	13.5*a*	12.8*a*	0.68*a*	18	3490*a*	1219*a*	7.98
Post-BMP	4.11*b*	3.25*b*	0.76	0.05*b*	5.23*b*	5.05*b*	0.18*b*	21	357*b*	564*b*	7.99

[z] TN = total nitrogen, ON = organic nitrogen, NO_3-N = nitrate nitrogen, NH_3-N = ammonia nitrogen, TP = total phosphorus, TDP = total dissolved phosphorus, PP = particulate phosphorus, TSS = total suspended solids, *E. coli* = *Escherichia coli*, EC = electrical conductivity.

[y] Because of too few samples, statistically comparisons were not make for snowmelt events for all sites, irrigation events for Stations 203 and 206, and for chloride data.

[x] Average BMP phase concentrations per parameter followed by letters are significantly different at P <0.1.

[w] Growing season average concentrations include irrigation and rainfall runoff events.

With some variation among the edge-of-field stations, many parameters were significantly improved while a few parameters were significantly increased in the post-BMP period, and still others showed no differences between the two BMP periods. Overall, the edge-of-field results suggest there was improvement in water quality from the pre-BMP period to the post-BMP period. More time (several years) would be required without manure application to determine additional improvement, particularly since the concentration of STP in the surface soil did not decrease during the 3-yr post-BMP period (Table 5.7).

5.4 Conclusions

- The main water quality risk at the BDF site was excess nutrients in the soil from the application of cattle manure. This site was an example of a worst case scenario in terms of nutrient accumulation from manure application and the risk of nutrient loss in runoff and leaching into shallow groundwater with direct connection to a nearby surface drain. High STP concentration in the surface soil was of primary concern for the loss of P in runoff. However, leaching of NO_3-N into the shallow groundwater was also a concern for water quality. The BMPs implemented at the site focused on the source and transportation of nutrients.
- Annual flow of water at the downstream station ranged from 4.9 million to 6.5 million m^3 yr^{-1}. More than 90% of the annual flow occurred from late-April/early-May to mid-October when irrigation water was released into the Battersea Drain (i.e., high flow). Flow from mid-October to spring was low in the drain (i.e., low flow) and was caused mainly by groundwater discharge.
- The total annual runoff flow through the four edge-off-field stations represented less than 0.4% of the annual flow at the downstream station in the drain. On average, 21% of annual runoff was caused by snowmelt, 42% by rainfall, and 31% by irrigation.
- During the high flow from upstream to downstream, the average concentration of ON, NH_3-N, TP, TDP, Cl, and EC were similar, TN increased by 8%, NO_3-N increased by 32%, and PP, TSS, and *E. coli* decreased.
- During low flow from upstream to downstream, the average concentration of TN and NO_3-N increased by four-fold and 11-fold, respectively. The source of this N was believed to have been from the manure applied to the BDF site with subsequent nitrate leaching through the soil profile and into the shallow groundwater, which discharged into the drain.
- The average concentrations of TN and NO_3-N were higher in runoff compared to water in the drain at the two instream stations during high flow and at the upstream station during low flow. In contrast, the average concentrations of TN and NO_3-N were lower in runoff compared to water in the drain at the downstream station.
- The average concentrations of TP and TDP were much higher in edge-of-field runoff compared to the instream water. The concentrations of *E. coli* and EC were also higher in runoff compared to water in the drain.

Nutrient source BMP

- The 6-yr average STP concentration in the surface soil (0 to 15 cm) was 405 mg kg^{-1}, which was nearly seven-fold greater than the agronomic threshold of 60 mg kg^{-1}. The field variability of STP concentration was quite high with values for individual samples ranging from 42 to 1300 mg ha^{-1}.
- The cessation of manure application caused a significant decrease in the concentration of extractable NH_4-N and NO_3-N in the 0- to 15-cm soil layer during the 3-yr post-BMP period. However, the concentration of STP was not affected during the post-BMP period.
- Since crop removal was the main mechanism for P removal, a greater period of no manure application, or other forms of P, would be required to reduce soil P, and hence, reduce the risk of P loss to runoff.
- In addition to no manure application and crop removal, other mechanisms, such as leaching and denitrification may have caused the reduction in extractable N in the surface soil.
- Deep-core (3 m) soil samples showed that most of the accumulated STP remained in the top (0 to 15-cm) soil layer, with some P leaching to greater depths. The concentration of NO_3-N and NH_4-N were relatively consistent with soil depth, and there was no obvious accumulation of extractable N within the soil profile. Chloride from manure readily leached through the soil profile. Because of the coarse-textured soil and added water by irrigation, leaching potential was high at this site, the NO_3-N likely leached relatively quickly through the soil profile and into the shallow groundwater.
- The concentration of STP in existing grass buffers was greater than 300 mg kg^{-1} after 11 yr without manure application and minimal crop removal by harvesting, but was less than compared to the field crop. This demonstrated that STP in the cropped field continued to increase with manure application after the buffers were established. Plus, the high STP in the buffers remained a source of P for loss in runoff. In addition to stopping manure application, active crop removal is required to drawdown soil P.
- Overall, the edge-of-field results suggest there was improvement in water quality from the pre-BMP period to the post-BMP period, though the concentration of some parameters significantly increased in the post-BMP period. More time would be required without manure application to determine additional improvement, particularly since the concentration of STP in the surface soil did not decrease during the 3-yr post-BMP period.
- The BMP had little effect on instream water quality in the reach of the Battersea Drain within the field site. This was mainly because the volume of water in the drain during the high-flow season overwhelmed the relatively small amount of edge-of-field runoff. However, during low flow, the concentrations of ON and EC were significantly reduced and the concentrations of TN, NO_3-N, and NH_3-N tended to be less in the post-BMP period. Therefore, cessation of manure application appeared to have reduced the leaching potential of N and salts into the shallow groundwater, which discharged into the drain during the low-flow periods.

Nutrient transport BMP

- The AIMM software was able to predict the soil moisture content at the BDF site and potentially could be used to prevent over irrigation and reduce runoff from irrigation. Rainfall shortly after irrigation increases the risk of runoff, and this cannot be prevented by using AIMM. The primarily purpose of AIMM is to schedule irrigation for optimum crop growth and reduction in runoff by preventing over irrigation would be a secondary benefit.
- The modification to the irrigation pivot system used to prevent water application in the critical source areas by shutting off part of the pivot reduced the volume, duration, and peak flow of irrigation runoff per irrigation event.
  - However, there were challenges in the implementation of the BMP. Due to technical difficulties in operating the modified pivot, this BMP was not always operational. Improvements to the precision irrigation technology may overcome these challenges.
  - The producer reported an increase in yields in the runoff sensitive areas of the field. This was attributed to the reduction in the amount of irrigation water applied, which in turn caused these areas to be less saturated with water, and this had a positive effect on crop growth.

Cost of BMPs

- The cost of the BMPs was about $43,600 during the post-BMP period, and was one of the more expensive sites in the overall project.
- The majority (69%) of the cost was for hauling manure greater distances for two of the three years during the post-BMP period. Most of the remaining cost was for the modifications to the pivot irrigation system.
- Many more years of no P application will be required to reduce the STP concentration and the risk of P loss in runoff at this site. Therefore, hauling manure to alternate fields at greater distances will result in continued higher manure transportation costs. The use of manure on other fields low in nutrients will provide nutrients to crops and reduce the need and cost of commercial fertilizer. However, the savings may not completely offset hauling costs, depending on the distance hauled.