Environment Canada Environnement Canada

Canada

Herbicide and Nutrient Transport in Irrigation Runoff Water from the South Saskatchewan River Irrigation District #1 into the South Saskatchewan River

Cessna, A.J., J.A. Elliott and W. Nicholaichuk

NWRI Contribution No. 99-193

Final Report to the Irrigation Sustainability Technical Committee

Herbicide and Nutrient Transport in Irrigation Runoff Water from the South Saskatchewan River Irrigation District #1 into the South Saskatchewan River

A.J. Cessna[1], J.A. Elliott[2] and W. Nicholaichuk[3]

[1]Agriculture and Agri-Food Canada, Lethbridge Research Centre, Lethbridge, AB;
Current address - National Water Research Institute, 11 Innovation Boulevard,
Saskatoon, Saskatchewan, Canada S7N 3H5
[2]National Water Research Institute, Saskatoon, Saskatchewan, Canada
[3]Retired, formerly with the National Water Research Institute, Saskatoon, Saskatchewan,
Canada

Executive Summary

This study investigated plant nutrient and herbicide inputs to the South Saskatchewan River in drainage water from flood-irrigated fields within the South Saskatchewan River Irrigation District #1 (also known as the Outlook Irrigation District). Funding for this study was allocated by the Irrigation Sustainability Technical Committee of the Canada-Saskatchewan Agriculture Green Plan Agreement (CSAGPA). The intent of the study was to address the concern that drainage water from the South Saskatchewan River Irrigation District #1 may be detrimental to the downstream quality of the water in the South Saskatchewan River

Plant nutrients [nitrogen (N) and phosphorus (P)] and herbicides (MCPA, mecoprop, 2,4-D, bromoxynil, dicamba, clopyralid, triallate, trifluralin and ethalfluralin) commonly used for crop production within the irrigation district were monitored in flood-irrigation drainage water in two major drainage ditches over three (1994 to 1996) growing seasons. Drainage water from one of the ditches passed through a wetland prior to entering the South Saskatchewan River.

Automated water samplers/flow monitors were used to intensively sample the drainage water daily and to monitor daily flow in the drainage ditches. Each daily drainage water sample consisted of 24 subsamples and daily flow was the average of 24 flow measurements, all collected hourly. Every third water sample was analysed for nutrient and herbicide content.

N and P were detected in all water samples. Total input to the South Saskatchewan River during the 1994 and 1995 growing seasons was 1103 kg of P (as total P) and 3,024 kg of N (as nitrate plus ammonia). These amounts corresponded to 1.9% of N applied to flood-irrigated fields and 2.2% of P. A considerable portion of the nutrients added to the 1C drainage ditch originated in

the wetland area and were likely not the result of irrigation runoff. Concentrations of P in the drainage water ranged from 0.02 to > 1.5 mg L^{-1} and even the irrigation water, which originated from the South Saskatchewan River, exceeded 0.012 mg L^{-1}, the guideline proposed for flowing waters in Alberta. Average ammonia concentrations were well below the Saskatchewan water quality objectives. However, the objectives are temperature and pH dependent and occasionally may have been exceeded. Nitrate concentrations were always within Canadian Water Quality Guidelines.

Maximum flows in the irrigation ditches were of the order of 2 m^3 s^{-1}. Summer (May to September) flows in the South Saskatchewan River varied from 60 to 1,280 m^3 s^{-1} so that the drainage water entering the river was diluted by greater than one to greater than two orders of magnitude. Thus, with the exception of P which was already present in the river water in concentrations exceeding the proposed guideline, concentrations of nitrate and ammonia in the drainage water would have been further reduced.

There were no detectable inputs of ethalfluralin into the South Saskatchewan River via the flood irrigation drainage water during any of the three years of the study. Inputs of trifluralin (<1 g), a herbicide with properties similar to those of ethalfluralin, were less than 0.002% of the amount applied to flood-irrigated fields within the irrigation district. Inputs of MCPA (505 g), bromoxynil (49 g), dicamba (12 g) and mecoprop (11 g) were 0.06 % or less of the amounts applied. Clopyralid, which has a longer field half-life than the other herbicides, was transported to the river in amounts (56 g) equivalent to 0.31% of what was applied (values are for 1996 only). In contrast, 1.2% (2,616 g) of applied 2,4-D was transported to the river in the drainage water. The relatively higher input of this herbicide to the river was most likely due to 2,4-D being already present in the irrigation water.

Passage of the drainage water through a natural wetland did not provide a consistent remedial effect

with respect to decreased amounts of the various herbicides entering the river. However, residence time of the drainage water in the wetland was estimated to be only of the order of two days.

Concentrations of the herbicides detected in the drainage water did not exceed Canadian Water Quality Guidelines for Drinking Water for those herbicides for which guidelines or interim guidelines have been established. No Livestock Watering Guidelines were exceeded either. However, herbicide concentrations in the drainage water sometimes exceeded Irrigation Guidelines for dicamba and MCPA and frequently for 2,4-D. Occasionally, Freshwater Aquatic Life Guidelines were exceeded for MCPA and 2,4-D.

Due to the dilution of the flood-irrigation drainage water by the river water, concentrations of herbicides in the drainage water which at times exceeded various water quality guidelines would have been diluted below those guidelines, with the exception of 2,4-D which was already present in the river water in concentrations frequently exceeding the irrigation water guideline. Increases in herbicide concentrations in the river water, due to herbicide fluxes to the river in the drainage water, were, with the exception of 2,4-D, generally two orders of magnitude less than the lowest water quality guideline.

Introduction

It is well established that pesticides and nutrients can be transported from treated agricultural land in either snowmelt (Nicholaichuk and Read, 1978; Nicholaichuk and Grover, 1983), rainfall (Wauchope, 1978) or irrigation (Spencer and Cliath, 1991; Cessna et al., 1994, 1996) runoff. Pesticides and nutrients considered susceptible to transport in runoff are those present within the runoff-soil interaction zone, generally considered to consist of the top 0.5 to 1 cm of soil (Wauchope, 1978; Leonard et al., 1979; Ahuja et al., 1981; Spencer and Cliath, 1991). With flood irrigation, excess irrigation water is allowed to run off the lower end of the field to ensure adequate irrigation. Nutrients and preemergence pesticides incorporated into the top cm of soil as well as postemergence pesticides which deposited on the soil surface would be available to interact with irrigation water as it moved across the soil surface. As excess irrigation water leaves an irrigated field, the runoff generally enters a system of drainage ditches which carries cumulative runoff from several flood-irrigated fields to some type of receiving water.

In the case of the South Saskatchewan River Irrigation District #1 (SSRID#1)near Outlook, Saskatchewan, the receiving water is the South Saskatchewan River. The SSRID#1 is the largest irrigation district in the province of Saskatchewan and encompasses more than 20,000 ha on the east side of the South Saskatchewan River near the town of Outlook. Approximately 15,700 ha in the District are currently irrigated with water originating from the river. In 1994, when this study was initiated, approximately 11,800 ha were irrigated by sprinkler systems, with the remainder (3,900 ha) irrigated using various flood-irrigation methods. Cereal, forage and oilseed production account for greater than 80% of the flood-irrigated area, with the remainder used to produce pulses, vegetables and other crops.

Runoff water from flood-irrigated fields or treated irrigation canals can be unsuitable for downstream irrigation of crops due to contamination with herbicides (Jame et al., 1999). As well, nutrients and pesticides entering receiving waters via agricultural runoff may endanger freshwater aquatic wildlife or render the water unsafe for human or animal consumption. Thus, there is concern that drainage water from SSRID#1 entering the South Saskatchewan River may be detrimental to the quality of the river water with potential implications for downstream water use.

This concern was somewhat addressed in a recently published study (Cessna et al., 1997) in which herbicide inputs to the South Saskatchewan River via flood irrigation drainage water from the SSRID#1 were reported for the 1982 growing season. However, in this study, the use of single daily grab samples of drainage water and single daily flow measurements may not have adequately represented inputs of herbicides to the river. In addition, nutrient inputs to the river were not addressed. In the present study, automated samplers provided more intensive drainage water sampling and flow measurement for the determination of both herbicide and nutrient inputs to the river. The objectives were to i) determine, over three growing seasons (1994 to 1996), inputs of nutrients (nitrogen and phosphorus) and several currently used herbicides into the South Saskatchewan River via flood-irrigation runoff from the SSRID#1 and ii) to relate these amounts to fertilizer and herbicide use on flood-irrigated fields within the irrigation district.

Materials and Methods

Study Area

The study area consisted of the areas drained by the 1C and 9A drainage ditches within SSRID#1

and incorporated all flood-irrigated land drained by these two ditches (Figure 1). Immediately upstream of the SSRID#1, the South Saskatchewan River has been dammed to form Lake Diefenbaker. Water from Lake Diefenbaker is pumped to the Broderick Reservoir from which a main supply canal delivers irrigation water to the study area. Excess irrigation water in this canal is diverted to the 1C drainage ditch at a point indicated by the Canal sampling site (Figure 1). Cumulative runoff collected by the 1C drainage ditch plus excess irrigation water passes through a wetland before entering the South Saskatchewan River. In contrast, the 9A drainage ditch drains directly into the river. In each year of the study, these two ditches together drained approximately 40% of flood-irrigated land within SSRID#1. Soils in the irrigation district are classified as Dark Brown Chernozems of the Asquith and Bradwell Associations (Ellis et al., 1970). Soil textures range from loam to very fine sandy loam

Water Sampling and Flow Measurement

Drainage water samples were collected from the two drainage ditches during the 1994 through 1996 growing seasons. In each year, automated water samplers (Sigma Streamline 800 SL Portable Liquid Sampler with Integral Flow Meter) were installed on the 1C and 9A drainage ditches. As mentioned previously, the 1C drainage ditch differed from the 9A ditch in that it passed through a wetland just prior to reaching the South Saskatchewan River (Figure 1)

Sampling Sites: In each year, a single automated sampler was installed on the 9A drainage ditch at a point (9A-River) just prior to the drainage water entering the South Saskatchewan River (Figure 1). Three automated samplers were installed on the 1C drainage ditch each year. One sampler was installed just downstream of the wetland at a point (1C-River) just prior to the drainage water

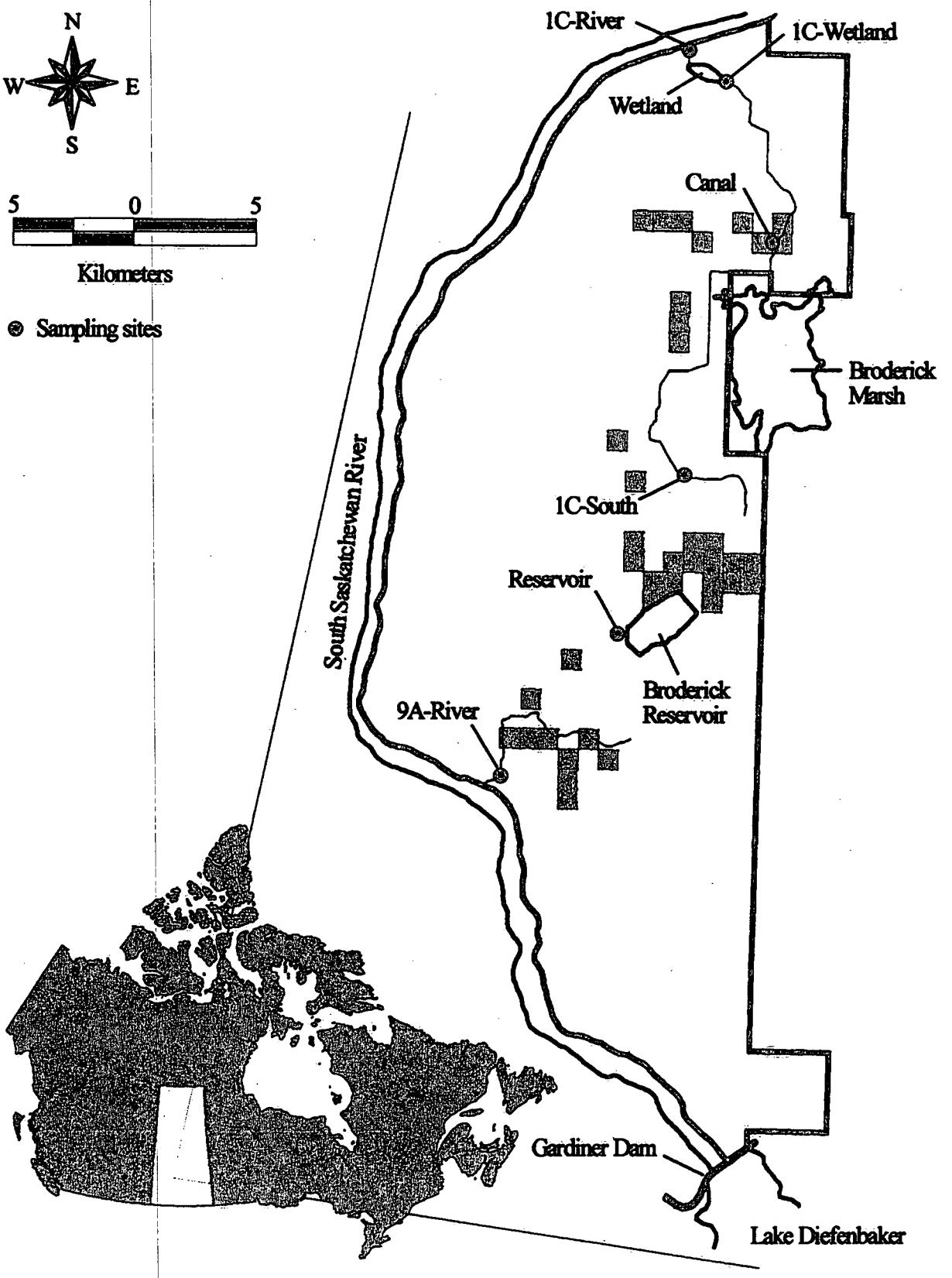


Figure 1: Map of the South Saskatchewan River Irrigation District #1 showing quarter sections of land which could potentially be flood irrigated.

entering the river and a second sampler was installed just upstream of the wetland (1C-Wetland), however, no flow measurements were made at the latter sampling site. The positioning of these two samplers permitted an assessment of possible remedial effects of passing irrigation drainage water through a natural wetland. In 1994, the third sampler was installed just downstream of the 1C drainage area (1C-South). In 1995 and 1996, this sampler was installed further upstream (1C-South) to better sample the drainage water from the relatively large flood-irrigated area near the Broderick Reservoir.

In 1995 and 1996, excess irrigation water was similarly sampled at a point (Canal) on the main supply canal just upstream of its juncture with the 1C drainage ditch (Figure 1). In 1996, irrigation water was also sampled from the main supply canal for the 1C drainage area at a point (Reservoir) just downstream of the Broderick Reservoir for a 2-wk period. No flow measurements were made at the Reservoir sampling site in 1996 or at the Canal sampling site in 1995 and 1996. The irrigation water was sampled to determine both the nutrient and herbicide content of the water applied to the flood-irrigated fields.

At each sampling site, daily water samples were collected from early June, when flood irrigation generally commenced, until early October each year. The automated water samplers were programmed to collect a subsample of drainage water every hour so that each daily sample of drainage water consisted of 24 subsamples. The integrated flow meters were programmed to record the flow of drainage water past the sampling point every hour and daily flows were determined as the mean of 24 hourly readings. Every third sample was initially analyzed for herbicide (clopyralid, dicamba, mecoprop, MCPA, bromoxynil, 2,4-D, ethalfluralin, trifluralin, triallate and diclofop) and nutrient (N and P) content.

Farmer Survey

All farmers who flood-irrigated cropland within the study area were surveyed at the end of each growing season. Farmers were asked to provide the following information for each flood-irrigated field: crops grown, fertilizers and herbicides applied, methods and rates of application for each fertilizer (kg ha^{-1}) and herbicide (g ha^{-1}), area treated with each fertilizer and herbicide (ha) and timing and amounts of irrigations (mm). This information was collected so that the relationship between the net outflow of nutrients and herbicides in the return flow water to the South Saskatchewan River and the total amounts applied with the SSRID#1 could be investigated.

Sample Analysis

Nutrient Analysis: All samples were analyzed for nitrogen (N; nitrate/nitrite and ammonia) and phosphorus (P; total P and ortho-P) content using standard colourimetric methods. In 1996, samples were not analyzed for ammonia.

Total P and Ammonia: Each water sample was shaken to suspend sediment and unfiltered aliquots were used for total P and for ammonia analysis. To determine total P, an unfiltered aliquot was treated with a sulfuric acid - persulfate mixture to release organically bound phosphates and hydrolyse polyphosphates to ortho-P prior to reduction using stannous chloride (Environment Canada, 1979a). A second unfiltered aliquot was stabilized using sulfuric acid, and ammonia was later determined by reaction with hypochlorite and alkaline phenol (Skougstad et al., 1979).

Nitrate/Nitrite and Ortho-P: Aliquots for nitrate/nitrite and ortho-P analysis were obtained by filtering the remainder of the water sample through a Whatman glass microfibre filter which had

been baked in a muffle furnace at 525°C for 4 h. The automated cadmium reduction method described by Clesceri et al. (1989) was used to determine nitrate plus nitrite. Ortho-P was determined by the stannous chloride reduction technique (Environment Canada, 1979b).

Herbicide Analysis: The water samples contained small and varying amounts of sediment. Prior to extraction, each sample was filtered under reduced pressure through a Buchner funnel equipped with a glass fibre filter paper to remove any sediments.

Extraction, Methylation and Florisil Column Cleanup: The water samples were extracted as described previously (Cessna et al., 1985) with the following modifications: a 500-mL rather than a 1-L sample was extracted and all extraction solvent and reagent volumes were reduced proportionally. Methylation of the acidic herbicides using diazomethane and Florisil column cleanup of the base/neutral herbicide extracts and the methylated acidic herbicide extracts were also as described previously (Cessna et al., 1985).

Gas Chromatographic Analysis: Quantification and confirmation of herbicide residues in the drainage water extracts were carried out using a Hewlett-Packard model 5890A gas chromatograph interfaced to the model 5970B mass selective detector (MSD) which was operated in the selected ion monitoring mode. The GC-MSD system was controlled with the model 5895A data station and the GC was equipped with a 25-m by 0.2-mm i.d. Ultra-1 capillary column (Hewlett-Packard; film thickness of 0.11 μm). Injections (2 μL) of sample extracts were performed using the model 7673A autoinjector. The split-splitless injector was operated in the splitless mode and maintained at a temperature of 230°C. The helium carrier gas flow was 25 cm s^{-1}, and the column temperature

program consisted of an initial temperature of 70°C for 1 min followed by a temperature increase of 5°C min^{-1} to 270°C and hold for 1 min. The capillary interface between the GC and the MSD was maintained at 280°C throughout each run. The retention times for the base/neutral herbicides and the methyl esters of the acidic herbicides under these operating conditions are presented in Table 1.

Three or four ions, characteristic of each base/neutral herbicide (ethalfluralin, trifluralin, triallate) and each methylated acidic herbicide (clopyralid, dicamba, mecoprop, MCPA, bromoxynil, 2,4-D and diclofop) were monitored for confirmation purposes. These ions and the mean peak area ratio values are presented in Table 1.

The presence of a herbicide was considered to be confirmed if i) all ions monitored were present, ii) a peak appeared at the retention time (± 0.02 min) obtained for a standard solution of the herbicide in the reconstructed chromatograms of all ions monitored, and iii) the peak area ratio was within ± 30% of the ratio obtained using a standard solution of the herbicide.

Nutrient and Herbicide Transport

Daily samples of drainage water were collected for nutrient and herbicide analysis. Samples collected on the Tuesday, Thursday and Sunday of each week were analyzed for nutrient and herbicide content. Nutrient concentrations in the unanalyzed samples were linearly interpolated. When quantifiable herbicide concentrations (> 0.05 $\mu g\ L^{-1}$) were detected in a drainage water sample, then water samples collected immediately before and after that sample were also analyzed. Herbicide concentrations in the unanalyzed samples were then linearly interpolated using measured values for both quantifiable and trace (< 0.05 $\mu g\ L^{-1}$) concentrations and zero when a herbicide was not detected.

Table 1. Retention times for the herbicides or their methyl derivatives and the ions and peak area ratios monitored for confirmation purposes.

Herbicide or Methyl Derivative	Retention Time	Mass Units of Ions Monitored[1]	Ion Ratios	Mean Peak Area Ratios[2]
	min			
Clopyralid	18.31	110, 147, 174	174/147	0.32 ± 0.02
Dicamba	20.49	187, 203, 205, 234	205/203	0.65 ± 0.02
Mecoprop	21.37	142, 169, 228	142/169	0.96 ± 0.07
MCPA	21.62	125, 141, 155, 214	155/141	0.70 ± 0.03
Bromoxynil	22.88	248, 276, 291	276/291	0.52 ± 0.03
2,4-D	23.18	175, 199, 234, 236	234/199	0.60 ± 0.02
Ethalfluralin	24.40	292, 276, 316	316/276	0.79 ± 0.11
Trifluralin	24.83	264, 306, 335	264/306	0.83 ± 0.09
Triallate	27.90	86, 128, 143, 268	268/86	0.48 ± 0.07
Diclofop	38.35	253, 281, 340	253/340	1.09 ± 0.12

[1]Mass unit values separated by the slash indicate the ion ratio monitored for confirmation purposes.
[2]Values [mean ± std dev (n = 14)] obtained for the herbicide standard solution (1 ng of each herbicide or methyl derivative per 2 µL injection) over a 10-week period.

Total amounts of N and P (kg) and the various herbicides (g) transported in the drainage water per day past sampling points on the 1C or 9A drainage ditches were determined as a product of the nutrie(mg L^{-1}) or herbicide (µg L^{-1}) concentration in the drainage water sample and the total volume per day (L d^{-1}) of drainage water which flowed past the sampling point. Daily flows were calculated from the mean flow rate (L h^{-1}) over that 24-h period. By summing the amounts of nutrients and herbicides transported each day, the total amounts transported to the river over each growing season were calculated. Trace concentrations (< 0.05 µg L^{-1}) of herbicides in the daily

drainage water samples were not included in the calculation of the total amounts transported to the river.

Results and Discussion

Farmer Survey

Geographic Information System (GIS) Calculations and Map Generation: The farmer survey data for each of the three years were imported into Arc/Info and merged with spatial data showing the quarter sections within the irrigation district. The production data for each quarter section was broken into between one and four parcels depending on individual management practices. The resulting Arc/Info files (one for each year) were imported into ArcView for GIS queries and map generation. Although there was generally more than one management parcel within a quarter section, most of the spatial analysis was conducted at the quarter section scale.

Land Use: The total area available for flood irrigation and drained by the 1C and 9A drainage ditches was 1609 ha in 1994 (Table 2). This area decreased somewhat in 1995 and 1996 due to conversion of some flood-irrigated land to sprinkler irrigation or the removal of land from irrigated crop production and coincided with a decrease in the total flood-irrigated land within the SSRID#1 from 3,924 ha in 1994 to 3,651 ha in 1996. Approximately 75 and 25% of the area available for flood irrigation within the study area each year was drained by the 1C and 9A drainage ditches, respectively.

Table 2: Farmer survey results: areas fertilized, treated with herbicides, and flood irrigated during the 1994, 1995 and 1996 growing seasons.

Total area	1994		1995		1996	
	---------- ha ----------					
available for flood irrigation	1609		1550		1483	
- 1C drainage area	1211	(75%)	1162	(75%)	1083	(73%)
- 9A drainage area	398	(25%)	388	(25%)	400	(27%)
irrigated	897	(56%)	924	(60%)	684	(46%)
- 1C drainage area	569	(47%)	583	(50%)	396	(37%)
- 9A drainage area	328	(82%)	341	(88%)	288	(72%)
irrigated/fertilized	674	(75%)	786	(85%)	554	(81%)
- 1C drainage area	468	(82%)	557	(96%)	288	(73%)
- 9A drainage area	184	(56%)	228	(67%)	266	(92%)
irrigated/herbicide(s) applied	739	(82%)	743	(80%)	437	(64%)
- 1C drainage area	569	(100%)	538	(92%)	254	(64%)
- 9A drainage area	170	(52%)	205	(60%)	183	(64%)

Not all of the land available for flood irrigation in the 1C and 9A drainage areas was irrigated each year. Over the three-year study, the portion of total available land in both drainage areas that was actually flood-irrigated varied from 46 to 60% (Table 2). However, a higher proportion (72 to 88%) of the 9A drainage area was flood-irrigated each year compared to the 1C drainage area (37 to 50%).

Fertilizer Use: Queries were made as to which quarter sections had fertilizer applied (Figure 2). The amounts of N and P, respectively, applied to every parcel within each quarter section were totalled, and this amount was divided by the total area (64.75 ha). This gave the average amount of fertilizer applied in kg ha^{-1} over the entire quarter section. We did not attempt to assess supplies of N and P in soils.

The portion of the flood-irrigated land in both the 1C and 9A drainage areas that was fertilized with either N or P varied from 75% in 1994 to 85% in 1995 (Table 2). However, during the three growing seasons, there was greater variability in the portion of flood-irrigated land that was fertilized within each drainage area. The portion of irrigated land that was fertilized in 1C drainage area varied from 73 to 96%, whereas that within the 9A drainage area varied from 56 to 92%.

Fertilizer applications in the 3-yr period totalled 222 Mg N and 69 Mg P (Table 3). The amount of N and P applied increased from 1994 to 1995 as the fertilized area increased and dropped in 1996 when the fertilized area was much smaller. Average application rates were approximately 60 kgN ha^{-1} and 20 kgP ha^{-1} but rates as high as 200 kgN ha^{-1} and 50 kgP ha^{-1} were reported. Urea (46-0-0) was the most common N source by far but use of anhydrous ammonia (82-0-0) and ammonium nitrate (34-0-0) in 1995 and 1996 may reflect their growing popularity within the Irrigation District.

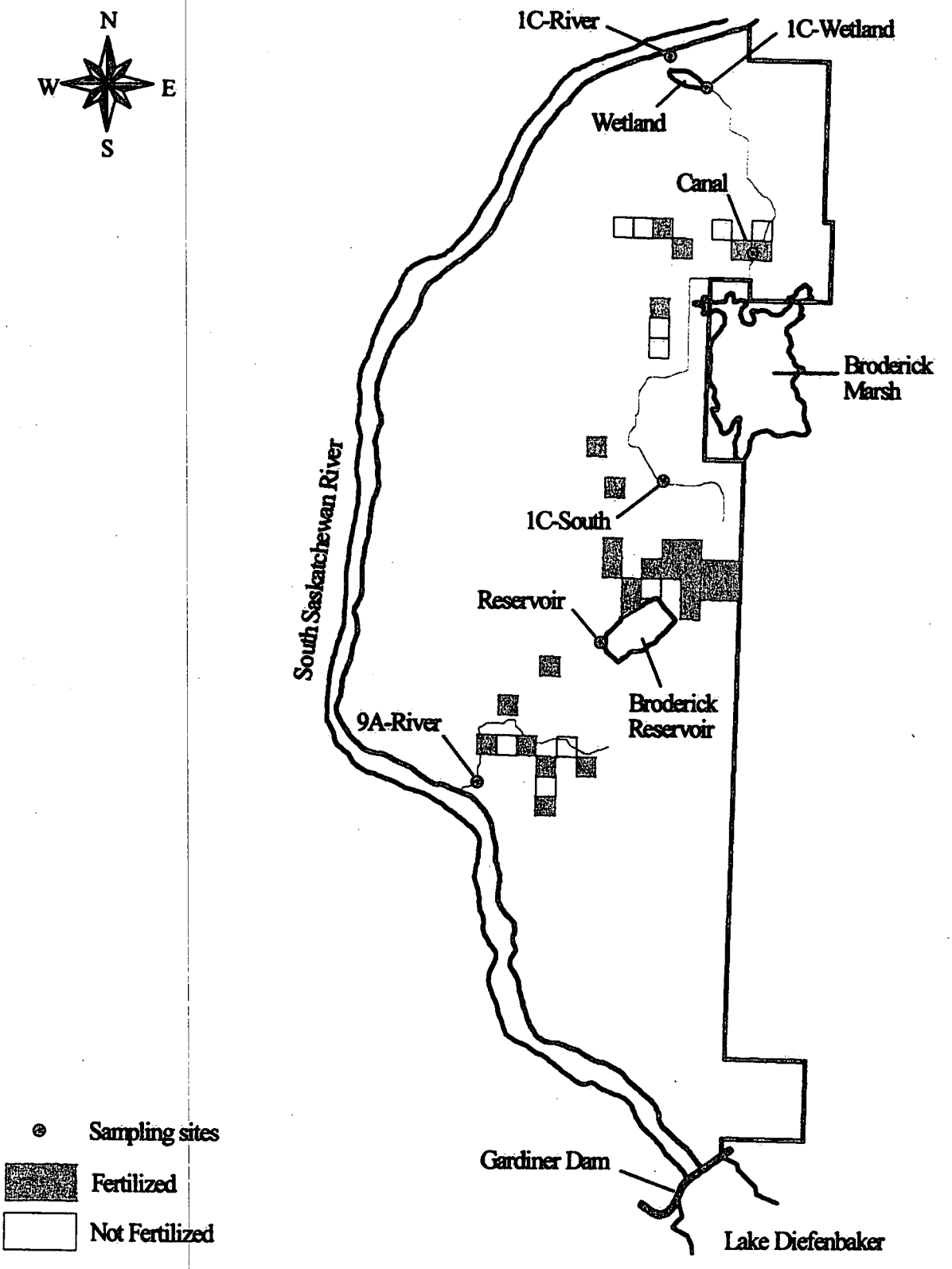


Figure 2: Map of the South Saskatchewan River Irrigation District #1 showing flood-irrigated quarter sections of land which were fertilized with N, P or both N and P during the 1995 growing season.

Table 3: Farmer survey results: Fertilizers, placement, maximum rates, areas treated and total N and P applications for 1994 to 1996.

Fertilizer Applied	Maximum Rate Applied	Area Treated and Amounts Applied											
		1994			1995			1996			Total		
		ha	kg N	kg P	ha	kg N	kg P	ha	kg N	kg P	ha	kg N	kg P
46-0-0 broadcast	112 kg ha^{-1} actual N	182	14866	-	309	28894	-	272	21427	-	763	65187	-
46-0-0 with seed	112 kg ha^{-1} actual N	65	6860	-	22	2294	-	19	584	-	106	9738	-
46-0-0 side-banded	200 kg ha^{-1} actual N	360	42239	-	326	42030	-	185	20726	-	871	104995	-
82-0-0 banded	112 kg ha^{-1} actual N	-	-	-	114	10441	-	94	9368	-	208	19799	-
34-0-0 broadcast	124 kg ha^{-1} actual N	-	-	-	49	3715	-	40	4632	-	89	8347	-
11-55-0 broadcast	49 kg ha^{-1} actual P	194	1614	8072	199	1591	7957	86	778	3880	479	3983	19909
11-55-0 with seed	49 kg ha^{-1} actual P	93	580	2982	182	1424	7123	199	1622	8109	474	3626	18214
11-55-0 side banded	34 kg ha^{-1} actual P	360	2696	13481	326	2193	10964	185	1243	6217	871	6132	30662
Total		1254	68855	24535	1527	92582	26044	1080	60380	18206	3861	221807	68785

Since the placement of fertilizers affects the amount of nutrients at the soil surface (in the soil-runoff interaction zone), the method of application will be a factor controlling nutrient transport. Broadcast applications are placed on the soil surface and even after incorporation, more fertilizer is left at the surface than with other placement methods. Banded and seed-placed applications are generally placed below the soil-runoff interaction zone. Most of the fertilizer in the study area was side-banded either during or just prior to seeding. Broadcasting accounted for around 30% of N and P applications while 25% of P and 6% of N were seed-placed.

Herbicide Use: In order to show the distribution of the various herbicides, the GIS was queried as to which quarter sections had each herbicide applied, and the resulting distribution was displayed on maps of the irrigation district. Maps were also generated showing quarter sections which had received any herbicide application (Figure 3). In cases where a herbicide was applied to one portion of the quarter section and not another, the entire quarter section was displayed. The number of hectares that received each herbicide were found by totalling the parcel areas for each herbicide in each quarter section.

Herbicides were applied to approximately 80% of the flood-irrigated land contained within both drainage areas in 1994 and 1995, but to only 64% in 1996 (Table 2). In 1994 and 1995, a much smaller portion of the flood-irrigated land in the 9A drainage area (52 and 60%) was treated with herbicides compared to the 1C drainage area (100 and 92%). In 1996, equal portions (64%) were treated in each drainage area.

Nineteen herbicides were applied to flood-irrigated land drained by the 1C and 9A drainage ditches during the 1994 to 1996 growing seasons (Table 4). Five herbicides (MCPA, fenoxaprop,

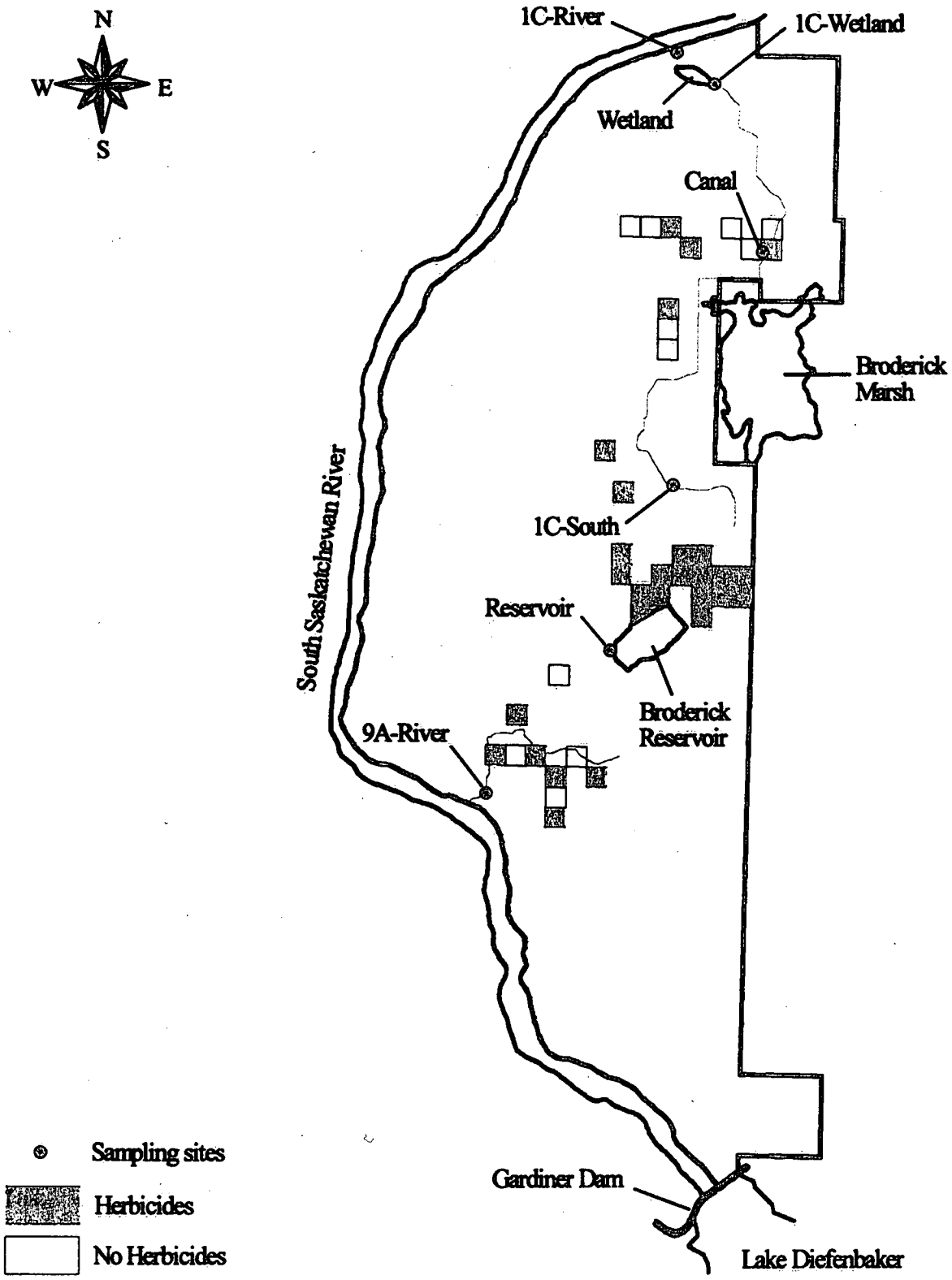


Figure 3: Map of the South Saskatchewan River Irrigation District #1 showing flood-irrigated quarter sections of land which received herbicide applications during the 1995 growing season.

Table 4: Farmer survey results: herbicides applied to flood-irrigated fields, their recommended application rates, area to which they were applied and amounts applied during the 1994, 1995 and 1996 growing seasons.

Herbicides	Rec. Applic.	Area treated/Amounts applied							
Applied	Rate	1994		1995		1996		Total	
	kg ha^{-1}	ha	kg	ha	kg	ha	kg	ha	kg
MCPA	up to 0.625	624	251	357	220	698	440	1,679	911
fenoxaprop	0.080 - 0.092	478	43	238	22	461	42	1,177	107
ethalfluralin	0.85 - 1.1	395	430	453	500	189	210	1,037	1,140
bromoxynil	0.28 - 0.34	99	34	107	36	565	190	771	260
thifensulfuron	0.010 - 0.015	423	6.3	132	2.0	-	-	555	8.3
2,4-D	up to 0.56	-	-	265	150	87	39	352	189
dicamba	0.04 - 0.14	-	-	130	18	139	16	269	34
clopyralid	0.15 - 0.3	18	5.4	49	15	61	18	128	38
glyphosate	0.27 - 0.89	67	60	-	-	49	44	116	104
fluazifop	0.075 - 0.175	36	6.3	-	-	59	10	95	16
tralkoxydim	0.20	-	-	20	4.0	69	14	89	18
2,4-DB	1.08 - 1.38	-	-	-	-	49	68	49	68
tribenuron	0.005 - 0.0075	-	-	36	0.27	12	0.09	48	0.36
clodinafop	0.055 - 0.070	-	-	-	-	34	2.4	34	2.4
glufosinate	0.3 - 0.6	-	-	33	20	-	-	33	20
trifluralin	1.1 - 1.4	32	45	-	-	-	-	32	45
imazamethabenz	0.39 - 0.48	20	9.8	-	-	-	-	20	9.8
quizalofop	0.072 - 0.144	-	-	20	2.9	-	-	20	2.9
mecoprop	0.825 -1.05	-	-	-	-	18	19	18	19
Total		2,261[1]	1,070	1,840[1]	1,043	2,554[1]	1,145	6,650	3,261

[1]Total area treated exceeds area irrigated (Table 2) because two or more herbicides were applied to some fields

ethalfluralin, bromoxynil, clopyralid) were applied in all three growing seasons, eight herbicides (thifensulfuron, 2,4-D, dicamba, glyphosate, fluazifop, tralkoxydim, tribenuron, clodinafop) in two of the growing seasons, and six herbicides (2,4-DB, glufosinate, trifluralin, imazamethabenz, quizalofop, mecoprop) in only one growing season. All nineteen herbicides have been arranged in order of decreasing area to which they were applied in Table 4. Nine herbicides (MCPA > fenoxaprop > ethalfluralin > bromoxynil > thifensulfuron > 2,4-D > dicamba > clopyralid > glyphosate) were applied to greater than 100 ha over the three years and accounted for 93.5% of the area treated with individual herbicides. Of the ten herbicides monitored for in the drainage water, eight herbicides were applied to flood-irrigated land during the three-year study and these collectively accounted for 66.5% of the area to which individual herbicides were applied. Although monitored for, the herbicides triallate and diclofop were not reported to have been applied to flood-irrigated land during the study.

Total amounts of herbicides applied during a single growing season or cumulatively over the three growing seasons were dependent upon the area treated (ha) and the application rate (kg ha^{-1}). In situations in which the farmer did not provide the rate of herbicide application, recommended application rates (SAF 1999) were used to calculate the amounts of each herbicide applied during each growing season. Recommended application rates of the nineteen herbicides range from 0.0075 to 1.4 kg ha^{-1} (Table 4) reflecting the wide range in phytotoxicity currently expressed by the various classes of chemicals registered for herbicide use in Canada. Thus, the amount of a very phytoactive herbicide applied to a relatively large area could be exceeded by that of a herbicide applied at a much higher application rate to a relatively small area. For example, although fenoxaprop and ethalfluralin were applied to essentially the same area over the three growing seasons, the amount of ethalfluralin applied exceeded that of fenoxaprop by an order of magnitude.

Approximately 1,100 kg of herbicides were applied to flood-irrigated land, drained by the 1C and 9A drainage ditches, each year (Table 4). Only six herbicides (ethalfluralin > MCPA > bromoxynil > 2,4-D > fenoxaprop > glyphosate) were applied in amounts greater than 100 kg over the three-year period and these six herbicides accounted for approximately 89.6% of the total amount of herbicide applied. The eight herbicides which were applied to flood-irrigated land and monitored for in the drainage water during the three-year study collectively accounted for 87.5% of herbicide applied.

Approximately 23% of the flood-irrigated land received no herbicide applications. The majority of this land was within the 1C drainage area. Crops grown on this land were generally forage crops, such as grasses (grown for hay) and alfalfa. Over the three-year study, the total area sprayed with individual herbicides was generally about 2.7 times the total flood-irrigated area and 3.5 times greater than the flood-irrigated area which received herbicide treatments (Tables 2 and 4). This indicates that during the three-year period, on average, three to four herbicides were applied to each flood-irrigated hectare that was treated with herbicides.

Irrigation: The irrigation amounts for each parcel on each quarter section were used to create the following four categories: total average irrigation for each quarter section for June, July, August, and for the entire growing season. These totals were then organized into classes and displayed on a map of the irrigation district (Figure 4). In cases where only a portion of the quarter section was irrigated, the entire quarter section was still displayed with the average irrigation amount for the quarter section shown. To calculate the total irrigated area drained by either the 1C or 9A drainage ditch, the areas of all parcels receiving irrigation water within each drainage area were summed for each year.

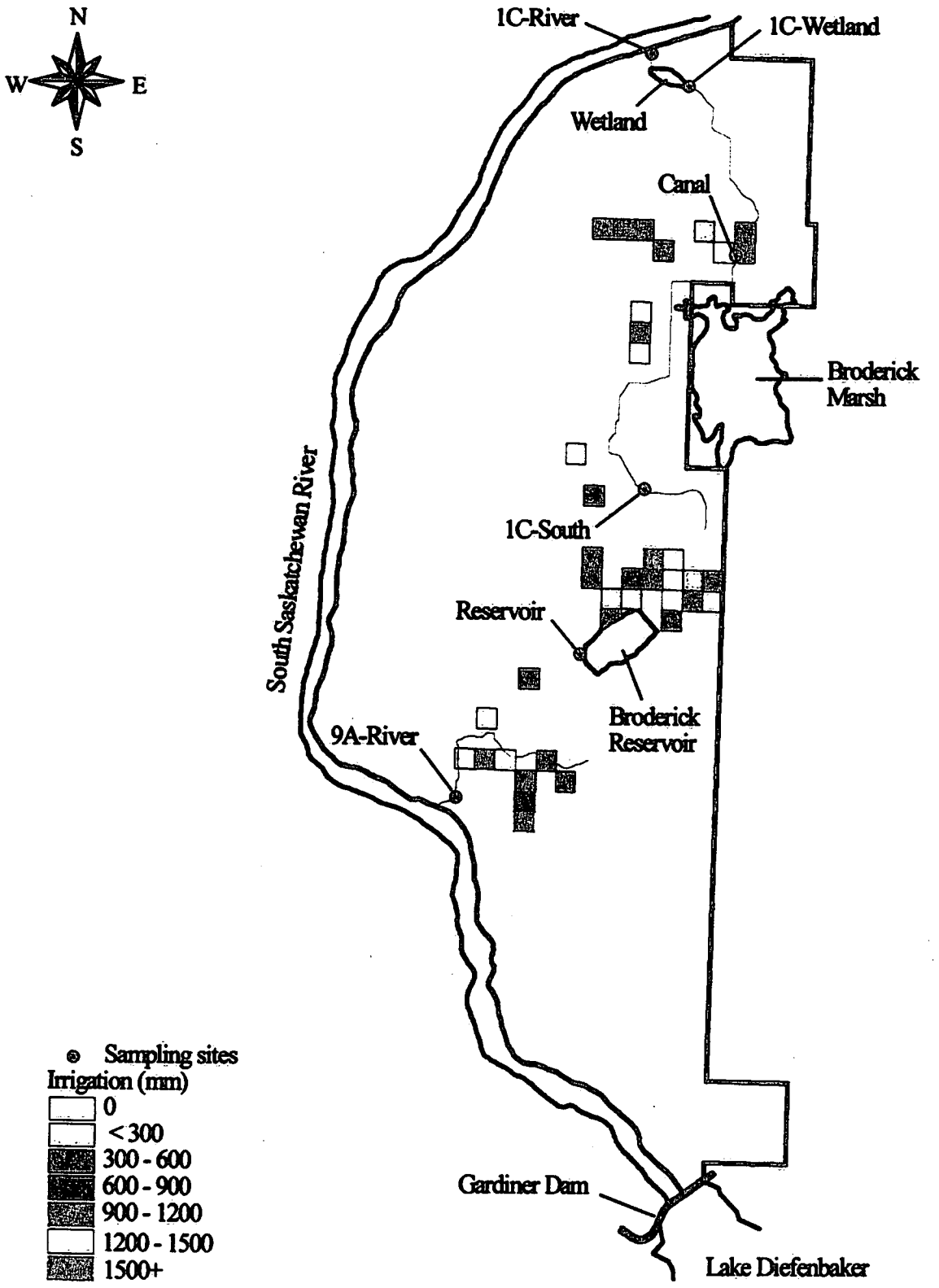


Figure 4: Map of the South Saskatchewan River Irrigation District #1 showing quarter sections of land which were flood irrigated during the 1995 growing season.

Irrigations generally began in early to mid-June each year and ceased by the end of August. The amount of irrigation water applied during each irrigation ranged from 25 to 50 mm. The total amount of irrigation water applied during a single growing season to parcels within quarter sections generally ranged from <200 to <600 mm and was mainly dependent on the crop grown. However, some parcels received more than 1200 mm. In 1995, the amounts of irrigation water applied to parcels tended to be greater than in the other two years of the study and the area irrigated was also greater (Table 2).

Drainage Water Flows

Daily flows were determined as the mean of 24 hourly measurements per day. The variation in daily flows ($m^3\ h^{-1}$) from early-June to late-September for each year at each sampling site is shown in Figures 5, 6 and 7. The total volume of water which flowed past each sampling site is also indicated in these Figures. The area of flood-irrigated land drained by the 9A drainage ditch was three times less than that drained by the 1C drainage ditch (Table 2) and this is reflected in the much lower flows in the 9A ditch. Following periods of high rainfall, flow of drainage water in the 9A drainage ditch occasionally ceased completely for periods of several days because of the corresponding decrease in flood irrigation.

Increased flows in the drainage ditches generally corresponded to periods of low rainfall. Conversely, decreased flows generally followed significant rainfalls and also occurred towards the end of August when crops no longer required irrigation. During the 1994 growing season, drainage water flows past the 1C-River and 1C-South sampling sites were similar (Figure 5). This similarity in flow occurred since the 1C-South sampling site was downstream of all flood-irrigated fields and the point at which excess irrigation water entered the 1C drainage ditch. In contrast, during the 1995

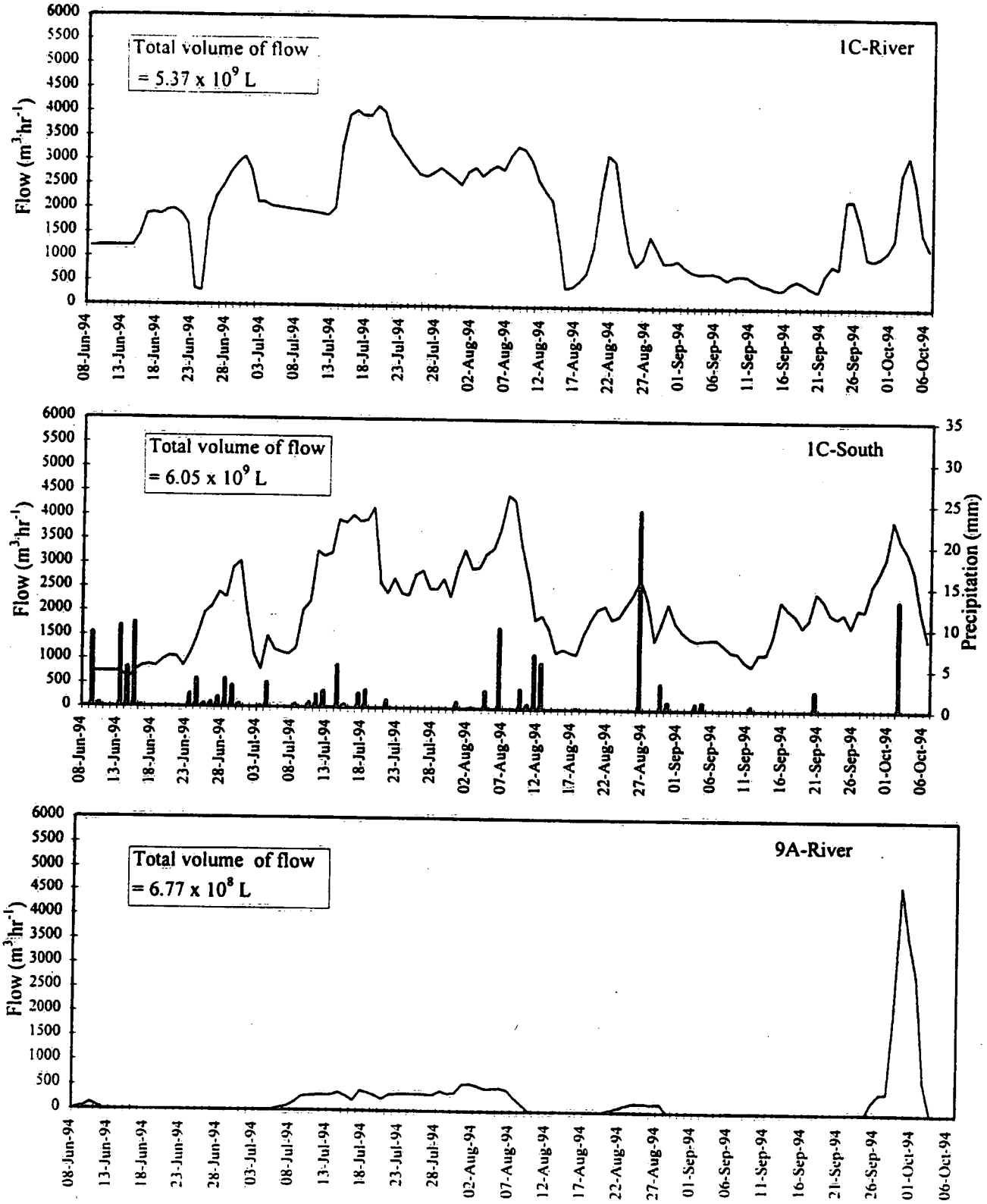


Figure 5: Rainfall and daily drainage water flows in the 1C (1C-River and 1C-South) and 9A (9A-River) drainge ditches during the 1995 growing season. Data gaps for 9A River indicate periods when drainage water flow at this sampling site completely ceased.

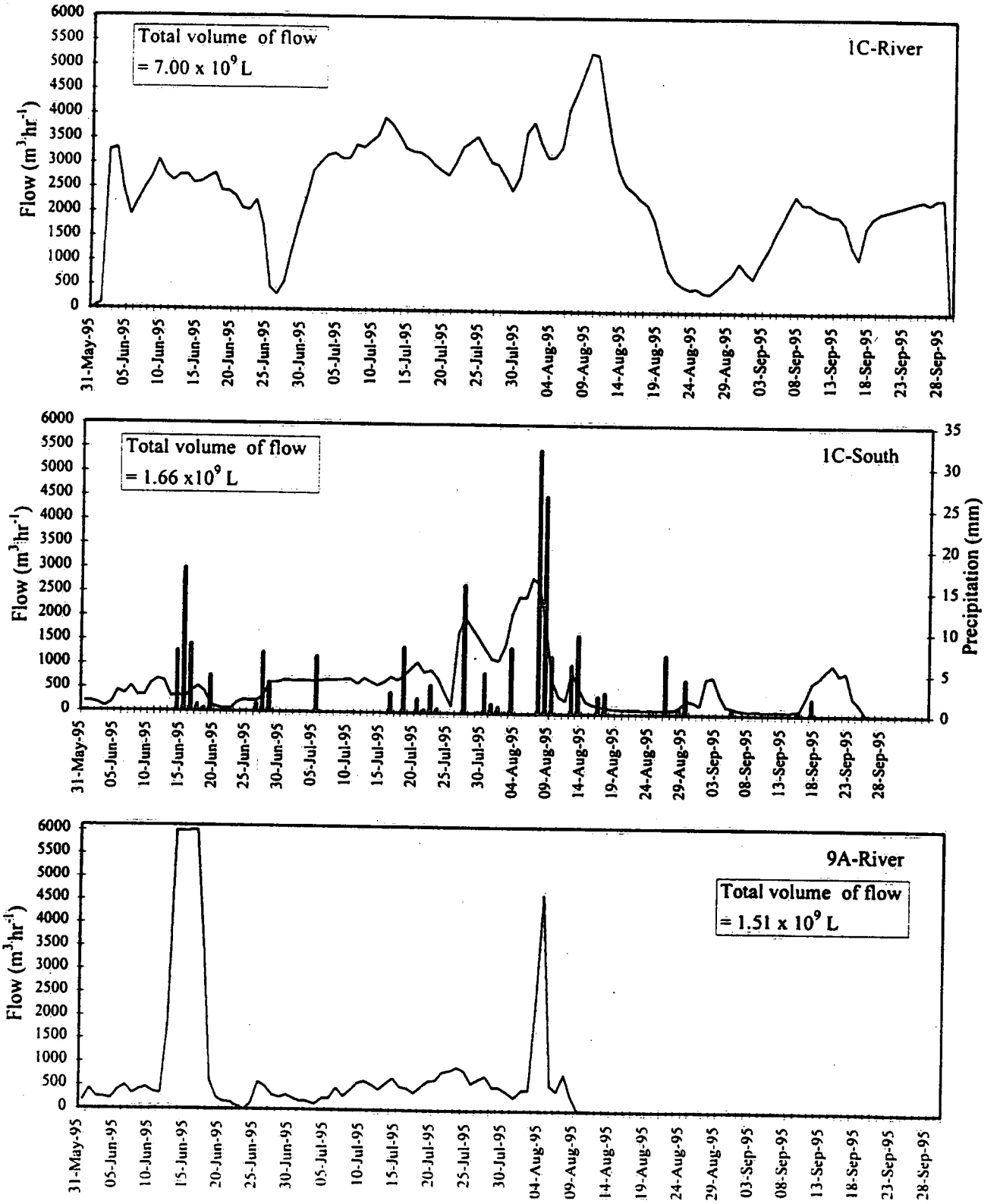


Figure 6: Rainfall and daily drainage water flows in the 1C (1C-River and 1C-South) and 9A (9A-River) drainge ditches during the 1995 growing season. Data gaps for 9A River indicate periods when drainage water flow at this sampling site completely ceased.

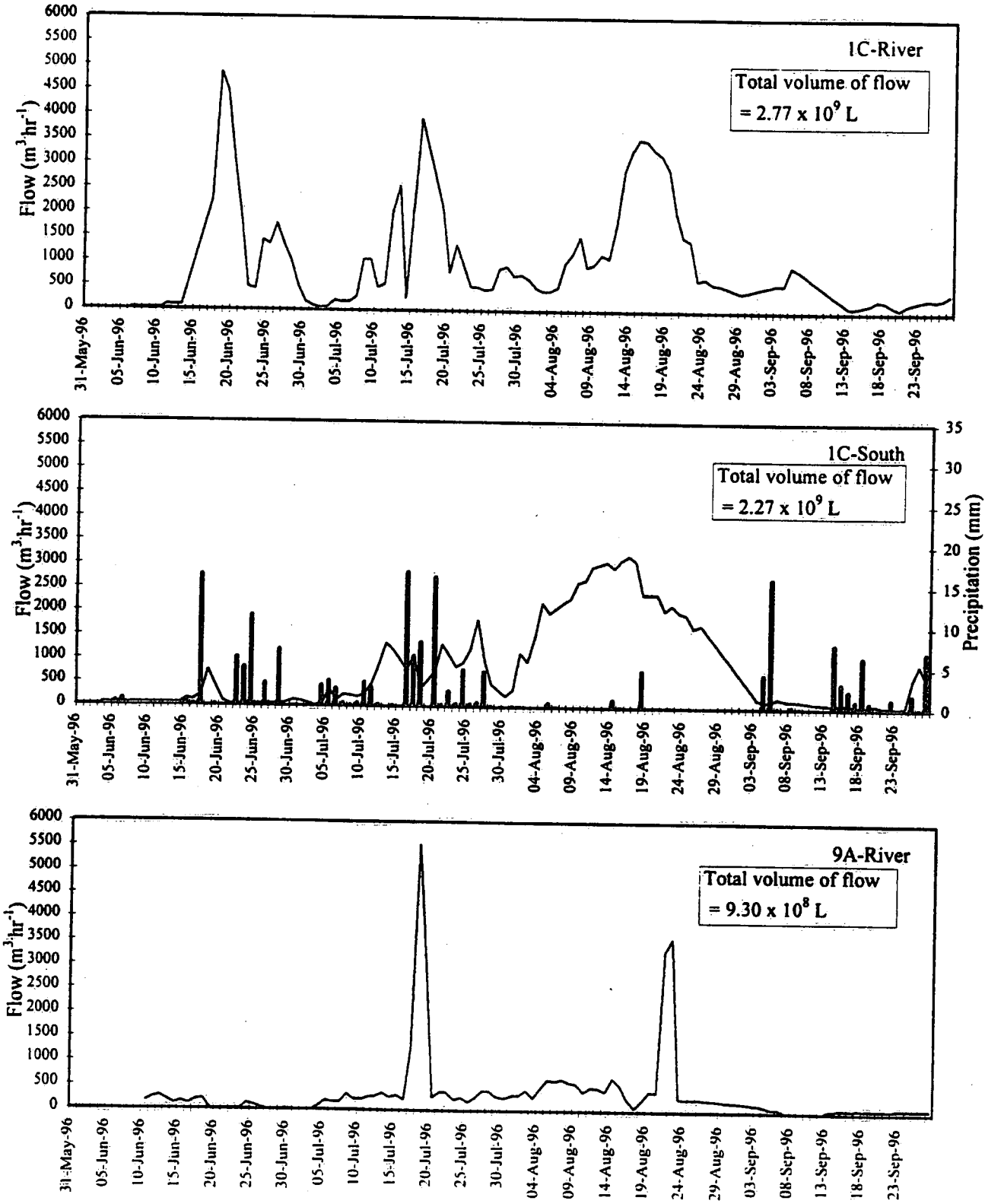


Figure 7: Rainfall and daily drainage water flows in the 1C (1C-River and 1C-South) and 9A (9A-River) drainge ditches during the 1995 growing season. Data gaps for 9A River indicate periods when drainage water flow at this sampling site completely ceased.

and 1996 growing seasons, flows past the 1C-River sampling site exceeded those past the 1C-South sampling site (Figures 6 and 7). During these two growing seasons, the 1C-South sampling site was upstream of several flood-irrigated fields and the point at which excess irrigation water entered the 1C drainage ditch (Figure 1). Flows in both the 1C and 9A drainage ditches were greatest in 1995.

Nutrient Transport

Nutrient concentrations measured at the sampling points on 1C and 9A drainage ditches are reported in Table 5. Geometric means of the nutrient concentrations were used in the analysis of the nutrient data because occasional extremely high concentrations obscured the overall trends if arithmetic means were used. In the determination of the geometric means of ortho-P and nitrate concentrations in the irrigation water (Reservoir and Canal sampling sites), all concentrations less than the limit of quantification (0.002 mgP L^{-1} and 0.010 mgN L^{-1}, respectively) were assumed to be equal to the limit of quantification. Concentrations of total P and ammonia in all irrigation water samples were greater than their respective limits of quantification of 0.002 mgP L^{-1} and 0.005 mgN L^{-1}. Due to resource constraints, ammonia concentrations were not determined in any of the 1996 samples

Irrigation Water: Irrigation water, collected from the Reservoir sampling site on the main irrigation water supply canal just downstream of the Broderick Reservoir in 1996, contained relatively low concentrations of the various nutrients (Table 5). The mean concentration of total P in these samples was 0.023 mgP L^{-1}, with concentrations in all samples (n = 5) greater than the limit of quantification. The mean ortho-P concentration was 0.003 mgP L^{-1} with two samples having concentrations less than the limit of quantification. The mean nitrate concentration was 0.017 mgN L^{-1} with one sample having a concentration less than the limit of quantification.

Table 5. Geometric means of nutrient concentrations at each sampling point in each year.

	Reservoir	Canal	1C-South	1C-Wetland	1C-River	9A-River
	---------- mg L^{-1} ----------					
Total P						
1994	-[1]	-	0.068	0.053	0.093	0.085
1995	-	0.017	0.064	0.032	0.039	0.048
1996	0.023	0.017	0.075	0.043	0.043	0.044
Ortho-P						
1994	-	-	0.023	0.015	0.032	0.042
1995	-	0.003[2]	0.030	0.007	0.012	0.024
1996	0.003[2]	0.003[2]	0.035	0.009	0.008	0.016
Nitrate						
1994	-	-	0.025	0.021	0.030	0.018
1995	-	0.010[2]	0.050	0.018	0.041	0.012
1996	0.017[2]	0.010[2]	0.044	0.038	0.041	0.024
Ammonia						
1994	-	-	0.066	0.048	0.137	0.027
1995	-	0.031	0.041	0.042	0.056	0.027
1996	na	na	na	na	na	na

[1]Samples were not collected
[2]For the determination of the geometric means for these concentrations, all samples in which the concentrations of ortho-P and nitrate were less than the limit of quantification were assumed to be equal to the limit of quantification.
na = not analyzed for

After passage of the irrigation water through the length of the main supply canal, nutrient concentrations had not changed significantly in irrigation water samples collected at the Canal sampling site in 1995 and 1996 (Table 5). Twenty percent and 73% of these samples had ortho-P and nitrate concentrations, respectively, less than their respective limits of quantification.

Drainage Water: Nutrient concentrations in drainage water collected at the 1C-Wetland and 9A-River sampling sites (Table 5) clearly show that as the flood-irrigation water passed over fertilized cropland, concentrations of total P, ortho-P and nitrate increased due to interaction of the irrigation water with the runoff-soil interaction zone. Concentrations of total P increased two to five times in the drainage water at these sampling sites, whereas those for ortho-P increased by greater than three to greater than fourteen times. Nitrate concentrations in the drainage water were also substantially greater, by up to a factor greater than five, with the exception of the 9A drainage water in 1995 in which the mean nitrate concentration showed the smallest increase relative to that detected in the irrigation water at the Canal site. In contrast, ammonia concentrations did not show a consistent increase in both the 1C and 9A drainage water. Concentrations increased only in the 1C drainage water (by a factor of up to four) but in the 9A drainage water were relatively unchanged from those detected in the irrigation water.

In 1995 and 1996, total P, ortho-P and nitrate concentrations were greater at the 1C-South sampling site than the downstream sampling points on the drainage ditch as a result of dilution of the drainage water by unused irrigation water as well as drainage water from farmland with lower nutrient inputs. The absence of this pattern in corresponding ammonia concentrations in 1995 suggests that manure from grazing cattle which had access to the drainage ditch and nutrient dynamics in the drainage system masked the amounts of ammonia contributed in surface runoff.

The temporal variability of nutrient concentrations is shown in Figures 8 and 9. There was considerable variation in the concentrations of all nutrients in both drainage ditches. The variation typically consisted of sharp increases in concentration that lasted for approximately one week. In 1994, these peak nutrient concentrations were found throughout the year but in 1995 and 1996 the peaks were only found early and late in the season. Average concentrations of total P measured at

the outflows of 1C and 9A drainage ditches were similar but the 9A drainage water had greater concentrations of ortho-P (Table 5). In contrast, nitrate and ammonia concentrations were greater in the 1C drainage water. The higher ortho-P concentration found in the 9A drainage water may be due to a greater proportion of broadcast fertilizer applications in the 9A drainage area. Since P is relatively immobile in soil, it may have remained near the soil surface within the soil-runoff interaction zone resulting in higher concentrations in runoff. The effect of broadcasting would not be seen with nitrogen applications because these nutrients are leached more readily into the soil profile.

Effect of Drainage Water on River Water Quality: Maximum flows in the drainage ditches over the three year study were of the order of 2 $m^3 s^{-1}$ (Figures 5 - 7) whereas average flows in the South Saskatchewan River over the summer months (May to September) of 1994 to 1996 ranged from 60 to 1,280 $m^3 s^{-1}$. This difference in flows means that the drainage water entering the river would have been diluted by factors greater than one order of magnitude to factors greater than two orders of magnitude. The effect of the drainage water on quality of the river water with respect to N and P would have depended on both on the daily flux (kg d^{-1}) of the various forms of these nutrients to the river and the corresponding average flow (L d^{-1}) of the river.

Nitrate and Ammonia: Even without taking this dilution effect into consideration, nitrate concentrations in the drainage water entering the river were well below the Canadian Drinking Water Quality Guideline of 10 mgN L^{-1} (CCREM, 1987). The maximum daily flux of nitrate (21.3 kg d^{-1}) to the river water during the 3-year study would have only increased the nitrate concentration from 0.010 to 0.0104 mgN L^{-1}; an increase of only 4% (Table 6). Similarly, average ammonia concentrations in the drainage water entering the river were also well below (by approximately one

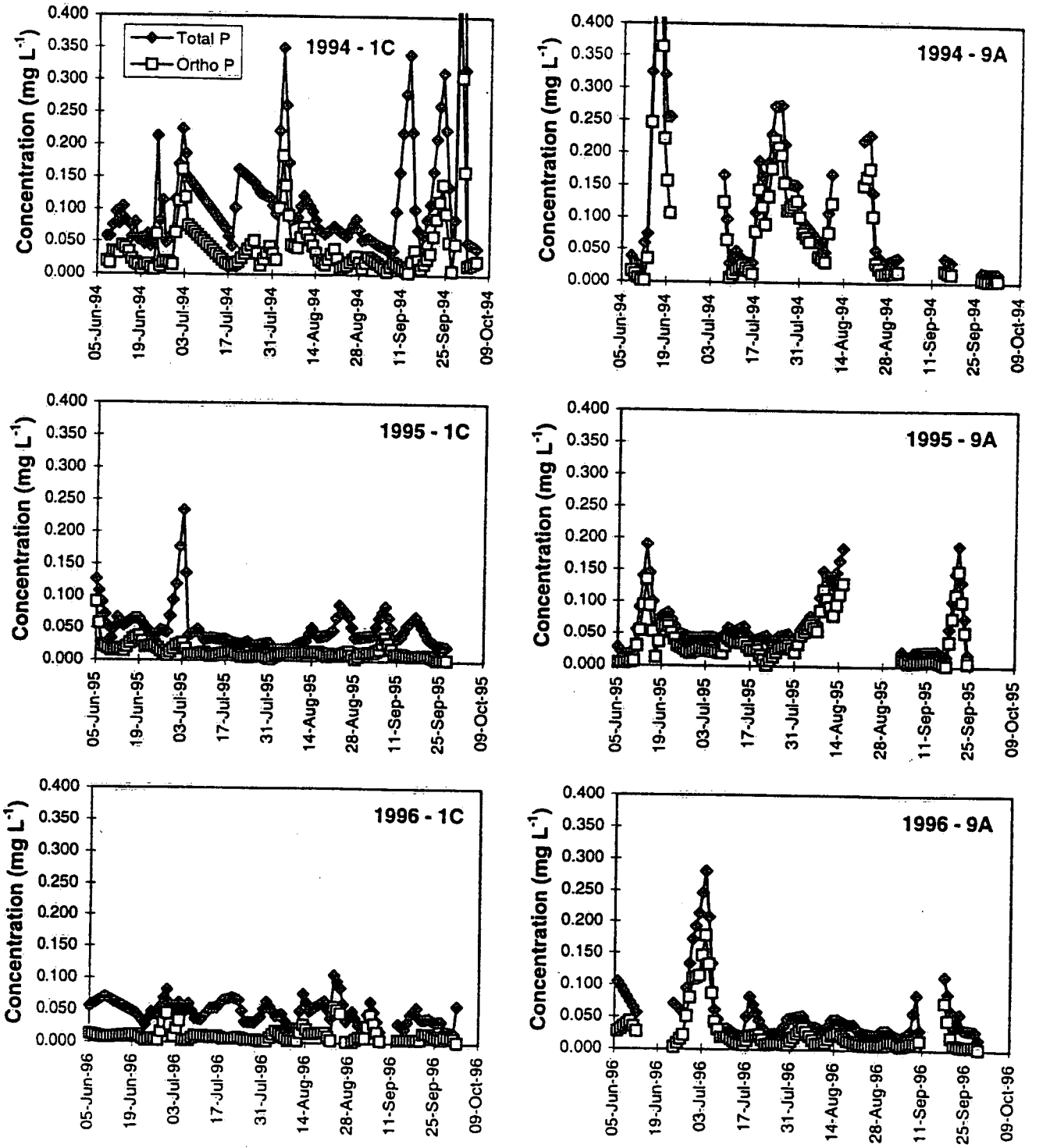


Figure 8. Total P and ortho P concentrations entering the S. Saskatchewan River. Data gaps for the 9A drainage area indicate periods when drainage water flow in the 9A drainage ditch completely ceased.

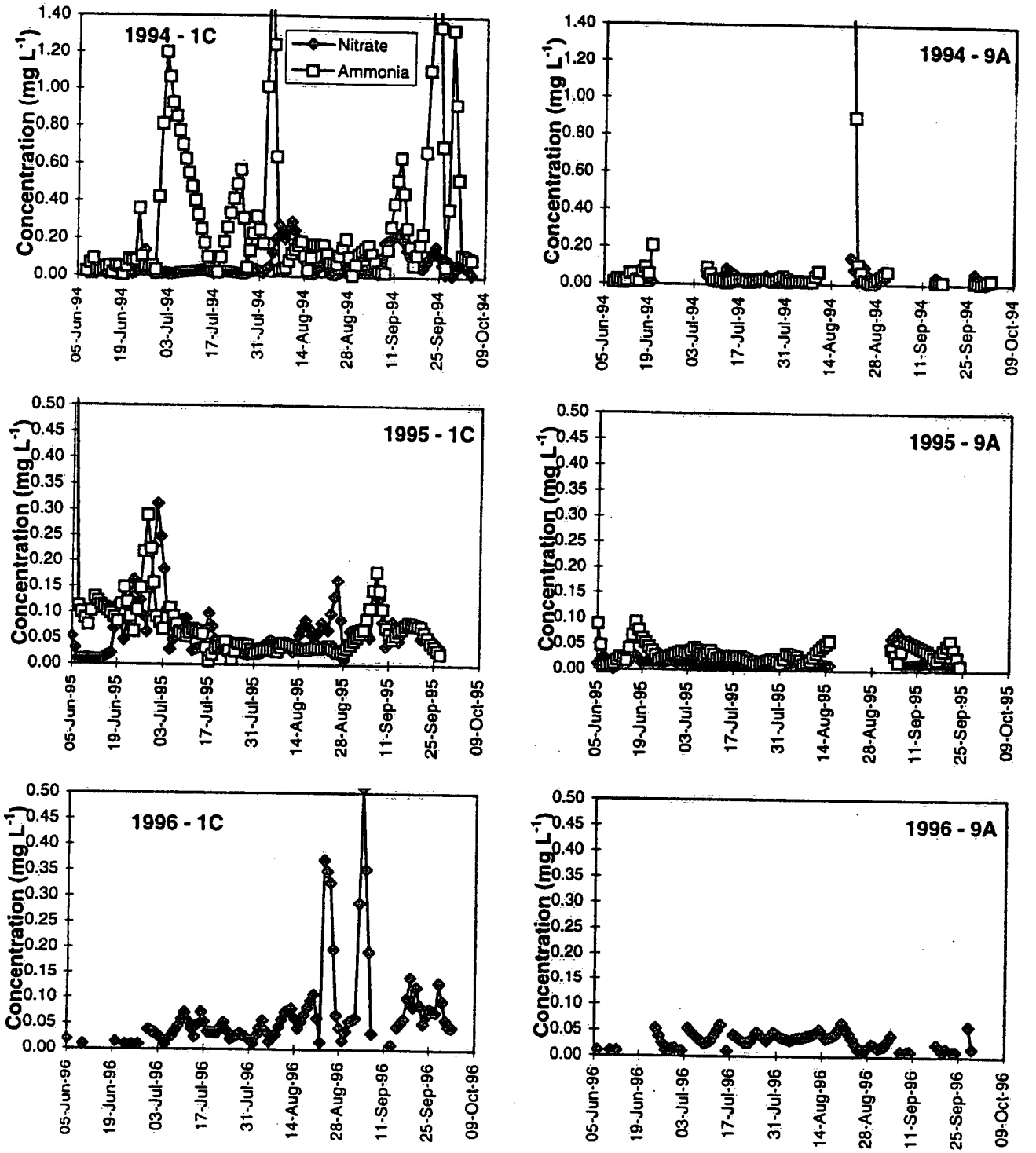


Figure 9. Nitrate and ammonia concentrations entering the S. Saskatchewan River. Data gaps for the 9A drainage area indicate periods when drainage water flow in the 9A drainage ditch completely ceased.

order of magnitude) water quality objectives, in this case, provincial guidelines for surface water (SERM, 1995). However, the maximum daily flux (120 kg d^{-1}) to the river occurred in August when the river flow was greatly reduced. Consequently, the ammonia concentration in the river water for that 24-h period increased by 41%, but remained well below the provincial guidelines. Such increases would have been infrequent because ammonia fluxes exceeding 10 kg d^{-1} occurred only four times during the 3-year study.

Total P and Ortho-P: SERM (1995) does not identify a specific guideline for phosphorus but states that phosphorus additions should not alter natural conditions sufficiently to cause nuisance growths of algae or aquatic weeds. Chambers (personal communication) has recently proposed a guideline of 0.012 mgP L^{-1} for Alberta. The applicability of this guideline to Saskatchewan has not been studied but above this concentration the growth of benthic algae in Alberta rivers increases. Phosphorus concentrations in the river water already exceeded this proposed guideline prior to the input of the drainage water (Table 5). Maximum fluxes of total P and ortho-P to the river occurred on the same day (Table 6). Inflow of the maximum daily flux of total P in the drainage water to the river would have resulted in only a 3.4% increase in total P concentration from 0.017 to 0.01759 mg L^{-1}. This small increase in total P concentration in the river water was accompanied by a simultaneous 14% increase in ortho-P during that 24-h period, but neither would not have contributed greatly to increased algal growth.

Table 6. Impact of nutrient fluxes, as a consequence of inputs of flood-irrigation drainage water from the SSRID#1, on the water quality of the South Saskatchewan River

Nutrient	Date of Maximum Flux	Sampling Site	Maximum Flux to River[1] kg d^{-1}	Average Monthly River Flow[2] m^3 s^{-1}	Daily River Flow L x 10^{10}	Increase in River Conc mg L^{-1}	Original Conc in River[3] mg L^{-1}	Percent Increase
Total P	14 Jun, 1995	9A-River	27.3	540	4.67	0.00059	0.017	3.4
Ortho-P	14 Jun, 1995	9A-River	19.4	540	4.67	0.00042	0.003	14
Nitrate	01 Jul, 1995	1C-River	21.3	611	5.28	0.00040	0.010	4.0
Ammonia	03 Aug, 1994	1C-River	120	109	0.94	0.013	0.031	41

[1]These are the maximum daily nutrient fluxes to the South Saskatchewan River which occurred during the 3-year study.
[2]River flow data obtained from: Environment Canada Hydat CD-ROM Version 96-1.04 - *Surface Water and Sediment Data*, Water Survey of Canada, Atmospheric Environment Program.
[3]Data from Table 5. It is assumed that nutrient concentrations in the river water prior to drainage water inflow were the same as the mean nutrient concentrations in the irrigation water at the Canal sampling site during the 1995 and 1996 growing seasons.

Percentage of Applied: Although fertilizer applications are only one of a number of sources of nutrients in the drainage areas, it is still interesting to view amounts of nutrients leaving in the drainage water in terms of amounts of nutrients added as fertilizer. Since ammonia was not measured in 1996, fluxes of N and P at the 1C-River and 9A-River sampling sites in 1994 and 1995 were used to calculate total amounts transported as percentages of the amounts applied. Totals of 161,437 kg of N (NO_3-N plus NH_3-N) and 50,579 kg of P were applied as fertilizer to the 1C and 9A drainage areas during 1994 and 1995 (Table 3). Amounts equivalent to 1.9% of applied N (3,024 kg) and 2.2% of applied P (1,103 kg) entered the river through the drainage ditches. However, effluent from the 1C drainage ditch corresponded to 2.4% of applied N and 2.8% of applied P while the 9A drainage ditch transported amounts corresponding to only 0.3% of applied N and 1.0% of applied P. The difference between the two drainage areas may have been partly due to nutrient contributions from the wetland on the 1C drainage ditch. When the calculations were repeated using concentrations measured for the 1C wetland site, only 0.6% of applied N and 1.6% of applied P were estimated to have entered the river in the drainage water.

Effect of Wetland: Drainage water samples were collected before and after the wetland on the 1C drainage ditch in order to investigate whether the passage of the drainage water through the wetland would have affected nutrient concentrations in the drainage water. Drainage water flow through the 1C drainage ditch varied over each growing season (Figures 5, 6 and 7), however, the ratios of nutrient concentrations at the 1C-River to 1C-Wetland sampling sites were not correlated with the rate of water flow in the drainage ditch.

In general, all nutrient concentrations tended to increase due to passage of the drainage water through the wetland (Table 5). However, the increase was greatest in 1994, less in 1995, and, in 1996, passage of the drainage water through the wetland had little or no effect on the nutrient concentrations. These inconsistent changes in nutrient concentrations on passage of the drainage water through the wetland most likely arose from the dynamics of the wetland ecosystem which may act as either a source or sink of nutrients depending on environmental conditions in the wetland and surrounding area. For example, increased nutrient concentrations may result from the release of nutrients from sediments and aquatic plants within the wetland or from ground water discharge into the wetland. Conversely, decreases in nutrient concentration after passage through the wetland may reflect nutrient uptake by aquatic plants or deposition on the wetland floor. In the present study, grazing cattle, that had direct access to both the ditch and wetland, were another source of nutrients between the 1C-Wetland and 1C-River sampling sites. The comparison of nutrient concentrations at 1C-Wetland and 1C-River sampling sites indicates that nutrients entering the river from the irrigation district would be derived only in part from flood-irrigation runoff occurring during the growing season.

Herbicide Transport

When discussing herbicide transport in flood-irrigation drainage water, it is important to note that drainage ditches from individual fields and the 1C and 9A drainage ditches are often adjacent to dryland fields which are also treated with herbicides. Thus, unexpected detections of herbicide concentrations in the drainage water may be due to application drift from dryland applications of herbicides adjacent to the drainage ditches. Similarly, there are dryland fields adjacent to the wetland on the 1C drainage ditch rendering the wetland susceptible not only to contamination by application

drift but also by rainfall runoff from these fields. Unexpected herbicide detections in the drainage water may also occur because of ditch bank treatment for weed control or because herbicide application was inadvertently not reported in the farmer survey.

Concentrations of nine herbicides (triallate, trifluralin, ethalfluralin, MCPA, mecoprop, 2,4-D, dicamba, bromoynil and diclofop) were monitored in all water samples collected in all three years of the study. Clopyralid concentrations were monitored only in the 1996 samples.

Irrigation Water: Excess irrigation water was sampled in 1995 and 1996 (~ 37 samples each year) at the Canal sampling site which was situated just prior to the excess irrigation water entering the 1C drainage ditch. There were no detections of trifluralin and ethalfluralin in the excess irrigation water in either year. Trace concentrations of dicamba, mecoprop, bromoxynil, triallate and diclofop were detected in only a few samples. Trace concentrations were considered to be those reported as > 0.01 and < 0.05 $\mu g\ L^{-1}$. Several 1996 samples had trace concentrations of clopyralid. In both years, over half the samples had trace concentrations of MCPA. In September 1995, quantifiable concentrations (> 0.05 $\mu g\ L^{-1}$) of MCPA were detected in the excess irrigation water, most likely due to fall applications of the herbicide. Essentially all of the samples in both years contained 2,4-D. In 1995, almost all of the samples contained 2,4-D concentrations > 0.05 $\mu g\ L^{-1}$ whereas approximately half of the 1996 samples had concentrations of this magnitude. Analysis of irrigation water samples collected on the main supply canal just downstream of the Broderick reservoir in 1996 gave similar results, except that no clopyralid was detected in these samples. These results suggest that MCPA and 2,4-D were most likely already present in the irrigation water pumped from Lake Diefenbaker to the Broderick Reservoir, and that herbicides may also have entered the irrigation water as it passed through the 1C drainage area in the main supply canal. Application drift from the treatment of both

dryland and irrigated fields and treatment of the banks of the main supply canal to control weeds may have contributed to herbicide concentrations detected in the excess irrigation water.

Drainage Water: *Base-Neutral Herbicides* - The three base-neutral herbicides monitored for in the drainage water were triallate, trifluralin and ethalfluralin. All three herbicides are applied directly to the soil and generally incorporated immediately after application. Compared to the acidic herbicides, these herbicides have relatively low water solubilities and sorb more strongly to soil (Table 7). Thus, incorporated residues would not be expected to leach below the runoff-soil interaction zone. Due to their relatively high vapour pressures (Table 7), the main route of dissipation of these herbicides from soil is volatility losses to the atmosphere (Grover et al. 1988; Glotfelty et al. 1984). Trifluralin and ethalfluralin are dinitroaniline herbicides and both are susceptible to photodegradation (Parochetti and Dec 1978), either when present on the soil surface or in runoff water.

Ethalfluralin: Ethalfluralin was applied to relatively large areas and in relatively large amounts in all three years of the study (Table 4). The herbicide was applied to the 1C and 9A drainage areas in 1994 and 1996 and to the 1C drainage area in 1995 (Table 8) but was not detected in any of the daily drainage water samples collected from the 1C-South, 1C-Wetland, 1C-River and the 9A-River sampling sites in any year (Table 9). This lack of ethalfluralin input to the South Saskatchewan River via flood-irrigation runoff water most likely reflects its limited mobility due to low water solubility and strong sorption to soil (Table 7), and its susceptibility not only to photodegradation in water but also loss to the atmosphere by volatilization from soil.

Table 7. Water solubilities, vapour pressures, average field half-lives and absorption coefficients for the herbicides applied in this study.[1]

Herbicide	Water Solubility (20 to 25°C)	Vapour Pressure (25°C)	Average Field Half-life	Absorption Coefficient (K_{oc})
	$g\ L^{-1}$	mPa	d	$L\ kg^{-1}$
Base/Neutral				
Ethalfluralin	0.0003	11.7	63	4000[2]
Trifluralin	0.0002	6.1	57-126	6400-13400
Triallate	0.004	16	56-77	2400
Acidic				
Dicamba	6.5	4.5	<14	2
Clopyralid	143	1.33	8-66	0.4-12.9
Diclofop	123	3.1×10^{-6}	30[2]	778[3]
Bromoxynil	0.13	6.3×10^{-3}	~10	300[3]
Mecoprop	0.73	0.31	7-13	12-25
MCPA	0.73	0.023	<7	110[2]
2,4-D	0.60	0.011	<7	~60

[1]Unless otherwise noted, all values are from PM 1997; [2]WSSA, 1994; [3]Calculated from Kenga and Goring (1980).

Table 8. Area treated with individual herbicides in each growing season in the 9A drainage area and the 1C drainage area divided into that upstream and downstream of the 1C sampling site in 1995 and 1996.

Herbicide	1994		1995			1996		
	1C	9A	1C-up	1C-down	9A	1C-up	1C-down	9A
	ha							
Base/Neutral								
Ethalfluralin	264	131	425	28	0	97	53	39
Trifluralin	32	0	0	0	0	0	0	0
Acidic								
Dicamba	0	0	30	0	100	72	18	49
Clopyralid	0	18	0	0	49	61	0	0
Bromoxynil	99	0	20	87	0	369	48	148
Mecoprop	0	0	0	0	0	0	18	0
MCPA	604	20	189	91	77	502	48	148
2,4-D	0	0	111	0	154	12	18	57

Trifluralin: Trifluralin was only applied to the study area in 1994 when a small area (32 ha) within the 1C drainage area was treated (Table 8). Because trifluralin has properties similar to those of ethalfluralin and was applied in much smaller amounts (Table 4), the detection of trifluralin in the drainage water from the 1C drainage ditch in 1994 (Table 9) was somewhat surprising. A single sample from the 1C-South sampling site contained 0.10 $\mu g\ L^{-1}$ and trace concentrations were detected at this and the 1C-wetland and 1C-River sampling sites. Although no water quality guidelines were exceeded (Table 10), the 0.10 $\mu g\ L^{-1}$ concentration was equal to the water quality guideline for

Table 9: Amounts of herbicides detected at the various sampling sites. Amounts detected at the 1C-River and 9A-River sampling sites represent total inputs of ten herbicides into the South Saskatchewan River in drainage water from the Outlook Irrigation District over the 1994 to 1996 growing seasons.

Year	Sampling Site	Clopyr[1]	Dicam[2]	Meco[3]	MCPA	Bromox[4]	2,4-D	Diclo[5]	Ethal[6]	Trifl[7]	Trial[8]
						g					
1994	1C-River	-[9]	3	0	85	0	1309	1	0	< 1	7
	1C-Wetland	-	18	0	134	4	1216	0	0	0	0
	1C-South	-	14	0	171	7	3845	0	0	7	0
	9A-River	-	4	0	0	0	411	0	0	0	0
1995	1C-River	-	5	11	251	0	530	0	0	0	0
	1C-Wetland	-	0	0	266	0	573	0	0	0	2
	1C-South	-	190	237	1381	0	578	0	0	0	0
	9A-River	-	0	0	145	47	223	0	0	0	0
1996	1C-River	56	0	0	24	2	141	15	0	0	17
	1C-Wetland	4	0	0	296	0	6	0	0	0	0
	1C-South	92	0	0	130	5	0	0	0	0	0
	9A-River	0	0	0	0	0	2	0	0	0	0
Total		56[10]	12	11	505	49	2616	16	0	< 1	24

[1]Clopyralid; [2]Dicamba; [3]Mecoprop; [4]Bromoxynil; [5]Diclofop; [6]Ethalfluralin; [7]Trifluralin; [8]Triallate; [9]Not analysed for; [10]Amount of clopyralid which entered the river only in 1996.

aquatic life. Trifluralin was not detected in drainage water from these sites in 1995 and 1996 or at the 9A-River sampling site in any year. Less than 1 g of trifluralin entered the river in 1994 (Table 9).

Table 10. Maximum herbicide concentrations detected in the drainage water, and Canadian Water Quality Guidelines for irrigation water, livestock watering, aquatic life and drinking water.

Herbicide	Maximum concentration	Irrigation water	Livestock Watering	Aquatic Life	Drinking Water
		---------- $\mu g\ L^{-1}$ ----------			
Ethalfluralin	nd	-[1]	-	-	-
Trifluralin	0.10	-	45	0.1	45
Triallate	0.22	-	230	0.2	230
MCPA	2.8	0.03, 0.16[2]	25	2.6	-
Bromoxynil	0.32	0.35, 1.0, 7.4[3]	11	5.0	5.0
Clopyralid	0.50	-	-	-	-
Dicamba	0.46	0.006	122	10	120
2,4-D	3.9, 76[4]	0.1	100	4.0	100
Mecoprop	0.71	-	-	-	-
Diclofop	0.09	0.18	9.0	6.1	9.0

[1]Guidelines have not yet been established.
[2]Guidelines of other crops and "cereals, tame hays and pastures"
[3]Guidelines for legumes, other crops and cereals, respectively.
[4]The 76 $\mu g\ L^{-1}$ concentration was detected at the 9A-River sampling site in 1994 and probably resulted from direct application of the herbicide to a drainage ditch.

Triallate: Since no triallate was reported in the farmer survey to have been applied to flood-irrigated fields within the study area in any year, detection of quantifiable concentrations in two samples both

in 1994 and 1996 at the 1C-River sampling site was unexpected. Concentrations > 0.05 $\mu g\ L^{-1}$ occurred in late August and September, possibly as a consequence of fall dryland applications in the vicinity of the wetland. The maximum concentration of triallate detected was 0.22 $\mu g\ L^{-1}$ and, during 1994 and 1996, 24 g of the herbicide were estimated to have entered the river (Table 9).

Acidic Herbicides - All of the acidic herbicides were applied as postemergence treatments. Thus, the majority of each herbicide application not intercepted by the crop/weed canopy would have deposited on the top few millimetres of soil within the runoff-soil interaction zone. In the farmer survey, MCPA, bromoxynil and clopyralid were reported to be applied in all three years, dicamba and 2,4-D in 1995 and 1996, and mecoprop only in 1996 (Tables 4 and 8). These acidic herbicides have shorter field half-lives than the soil-incorporated herbicides (Table 7) but, due to their relatively lower vapour pressures, volatility losses would not have played a significant role in their dissipation from the runoff-soil interaction zone. However, due to their much higher water solubility and decreased soil sorption (Table 7), a portion of these herbicides may have leached, due to rainfall and irrigation, below the runoff-soil interaction zone and not been available for transport in the surface runoff water.

MPCA: MCPA was the only herbicide applied to both drainage areas in all three years (Table 8). It was also applied in greatest amounts to the greatest area (Table 4). Quantifiable amounts of MCPA (Table 9) entered the river in all three years from the 1C drainage area in which relatively large areas were treated each year (Table 8). In general, quantifiable concentrations of MCPA were detected in the June/July drainage water samples and probably reflect the first irrigation runoff water following spring applications of MCPA. In September 1994, quantifiable concentrations of MCPA

were detected in the 1C drainage water reflecting fall application of the herbicide.

In contrast, much smaller areas within the 9A drainage area were treated with MCPA during the 3-year study (Table 8). Only trace concentrations of MCPA were detected in the 9A drainage water in 1994 and 1996 when smallest areas were treated and, during those two years, no quantifiable amounts of MCPA entered the river from the 9A drainage area (Table 9). However, in 1995 when the largest amount of MCPA was applied within the drainage area, quantifiable concentrations of MCPA were detected in 9A drainage water entering the river.

The maximum concentration of MCPA detected in the drainage water was 2.8 $\mu g\ L^{-1}$ and the maximum concentration that entered the river was 0.56 $\mu g\ L^{-1}$. The maximum concentration in the drainage water exceeded the water quality guideline for aquatic life, whereas both concentrations exceeded the guideline for irrigation water (Table 10). Some of the trace concentrations of MCPA detected in the drainage water may reflect the presence of trace concentrations of the herbicide in the irrigation water. The total amount of MCPA estimated to enter the river during the three-year period was 505 g (Table 9).

Bromoxynil: Bromoxynil was also reported to have been applied to the study area in all three years, with smaller but similar amounts applied in 1994 and 1995 (Table 4). The total amount of bromoxynil applied was less than half the amount of MCPA applied. In both years, a few trace concentrations were detected in the drainage water at the 1C-South sampling site. Trace concentrations were detected at the 1C-River site only in 1994 so that quantifiable amounts of the herbicide did not enter the river in either year. In 1996, when a relatively large amount of bromoxynil was applied (Table 4) to a relatively large area (Tables 4 and 8), only a single quantifiable concentration was detected at each sampling site. The susceptibility of bromoxynil to

photodegradation in natural waters probably explains why there were so few samples with bromoxynil concentrations > 0.05 $\mu g\ L^{-1}$ even though a relatively large amount of the herbicide had been applied. Detections generally occurred in samples collected in June and July.

Bromoxynil was applied within the 9A drainage area only in 1996 (Table 8) and, in that year, a trace concentration of bromoxynil was detected in only one drainage water sample that entered the river. Unexpectedly, quantifiable amounts also entered the river from the 9A drainage ditch in 1995.

The maximum concentration of bromoxynil (0.32 $\mu g\ L^{-1}$) was detected in the drainage water from the 9A sampling site in 1995 and approached the water quality guideline for irrigation water used for the irrigation of legumes (Table 10). A total of 49 g of bromoxynil was estimated to have entered the river during the three-year period (Table 9).

Clopyralid: Although clopyralid was applied to the 9A drainage area in 1994 and 1995 and to the 1C drainage area in 1996 (Table 8), concentrations in the drainage water were only monitored in the 1996 samples. In 1996, there was no clopyralid applied to the 9A drainage area and only a few trace concentrations were detected in drainage water samples from the 9A sampling site. However, quantifiable concentrations were detected at both the 1C-South and 1C-River sampling sites from the 1C drainage area where 18 kg of clopyralid were applied (Table 4). The maximum concentration of clopyralid detected in the drainage water was 0.50 $\mu g\ L^{-1}$. A total of 56 g of clopyralid was estimated to have entered the river during the 1996 growing season (Table 9) .

Dicamba: Dicamba was applied to both drainage areas in 1995 and 1996 (Table 8). In both years, a few samples showed trace concentrations of dicamba in the drainage water entering the river from the 9A drainage area. Trace concentrations in a few drainage water samples were detected from the

1C-South and 1C-River sampling sites in 1966, whereas in 1995, concentrations of dicamba > 0.05 $\mu g\ L^{-1}$ were detected in some samples at these sites. The maximum concentration of dicamba detected in the drainage water was 0.46 $\mu g\ L^{-1}$ which exceeded the water quality guideline for irrigation water (Table 10). As with the other postemergence-applied herbicides, detections of dicamba generally occurred in samples collected during June and July. Only 8 g of dicamba was estimated to have entered the river during the three years (Table 9).

2,4-D: As discussed earlier, concentrations of 2,4-D > 0.05 $\mu g\ L^{-1}$ were very frequently detected in the excess irrigation water. Thus, it was not surprising that 2,4-D was detected with essentially the same frequency in samples collected at the 1C-South, 1C-Wetland, 1C-River and 9A-River sampling sites in all three years of the study, even though 2,4-D was applied to both drainage areas only in 1995 and 1996 (Table 8). However, concentrations of 2,4-D in the excess irrigation water were generally < 0.2 $\mu g\ L^{-1}$, whereas 2,4-D concentrations in the drainage water that entered the river exceeded this value for extended periods in 1995 and 1996. Maximum concentrations of 2,4-D were 0.70 and 0.34 $\mu g\ L^{-1}$ in 1995 and 1996, respectively and these concentrations exceeded the water quality guideline for irrigation water (Table 10). Thus, the amounts of 2,4-D entering the river from each drainage area in these two years probably reflect concentrations of 2,4-D originally in the irrigation water plus concentrations in the drainage water from treated fields. In the fall of 1994, a maximum concentration of 3.9 $\mu g\ L^{-1}$ was detected at the 1C-River sampling site which was essentially equal to the water quality guideline for aquatic life. At the 9A-River sampling site, a maximum concentration of 75.7 $\mu g\ L^{-1}$ was detected suggesting that a drainage ditch from an individual field or the 9A drainage ditch had been directly sprayed with 2,4-D. It was estimated that a total of 2,616 g of 2,4-D entered the river over the three growing seasons (Table 9).

Mecoprop: Although applied to a relatively small area within the 1C drainage area only in 1996 (Table 8), mecoprop was detected in the 1C drainage water in all three years. In 1994, trace concentrations were detected in a few 1C-South and 1C-River samples. Unexpectedly in 1995, concentrations > 0.05 $\mu g\ L^{-1}$ were detected in samples collected at the these sampling sites. A maximum concentration of 0.71 $\mu g\ L^{-1}$ was detected in the drainage water from the 1C-South sampling site and 237 g of the herbicide was transported past that site (Table 9). However, only 11 g of mecoprop entered the river in that year indicating that mecoprop dissipated rapidly in the drainage water. In 1996, there were no detections in the 1C-South samples because mecoprop had been applied downstream from that site, but trace concentrations were detected in samples from the 1C-Wetland and 1C-River sampling sites.

Mecoprop was reported not to have been applied to the 9A drainage area in any year and was not detected in any drainage water samples collected from the 9A-River sampling site in either 1995 or 1996. However, trace concentrations were detected in a few samples from this site in 1994. Thus, no quantifiable amounts of mecoprop entered the river from the 9A drainage area in any year.

Diclofop: Diclofop was reported not to have been applied to either drainage area in any of the three years. However, trace concentrations were detected in a few samples collected at the 9A-River and 1C-South sampling sites in 1994 and 1995, but not in 1996. Some trace and quantifiable concentrations were detected in samples from the 1C-River sampling site in 1994 and 1996 and a total of 16 g of diclofop were estimated to have entered the river (Table 9). The maximum concentration of diclofop detected was 0.09 $\mu g\ L^{-1}$ which did not exceed any water quality guidelines (Table 10).

Effect of Drainage Water on River Water Quality: With the exception of 2,4-D which was already present in the South Saskatchewan River in concentrations which frequently exceeded the water quality guideline for irrigation water (as indicated by its presence in the irrigation water which originated from the river), dilution of the drainage water by greater than one to greater than two orders of magnitude by the much larger river flow meant that herbicide concentrations in the drainage water which exceeded various water quality guidelines would most likely have been diluted below guidelines soon after entering the river. As with the nutrients, the effect of the drainage water on quality of the river water with respect to the various herbicides would have depended both on the daily flux (kg d^{-1}) of the various herbicides to the river and the corresponding average flow (L d^{-1}) of the river.

Ethalfluralin: Since this herbicide was not detected in any of the drainage water samples during the 3-year study, ethalfluralin would have had no effect on the quality of the river water.

Trifluralin, Triallate, MCPA, Bromoxynil, Clopyralid, Dicamba, Mecoprop, Diclofop: With the exception of MCPA, each of these herbicides was detected in the irrigation water only in trace concentrations; that is, at concentrations > 0.01 μg L^{-1} and < 0.05 μg L^{-1}. The maximum increase

Table 11: Impact of herbicide fluxes, as a consequence of inputs of flood-irrigation drainage water from the SSRID#1, on the water quality of the South Saskatchewan River.

Herbicide	Date of Maximum Flux	Sampling Site	Maximum Flux to River[1] $g\ d^{-1}$	Average Monthly River Flow[2] $m^3\ s^{-1}$	Daily River Flow $L \times 10^{10}$	Increase in River Conc $\mu g\ L^{-1}$	Original Conc in River[3] $\mu g\ L^{-1}$
Ethalfluralin	-	-	0	-	-	-	nd[4]
Trifluralin	12 Sep, 1994	1C-River	0.57	119	1.03	0.000055	nd
Triallate	22 Aug, 1996	1C-River	8.7	177	1.53	0.00057	tr[5]
MCPA	17 Jun, 1995	9A-River	83	540	4.67	0.0018	tr, > 0.05[6]
Bromoxynil	17 Jun, 1995	9A-River	46	540	4.67	0.0010	tr
Clopyralid	22 Aug, 1996	1C-River	7.5	177	1.53	0.00049	tr
Dicamba	03 Jul, 1995	1C-River	5.2	611	5.28	0.000099	tr
2,4-D	24 Sep, 1996	1C-River	120	119	1.03	0.012	tr, > 0.056
Mecoprop	03 Jul, 1995	1C-River	6.7	611	5.28	0.00013	tr
Diclofop	19 Jun, 1996	1C-River	6.8	317	2.74	0.00025	tr

[1]These are the maximum daily herbicide fluxes to the South Saskatchewan River which occurred during the 3-year study.
[2]River flow data obtained from: Environment Canada Hydat CD-ROM Version 96-1.04 - *Surface Water and Sediment Data*, Water Survey of Canada, Atmospheric Environment Program.
[3]It is assumed that herbicide concentrations in the river water prior to drainage water inflow were the same as the mean herbicide concentrations in the irrigation water at the Canal sampling site during the 1995 and 1996 growing seasons.
[4]Not detected.
[5]Trace concentration. A trace concentration was considered to be > 0.01 and < 0.05 $\mu g\ L^{-1}$.
[6]Both trace concentrations and concentrations > 0.05 $\mu g\ L^{-1}$ were detected in the irrigation water.

in concentration in the river water due to inflow of the drainage water would have been 0.0018 μg L^{-1} or less (Table 11); that is, almost three orders of magnitude less than the lowest water quality guideline (Table 10). Such small increases in concentration, even if trace concentrations (> 0.01 and < 0.05 μg L^{-1}) were already present in the river water, would not have increased concentrations in the river water above any of the water quality guidelines during that 24-h period.

2,4-D: This herbicide was detected in the irrigation water both in trace (> 0.01 and < 0.05 μg L^{-1}) and quantifiable (> 0.05 μg L^{-1}) concentrations, with quantifiable concentrations detected in the majority of samples. The mean concentration of 2,4-D in the irrigation water at the Canal sampling site for 1995 and 1996 was 0.074 μg L^{-1}. The increase in river concentration (0.012 μg L^{-1}), due to the maximum flux of 2,4-D to the river water, was an order of magnitude greater than for the other herbicides (Table 11) and was equivalent to a 16% increase. This increase in concentration would increase some trace concentrations to > 0.05 μg L^{-1} and would increase concentrations between 0.09 and 0.1 μg L^{-1} above 0.1 μg L^{-1}, the water quality guideline for irrigation water (Table 10). However, daily fluxes of 2,4-D greater than 50 g d^{-1} occurred only five times during the 3-year study, so that increases in the river concentration due to the drainage water inflow were generally < 7%.

Percentage of Applied: Herbicide transport to the South Saskatchewan River, as a percent of the amount of each herbicide applied to flood-irrigated fields over the three-year study, is presented in Table 12. There was no detectable transport of ethalfluralin in the irrigation drainage water to the river. Transport of trifluralin, also a dinitroaniline herbicide, was also very low, being less than 0.002% of what had been applied. The lack of ethalfluralin transport and the very low percentage of trifluralin transported to the river are most likely due to the photolability of these herbicides, their

low water solubility and strong adsorption to soil, and the fact that their main route of dissipation, due to their relatively high vapour pressures and low Henry's law constants, is loss to the atmosphere by volatilization.

Table 12: Amounts of nutrients and herbicides and the percent of applied amounts transported to the South Saskatchewan River in flood irrigation drainage water from the South Saskatchewan River Irrigation District #1 over a three-year period (1994 to 1996).

Chemical	Amount Applied	Input into River	Percent of Amount Applied
	---------- kg ----------		
Ethalfluralin	1,140	0	0
MCPA	1,090	0.505	0.046
Bromoxynil	260	0.049	0.019
2,4-D	217	2,616	1.2
Trifluralin	157	<0.001	<0.001
Dicamba	42	0.012	0.029
Clopyralid	18[1]	0.056[2]	0.31
Mecoprop	19	0.011	0.06[3]

[1]Amount of clopyralid applied to the 1C drainage area only in 1996
[2]Amount of clopyralid transported to the river only in 1996
[3] The value for mecoprop is based on amounts entering the river in a year when no mecoprop was reported to have been applied.

Of the acidic herbicides, input to the river by bromoxynil was smallest (0.019%), followed by that of dicamba (0.029%) (Table 12). The low input of bromoxynil may reflect its relatively high photolability In contrast, the high water solubility of dicamba may have resulted in relatively greater proportions being leached below the soil-runoff interaction zone and, consequently,

unavailable for transport in the runoff water. Transport of the chlorophenoxyalkanoic acid herbicides, MCPA and mecoprop was of the order of 0.05% of amounts applied. The much larger percentage transport (1.2%) of 2,4-D, also a chlorophenoxyalkanoic acid herbicide, was probably due to the presence of significant concentrations of this herbicide in the irrigation water and the possible spraying of a portion of the 9A drainage system in the fall of 1994. With the exception of this unique situation with 2,4-D, clopyralid transport represented the largest percentage of what had been applied to flood-irrigated land. During the 1996 growing season, 0.31% of the amount applied was transported to the river. This most likely reflects the greater environmental stability of the herbicide and its correspondingly longer average field half-life (Table 7). Thus, small percentages of applied amounts of these eight herbicides were transported in drainage water from the irrigation district to receiving waters of the South Saskatchewan River over the three years of the study. These losses are generally less than edge-of-field losses reported for some of the same herbicides in runoff water from individual fields within the irrigation district (Cessna et al., 1994, 1996). Such edge-of-field losses ranged from 0.07 to 1.0%, depending on the field half-life of the herbicide and the length of the interval between herbicide application and the first irrigation. Smaller percent-of-applied losses, compared to edge-of-field losses, were not unexpected because herbicide concentrations in edge-of-field drainage water would frequently be diluted to trace concentrations within the drainage system by drainage water from untreated fields, and trace concentrations were not included in the calculation of the percent losses presented in Table 12. Thus, the percent losses presented in Table 12 are somewhat of an underestimation.

Effect of Wetland: Water samples were collected from the 1C drainage ditch before and after the wetland in order to investigate whether the passage of the drainage water through a natural wetland

provided any remedial effect with respect to amounts of herbicides entering the river. Contaminant removal from water can result, in part, via uptake by aquatic plants. Constructed wetlands, used for remedial purposes, are generally designed to maximize the residence time of the contaminated water in the wetland and to enhance contact of the contaminated water with vegetative growth. Longer residence times also enhance other routes of herbicide dissipation from water, such as photodegradation, volatilization, microbial degradation etc.

In the present study, vegetative growth, such as cattails and grasses, occurred mainly along the outer perimeter of the wetland. This resulted in a relatively wide vegetation-free channel along the length of the wetland, from the inlet of the 1C drainage ditch to its outlet to the river, that offered relatively unimpeded flow to the incoming drainage water. Consequently, based on the time interval between detection of pulses of herbicide in drainage water at the 1C-Wetland sampling site and subsequently at the1C-River sampling site, the residence time of the drainage water in the wetland was estimated to be of the order of two days.

During the 1995 and 1996 growing seasons, the greatest amount of each herbicide was generally applied upstream of the 1C-South sampling site (Table 8). It is obvious from the data in Table 9 that, in the majority of cases for all three years, the total amounts of each herbicide entering the river via the drainage water in any year were less than the corresponding amounts which passed the 1C-South sampling site. Some of this dissipation, which occurred in the drainage water between the 1C-South and 1C-River sampling sites, would have been due to dilution to concentrations < 0.05 $\mu g\ L^{-1}$ (by entry of downstream non-contaminated drainage water in 1995 and 1996), as well as other routes of dissipation, such as photodegradation, volatilization, microbial degradation etc. A portion may also have been due to possible remedial effects of passage of the drainage water through the wetland as discussed above.

The most realistic assessment of a possible remedial effect by the wetland would be to consider those herbicides which were detected several times in concentrations > 0.05 $\mu g\ L^{-1}$ in samples collected at the 1C-Wetland sampling site. These included dicamba, MCPA and 2,4-D in 1994, MCPA and 2,4-D in 1995 and MCPA in 1996. Since flow measurements were not taken at the 1C-Wetland sampling site, calculations of amounts entering the wetland were made using flow data from the 1C-River sampling site, assuming that two days were required for the water to flow between the 1C-Wetland and 1C-River sampling sites. Amounts of dicamba, 2,4-D and MCPA entering the river were generally lower than amounts entering the wetland. The possibility of a remedial effect was most pronounced for dicamba and MCPA in 1994 and MCPA in 1996 (Table 9). In contrast, amounts of 2,4-D in 1994 and 1995 and MCPA in 1995 entering the river were essentially unchanged from amounts entering the wetland, indicating little or no remedial effect. Thus, a well-defined remedial effect by the natural wetland with respect to amounts of herbicides entering the river has not been established by the results of this study.

Since half-lives of some herbicides in ditch and pond water have been reported to range from 21 to > 170 days (Table 13), such a short residence time may not have permitted sufficient dissipation to consistently show differences in the amounts of the various herbicides entering and leaving the wetland. Other factors could also have confounded attempts to show differences in amounts entering and leaving the wetland. Apparent dissipation, due to dilution of herbicide concentrations during passage of the drainage water through the wetland, could possibly have been a complicating factor.

Table 13. Half-lives of some herbicides in ditch and pond water.

Herbicide	Half-Life	Reference
2,4-D	> 64 d > 170 d	Robson 1968 Erne 1963
dicamba	~ 40 d	Scifres et al., 1973
simazine	> 32 d	Tucker and Boyd 1981
glyphosate	70 d	Ghassemi et al., 1981
fluridone	21 to 26 d	West and Parka 1981

Herbicide concentrations, diluted to $< 0.05\ \mu g\ L^{-1}$, would have been considered trace concentrations and not used in calculating amounts leaving the wetland and entering the river. In addition, herbicides such as dicamba, 2,4-D and MCPA, which have a history of long use within the irrigation district, were most likely also present in the sediments of the wetland. Thus, under some environmental conditions, release of sorbed herbicides from wetland sediments to the water column may have played a role in determining amounts of the various herbicides which entered the river. As well, herbicide inputs from adjacent dryland crop production may have also been a contributing factor. With the relatively short residence time of the drainage water in the wetland and the number of other factors associated with the wetland which may have affected herbicide inputs to the river, it may not be surprising that a well-defined remedial effect by the wetland was not observed.

References

Ahuja, L.R., A. N. Shapely, M. Yamamoto, and R.G. Menzel. 1981. The depth of rainfall-runoff-soil interaction as determined by ^{32}P. Water Resour. Res. 17:969-974.

CCREM, 1987. Canadian water quality guidelines. Task force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers. Canadian Council of Resource and Environment Ministers. Water Quality Branch, Environment Canada, Ottawa, ON.

Cessna, A.J., K.B. Best, R. Grover, and W. Nicholaichuk. 1997. Potential for contamination of the South Saskatchewan River with herbicides applied in an irrigation district. Can. Water Resour. J. 22:237-248.

Cessna, A.J., J.A. Elliott, L.A. Kerr, K.B. Best, W. Nicholaichuk, and R. Grover. 1994. Transport of nutrients and postemergence-applied herbicides during corrugation irrigation of wheat. J. Environ. Qual. 23:1038-1045.

Cessna, A.J., J.A. Elliott, K.B. Best, R. Grover, and W. Nicholaichuk. 1996. Transport of nutrients and postemergence-applied herbicides in runoff during corrugation irrigation of wheat. p. 151-164. *In* M.T. Meyer and E.M. Thurman (ed.) Herbicide Metabolites in Surface Water and Ground water, ACS Symposium Series No. 630, American Chemical Society, Washington, DC.

Cessna, A.J., R. Grover, L.A. Kerr, and M.L. Aldred. 1985. A multiresidue method for the analysis and verification of several herbicides in water. J. Agric. Food Chem. 33:504-507.

Clesceri, L.S., A.E. Greenberg, and R.R. Trussell. 1989. Standard methods for the examination of water and wastewater. Automated Cadmium Reduction Method. p. 4.137-4.139. 17th ed. APHA-AWWA-WPCF, Washington, DC.

watersheds - data and implications for modelling pesticide transport. J. Environ. Qual. 8:223-229.

Nicholaichuk, W. and R. Grover. 1983. Loss of fall-applied 2,4-D in spring runoff from a small agricultural watershed. J. Environ. Qual. 12:412-414.

Nicholaichuk, W. and D.W.L. Read. 1978. Nutrient runoff from fertilized and unfertilized fields in Western Canada. J. Environ. Qual. 7:542-544.

Parochetti, J.V. and Dec, Jr., G.W. 1978. Photodecomposition of eleven dinitroaniline herbicides. Weed Sci. 26:153-156.

PM 1997. Pesticide Manual, 11th edition, C.D.S Tomlin, ed., British Crop Protection Council, Farnham, Surrey, UK

Robson, T.O. 1968. Some studies of the persistence of 2,4-D in natural waters. Proc. 9th Brit. Weed Control Conf. Vol. 1:404-408.

SAF. 1999. Crop Protection Guide 1999. Saskatchewan Agriculture and Food, Regina, Saskatchewan

Scifres, C.J., Allen, T.J., Leinweber, C.L., and Pearson, K.H. 1973. Dissipation and photoxicity of dicamba residues in water. J. Environ. Qual. 2:306-309.

SERM. 1995. Surface Water Quality Objectives. Saskatchewan Environment and Resource Management. Municipal Branch, Publication MB110.

Skougstad, M.W., M.J. Fishman, L.C. Friedman, D.E. Erdmann, and S.S. Duncan. 1979. Nitrogen, ammonia, colorimetric. P. 425-427. *In* Techniques of water-resources investigations of the United States Geological Survey. Book 5. Laboratory Analysis. U.S. Govt. Print. Office, Washington, DC.

Spencer, W.F. and M.M. Cliath. 1991. Pesticide losses in surface runoff from irrigated fields. Environ. Sci. Res. 42 (Chem. Prot. Environ.):277-289.

Tucker, C.S. and Boyd, C.E. 1981. Relationships between pond sediments and simazine loss from waters of laboratory systems. J. Aquat. Plant Manag. 19:55-57.

Wauchope, R.D. 1978. The pesticide content of surface water draining from agricultural fields - a review. J. Environ. Qual. 7:459-472.

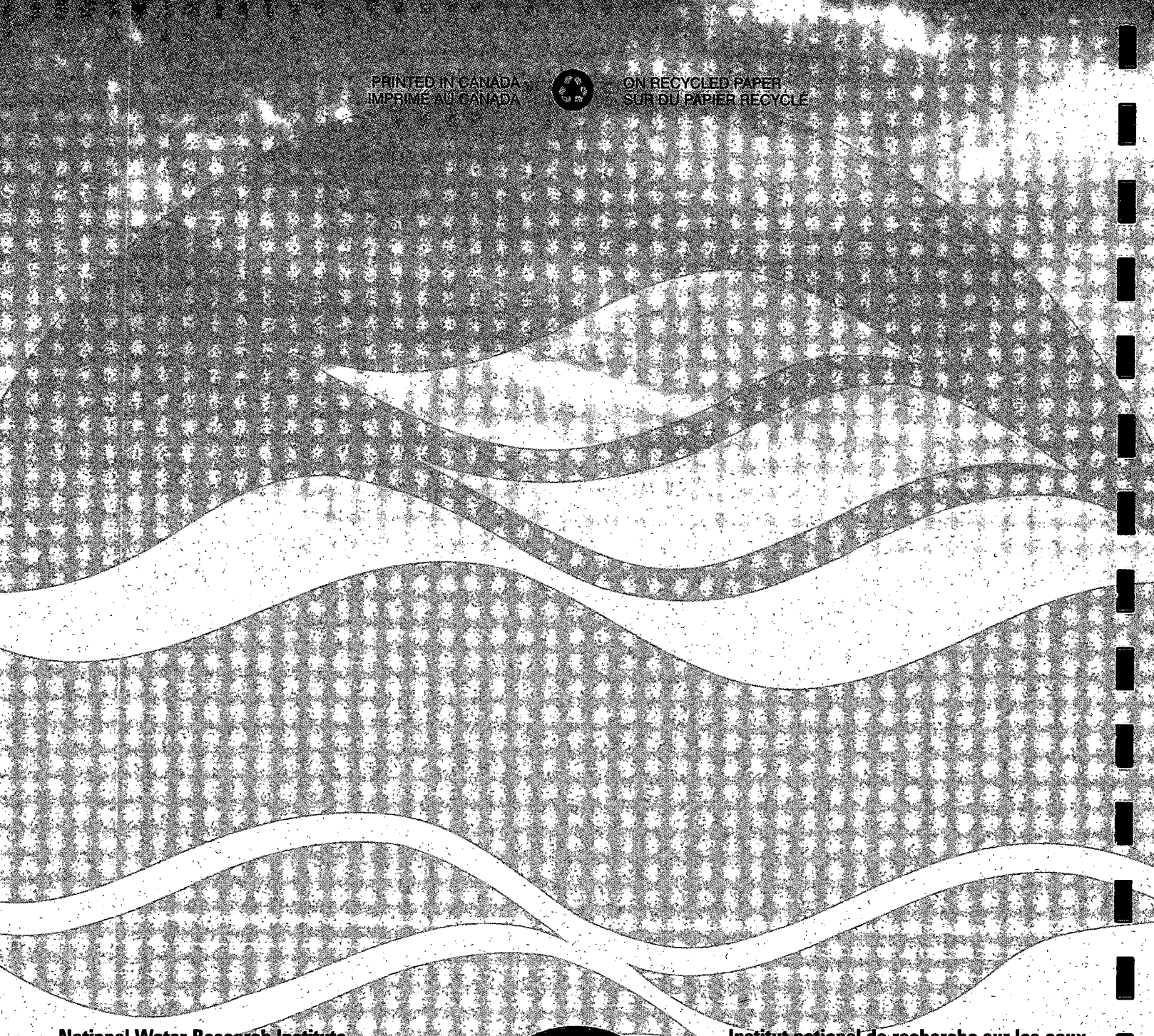
West, S.D. and Parka, S.J. 1981. Determination of the aquatic herbicide fluridone in water and hydrosoil: Effect of application method on dissipation. J. Agric. Food Chem. 29:223-226

WSSA 1994. Herbicide Handbook, 7th edition, W.H. Ahrens, ed., Weed Science Society of America, Champaign, IL

13034

PRINTED IN CANADA
IMPRIMÉ AU CANADA

ON RECYCLED PAPER
SUR DU PAPIER RECYCLÉ



National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

Institut national de recherche sur les eaux
Environnement Canada
Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington, Ontario
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon, Saskatchewan
S7N 3H5 Canada

Environment Canada Environnement Canada

Canada