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The effectiveness of small-scale headwater storage dams and reservoirs on stream water quality and quantity in the Canadian Prairies

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Abstract: In response to flooding and soil erosion impacting the South Tobacco Creek watershed in southcentral Manitoba, local landowners constructed a network of small dams and reservoirs in the headwaters. Between 1999 and 2007, two of the small dams/reservoirs (Steppler multipurpose dam and Madill dry dam) were intensively monitored for their effectiveness in reducing peak flows and downstream sediment and nutrient loading during spring snowmelt (typically mid-March to mid-April) and summer rainfall (typically May to November) periods. These small-scale headwater storage dams were effective in reducing peak flows from agricultural land. The two dams/reservoirs monitored also reduced annual concentrations of sediment and total nitrogen (TN) to downstream receiving waters. However, annual concentrations of total phosphorus (TP) were only significantly reduced at the Madill dry dam, and the average concentrations of nitrogen (N) and phosphorus (P) within outflow water samples still exceeded guidelines for freshwater in the Canadian Prairies. Both dams/reservoirs significantly reduced annual loads of sediment, TN, and TP (Steppler dam, average of 77%, 15%, and 12%, respectively; Madill dam, average of 66%, 20%, and 9%, respectively). This corresponded to an average annual retention of 25 Mg y^{-1} (28 tn yr^{-1}) of sediment, 166 kg N y^{-1} (366 lb N yr^{-1}) and 17 kg P y^{-1} (37 lb P yr^{-1}) by the Steppler dam, while 6 Mg y^{-1} (7 tn yr^{-1}) of sediment, 181 kg N y^{-1} (399 lb N yr^{-1}) and 10 kg P y^{-1} (22 lb P yr^{-1}) were retained by the Madill dam. Both reservoirs reduced annual loads of dissolved N and P to downstream water bodies (Steppler, average of 14% and 10%, respectively; Madill, average of 23% and 15%, respectively), and were generally effective in removing dissolved N and P during both snowmelt and rainfall-generated runoff. The percent retention of dissolved nutrients was consistently higher during the summer than the spring. While the reservoirs removed particulates during snowmelt-generated runoff, they were often sources of suspended nutrients during rainfall-generated events. However, since dissolved nutrients were the dominant form of both N and P (>70% for both snowmelt and rainfall events), the two dams/reservoirs successfully reduced overall nutrient loads to downstream water bodies, annually and seasonally. In combination with improving flood and erosion control for the region, small headwater storage dams and reservoirs deserve consideration when developing watershed nutrient management plans, especially for undulating and hummocky regions on the Great Plains.

Key words: nutrient loading—rainfall—snowmelt—small dams/reservoirs—water quality—water quantity

Runoff during both spring snowmelt and summer rainfall is a common source of sediment and nutrient loading to surface waters from agricultural landscapes in the Canadian Prairies. Of growing concern in the Canadian province of Manitoba is the increasing transport of nitrogen (N) and phosphorus (P) into Lake Winnipeg, the 10th largest freshwater lake in the world. In fact, among the world's largest lakes Lake Winnipeg appears to be one of the most eutrophic as measured by levels of chlorophyll, an indicator of the amount of algae present during summer (Jones and Armstrong 2001). In response, the Manitoba Government has recently announced intentions to reduce nutrient loadings into Lake Winnipeg to pre-1970 levels, which represents a 13% reduction in N and a 10% reduction in P (Lake Winnipeg Stewardship Board 2006). Chambers et al. (2001) and Glozier et al. (2006) both suggested that nonpoint source loading of nutrients from small, agriculturally dominated watersheds in the Canadian Prairies have the potential to significantly contribute to cumulative nutrient loads in larger downstream rivers (e.g., the Red River) and lakes (e.g., Lake Winnipeg). Similarly, the Lake Winnipeg Stewardship Board (2006) estimated that 5% of the total N and 15% of the total P loading (38 and 32% of Manitoba's contribution, respectively) into Lake Winnipeg is the result of agricultural activities in Manitoba. Therefore, to meet the projected reduction in nutrients, recent policy and research has focused on reducing nutrient loading from agriculturally dominated watersheds upstream in the Lake Winnipeg watershed.

When strategically located in the landscape, small dams and/or reservoirs, constructed wetlands, predams (i.e., small reservoirs located immediately upstream of larger reservoirs), and water and sediment control basins (WASCOBs) are all recommended—in various parts of the world—for use to improve surface water quality by reducing the transport of sediment and particulate nutrients to downstream water bodies (Sharpley et al. 2000; Ulen et al. 2007; Bechmann et al. 2008; Verstraeten and Prosser 2008; Hoffmann et al. 2009). For example, Sharpley et al. (1996) report that the construction of a runoff detention pond reduced sediment yield by >80%, and more than halved nutrient losses in Oklahoma. Also in the American

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Midwest, Kovacic et al. (2006) report that constructed wetlands reduced loads of N and P by an average of 35% and 56% y^{-1}, respectively. In Luxembourg, Salvia-Castellvi et al. (2001) report that a shallow predam retained ~60% of total P within inflow waters, while a deep predam retained ~82%. Similarly, in Spain, Aviles and Niell (2007) report that a small dam reduced downstream loads of total phosphorus (TP) by >25%; while in a review, Uusi-Kammpa et al. (2000) report that small ponds and wetlands reduced total P loads by 17% and 41%, respectively in Northern Europe. Although there is no clear consensus on the design of conservation retention structures, previous studies have suggested that retention time and location are critical elements in effectively treating agricultural runoff water (Woltemade 2000; Paul 2003). In general, the lack of turbulent flow in these structures allows sediment and particulate nutrients to settle.

The overall effectiveness of these conservation structures, however, in cold climate regions and in reducing dissolved nutrients is much less certain (e.g., Uusi-Kamppa et al. 2000; Braskerud 2002a, 2002b; Koskiaho et al. 2003; Liikanen et al. 2004; Braskerud et al. 2005; Reinhart et al. 2005; Kovacic et al. 2006; Ollesch et al. 2008). This is the concern in the cold, dry agricultural landscapes of the Canadian Prairies, where (1) spring snowmelt is typically the primary runoff and nutrient loading event during the year, and (2) dissolved nutrients can dominate total nutrient loads in runoff waters, in both the spring and summer (Little et al. 2007; Salvano et al. 2009; Tiessen et al. 2010). These environmental conditions are very different to those typically experienced in more humid regions of North America and Europe, where nutrient transport occurs predominantly through rainfall runoff and dissolved nutrient losses account for a small portion of the total loss. Even in the cold-climate countries of northwest Europe, where Ulen et al. (2007) report that losses of soluble reactive P can be high (i.e., 9% to 93% of total P losses), particulate nutrients still tend to dominate overall. Similarly, in Scandinavia, Uusi-Kamppa et al. (2000) report that ~90% of the TP loads were in the particulate form, even though P loading during the wintertime was ~95% of the total P loading for the entire year. As a result, in most regions recommending the use of constructed wetlands and ponds, much of the focus has still been with the aim to control losses of sediment and sediment-bound nutrients to downstream surface waters (e.g., Ulen et al. 2007; Bechmann et al. 2008; Sharpley et al. 2009). As suggested by Mitsch et al. (2000), additional comparative studies are needed under a wide range of climatic conditions to better understand the capacity of these structures to contribute to the clean-up of streams and rivers across both small and large geographic scales.

In southcentral Manitoba, flooding and soil erosion during snowmelt and after heavy rains would regularly impact the land surrounding the South Tobacco Creek watershed (on the edge of the Manitoba Escarpment), causing significant damage to roads, culverts, bridges, and crops. In particular, a major flood in the spring of 1979 caused the flooding of more than 3,000 ha of land, and local landowners suspected that small-scale headwater storage (instead of one large dam or more efficient drainage) was the key to addressing the escarpment's historical water problems. A network of 26 small dams and/or reservoirs was constructed in the headwaters of the South Tobacco Creek watershed and ~30% of the total drainage area is now managed for flow-reduction (Yarotski 1996). While the network of constructed dams and reservoirs has collectively been effective in reducing rapid runoff and flooding from the Manitoba Escarpment, their effectiveness in reducing flood peak flows and downstream sediment and nutrient loading—in particular dissolved nutrients—during the spring snowmelt and summer rainfall periods is not well known. Therefore, the objective of the current study was to determine whether these small headwater storage dams and reservoirs are able to reduce peak flows and concentrations and loads of sediment, N, and P to downstream water bodies under conditions typical of the Canadian Prairies.

Materials and Methods

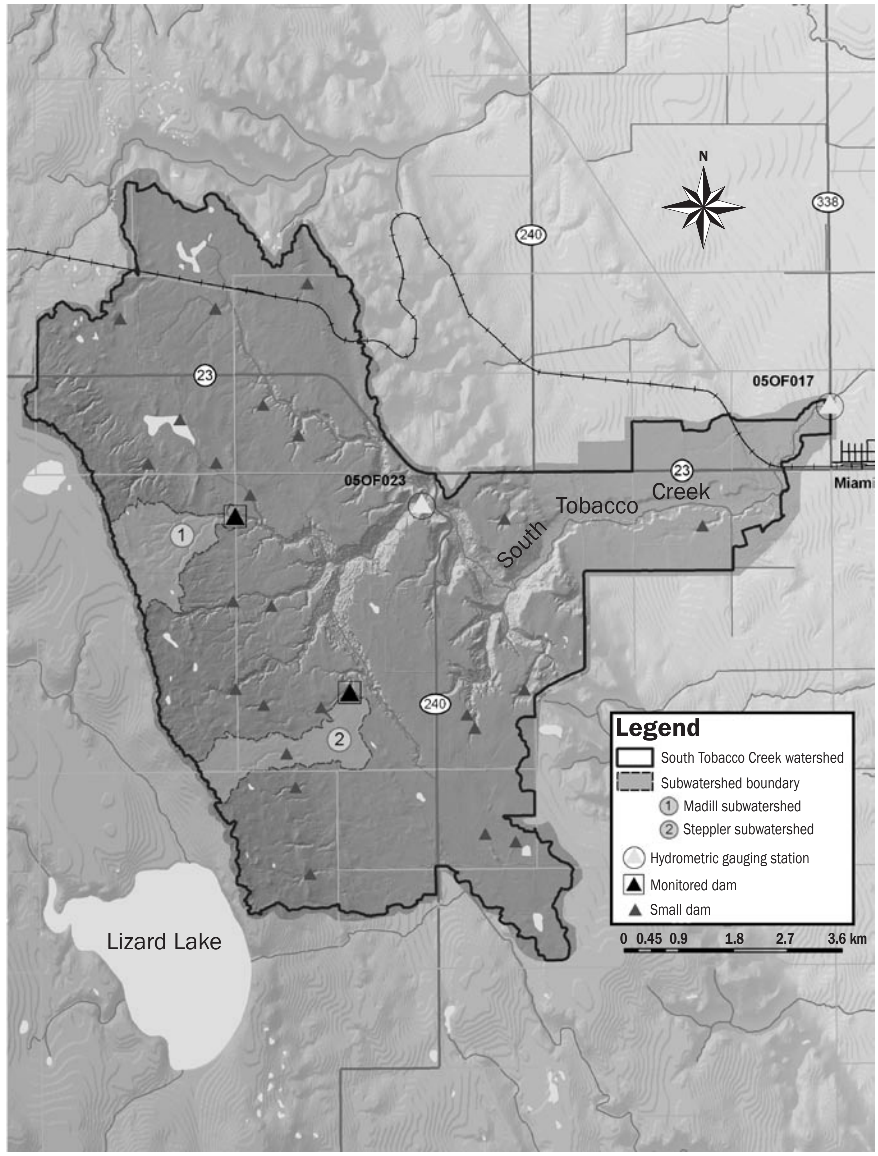
The South Tobacco Creek watershed (figure 1) is situated ~150 km (~90 mi) southwest of Winnipeg, near the town of Miami, and has a drainage area of 74.2 km^2 (28.6 mi^2). The creek originates above the Manitoba Escarpment and flows eastward over the escarpment and onto the lacustrine plain of glacial Lake Agassiz, eventually reaching the Red River and Lake Winnipeg. This region is a transitional area between the lower Manitoba Plain and the higher Saskatchewan Plain (Michalyna et al. 1988). It is characterized by undulating to hummocky landscapes, with elevation dropping nearly 60 m (197 ft) in less than 3 km (1.9 mi) at the escarpment. The dominant soil series in the watershed are Dark Grey Chernozems (Mollisols), and soils are primarily clay-loam and were formed on moderately to strongly calcareous glacial till that overlay shale bedrock. Most of the land in the watershed is used for agricultural production, including cereal crops, oilseeds, forages and livestock. The climate is classified as subhumid continental with short, cool summers and long cold winters. The mean annual temperature is ~3°C (~37°F) and the mean annual precipitation is ~550 mm (~22 in), of which 25% to 30% occurs as snow (Environment Canada 2009).

Three types of small-scale headwater flood control dams and reservoirs were constructed within the South Tobacco Creek watershed between 1985 and 1995: (1) dry dam/flood control dams, which fill and then slowly and continuously release water in a controlled manner (are often incorporated into existing municipal roads); (2) back-flood dams, which retain water at a shallow depth over a large acreage of cropped or pastured land for at least two weeks before the water is released in a controlled manner until the reservoir is empty; and (3) multipurpose dams, which are similar to dry dams, but retain ~15% to 20% of storage capacity for summer water use (and can be drained in the fall in preparation for full flood control potential in the spring). Each dam/reservoir was designed to store, at full supply level, ~20 to 25 mm (~0.8 to 1.0 in) of runoff from their immediate catchment area. In total, 5 dry dams, 6 back-flood dams, and 15 multipurpose dams were constructed in the region (figure 1). Collectively, Yarotski (1996) estimated that this network of small dams and reservoirs reduced peak flows in the South Tobacco Creek watershed due to snowmelt- and rainfall-induced runoff by 9% to 19% and 13% to 25%, respectively. This reduction was comparable to the estimated runoff control that would be provided by one large dam near the town of Miami, but the cost to develop and maintain the small dam network was only 30% of the projected construction cost of the large dam.

Of the 26 small dams/reservoirs, the Steppler multipurpose dam (49°20' N, 98°21' W) and the Madill dry dam (49°21' N, 98°23' W) have been intensively monitored for their effectiveness in reducing (1) flood peaks and (2) downstream sediment and nutrient loading (figure 1). Both the Steppler multipurpose dam and the Madill dry dam have a drainage area of ~200 ha (~500 ac) (table 1). Outflow from the Steppler multipurpose dam is through an uncontrolled drop inlet ~4 m (~13 ft) above the bottom of the reservoir. At this elevation, the reservoir will store ~10,000 m^3 (~2,600,000 gal) of water before water outflow begins. At the top of the dam, the reservoir has a storage capacity of ~60,000 m^3 (~16,000,000 gal), resulting in a relatively large storage capacity to store inflow. The available storage of 50,000 m^3 (13,200,000 gal) in the Steppler multipurpose dam is ~24 mm (~0.94 in) of runoff from the upstream drainage area. Typically, the maximum outflow the reservoir releases through the drop inlet is ~0.21 m^3 s^{-1} (~7.4 cfs). However, at the top of the dam the outflow from the reservoir could exceed 6.0 m^3 s^{-1} (210 cfs) because the Steppler multipurpose dam has an earth spillway which can release a much larger flow than the drop inlet (and flow through the earth spillway will occur at an elevation lower than the top of dam). The Madill dry dam has a drop inlet elevation ~1 m (~3.3 ft) above the bottom of the reservoir, resulting in less than 500 m^3 (130,000 gal) being stored before water is released through the drop inlet. The reservoir can store ~45,000 m^3 (~12,000,000 gal) before the dam (roadway) is overtopped, resulting in a similarly large storage capacity to store inflow (note, the roadway was designed to handle flow and act as a spillway, but since the dam was constructed no flow has occurred over the Madill dam). The available storage of 44,500 m^3 (11,800,000 gal) in the Madill dry dam is ~21 mm (~0.83 in) of runoff from the upstream drainage area, and at the top of the Madill dam, the maximum flow the reservoir can release is ~0.18 m^3 s^{-1} (~6.4 cfs).

Figure 1

Location of the Steppler and Madill subwatersheds within the South Tobacco Creek watershed in southern Manitoba, ~150 km southwest of Winnipeg.



Yearly runoff patterns at both dams/reservoirs typically displayed a spring melt peak (usually in March and/or April) and multiple rainfall event peaks (various times between May and November). Runoff monitoring of inflow and outflow waters for the Steppler and Madill dams/reservoirs was initiated in 1990, with water quality sampling for nutrients conducted between 1999 and 2007 (i.e., the study period). However, no water quality samples were taken in 2003, and sediment has only been monitored at both

Table 1

Background information of the Steppler and Madill dams/reservoirs monitored in this study.

Location	Type	Year constructed	Storage (m^3) Top of drop inlet	Storage (m^3) Top of dam/reservoir	Surface area at top of dam/ reservoir (ha)	Subwatershed Catchment area area (ha)	Subwatershed Land in agriculture (%)
Steppler	Multipurpose	1989	10,000	60,000	3.1	205	91
Madill	Dry	1988	500	45,000	2.0	207	71

reservoirs since 2004. Water quality sampling at the two dams/reservoirs was performed in conjunction with flow measurements. The inflow water sampling stations were located upstream of each dam/reservoir, so that water samples were taken before mixing of the water occurred in the reservoir. These sampling stations consisted of an auto-sampler (Sigma 800SL) triggered using a float system. The float would activate the auto-sampler as the water level rose in the stream and then would continue taking water samples at timed intervals. The outflow from the dams/reservoirs was sampled manually as the water was spilled from the reservoir. Since sampling was event based, with periodic base flow sampling, the majority of samples were collected during the spring snowmelt period (i.e., runoff induced by snowmelt only). Due to equipment problems, flow measurements were not recorded at the Madill dry dam for the spring snowmelt period in 2005. Similar equipment problems occurred at the Steppler multipurpose dam in 2005. However, because runoff was also monitored at various subwatersheds upstream of the Steppler multipurpose dam (Agriculture and Agri-Food Canada 2009), this additional data were used to estimate the snowmelt runoff into the dam for this year. During the summer growing season, water samples were taken whenever a rainfall event generated sufficient runoff to activate the auto-sampler. During low flow events, additional samples were collected manually and used to augment the auto-sampler water collected samples. After sample collection, sample bottles were extracted from the auto-sampler, packed on ice and sent to the Fisheries and Oceans Canada's Freshwater Institute Laboratory in Winnipeg, Manitoba for analysis. A comprehensive nutrient evaluation of each water sample included total nitrogen (TN), suspended nitrogen (SUSPN), total dissolved nitrogen (TDN), ammonia (NH_3), nitrate + nitrite (NO_3), TP, suspended phosphorus (SUSPP), total dissolved phosphorus (TDP) and total suspended sediment (TSS). The dissolved fractions of N and P were differentiated as passing through a 0.45 μm (0.018 mil) filter, while the suspended fractions remained on the filter.

Water levels in the two reservoirs were monitored on a continuous basis (20-minute intervals) using electronic water-level recorders—either a float system or a pressure transducer integrated with a data logger. One of the water level monitoring systems used was the CR10X Campbell Scientific data logger, in conjunction with a vented Keller (model 173) pressure transducer. The other system used to monitor water levels was the Unidata water level data logger in conjunction with a float mechanism. Using reservoir-routing software developed by Agriculture and Agri-Food Canada (HY71 Reverse Flood Routing Program [Martin 2006]), the water levels (in conjunction with the hydraulic parameters of each reservoir) were used to calculate the inflow and outflow hydrographs.

Yearly water quality data were split into seasonal (snowmelt and rainfall) time periods, which are not similar in length but represent seasons that are considered to be hydrologically distinct. Using the method similar to that described in detail by Tiessen et al. (2010), total sediment and nutrient loads (in and out of each dam/reservoir) were calculated as the product of the 15, 30, and/or 60 minute flow volumes (m^3) and nutrient concentrations (estimated from actual sample concentrations through linear interpolation between sampling times), summed over the entire time period of each event, season and year. There were a few low intensity rainfall events where less than three water samples were collected throughout the hydrograph, and in these situations, linear interpolation between sampling times would have been unreliable. For runoff events where only two samples were collected, water quality data were averaged across the entire event for each parameter of interest. For runoff events where only one sample was collected, that sample concentration value was assumed to be constant throughout the event. Finally, similar to the method used by Little et al. (2007), if a rainfall runoff event was so low that it did not trigger the automated sampler, the seasonal average (e.g., the average of all rainfall-induced runoff events of that year) was used throughout that event. However, since these events were small in magnitude and infrequent, their influence on overall nutrient loads was minor.

Flow-weighted mean concentrations (FWMCs) were calculated by dividing the total load for each individual runoff event by that event's total flow volume. Similarly, FWMCs were calculated on an annual and seasonal basis. Note, at the Steppler multipurpose dam in 2002 there was very little snowmelt and no outflow of water occurred from the dam/reservoir (resulting in 100% retention of inflow water, sediment and nutrients). The data from this year were removed from all statistical analyses related to concentration, because FWMCs cannot be estimated for zero or nonevents. However, this year was included in the statistical analyses for sediment and nutrient loads, since the export of a water quality parameter from a dam/reservoir with no flow is equal to 0 kg y^{-1}.

The reduction in either concentration or export of sediment and nutrients within the two dams/reservoirs were estimated by subtracting either the concentration or mass of each respective water quality parameter in the outflow waters from the concentration or mass in the inflow waters. Similarly, the percent retention (also commonly known as trap efficiency) of sediment and nutrient loads within the two reservoirs was calculated using the following:

$$\% \text{ retention} = \text{inflow}_{ij} - \text{outflow}_{ij}/\text{inflow}_{ij}, \quad (1)$$

where i is the water quality parameter of interest within each reservoir at event j.

Changes in mean nutrient concentration and load (between inflow and outflow locations at each small dam/reservoir) were measured and compared using a paired two-sample Student's t-test in the Statistical Analysis System (SAS) package 9.1. The data fit the criteria for this test, as the population of differences in the paired data was approximately normally distributed (descriptive statistics were used to test the data for normality and skewness using the Proc Univariate function of SAS) and the sample differences were randomly selected from the population of differences (McClave and Dietrich 1994). Pearson correlation coefficients (r) were used to determine if significant relationships existed between annual and seasonal inflow water and the percent retention of the various variables within each reservoir/dam. Due to the high variability inherent in field and watershed-based experiments, an α = 0.1 was used as the significance threshold for all statistical analyses.

Results and Discussion

Climate and Runoff Characterization. Using the data recorded at the Miami-Orchard Environment Canada climate station (49°22' N, 98°17' W), an annual average of 386 mm (15.2 in) of rain and 108 cm (42.5 in) of snow fell in the South Tobacco Creek watershed during the study period (table 2); while the long-term means for this region are ~413 mm (~6.25 in) of rain and ~131 cm (~51.6 in) of snow per year (Environment Canada 2009). As is typical for the Prairie region of western Canada, year-to-year variability in both rainfall and snowfall were high. Rainfall for the April to October growing season period varied from 253 mm (9.96 in) in 2006 to 492 mm (19.3 in) in 2005. Overall, 1999, 2000, 2004, and 2005 were the wettest rainfall years during the study period. Similarly, for snowfall year to year variability was high, ranging from a minimum of 77 cm (30.3 in) of snow in 2001, to a maximum of 126 cm (49.6 in) of snow in 2000. Snowfall during

Table 2
Precipitation data for the South Tobacco Creek region during the study period.

Year	Rainfall (mm)	Snowfall (cm)
1999	436	124
2000	482	126
2001	340	77
2002	325	100
2003	295	112
2004	456	119
2005	492	116
2006	253	122
2007	394	78
Average	386	108

Notes: Meteorological data are available at Environment Canada (2009). Snowfall is from October of the previous year to April of the year stated.

Table 3
The instantaneous peak inflow and outflows and percent reduction in the outflow peak at the Steppler and Madill dams/reservoirs between 1999 and 2007.

Year	Type of runoff event*	Steppler multipurpose dam Inflow ($m^3 s^{-1}$)†	Steppler Outflow ($m^3 s^{-1}$)	Steppler Reduction in peak flow (%)‡	Madill dry dam Inflow ($m^3 s^{-1}$)†	Madill Outflow ($m^3 s^{-1}$)	Madill Reduction in peak flow (%)‡
1999	Spring	0.29	0.18	38	0.14	0.09	36
	Summer	0.77	0.19	75	0.14	0.09	36
	Summer	0.15	0.10	33	0.28	0.10	64
2000	Spring	0.07	0.0001	99.9	0.14	0.14	0
	Summer	0.20	0.08	60	0.09	0.08	11
	Summer	0.11	0.10	9	0.08	0.08	0
	Summer	0.12	0.06	50	0.09	0.09	0
	Summer	0.34	0.18	47	0.08	0.08	0
2001	Spring	0.52	0.18	65	0.20	0.20	0
	Summer	0.35	0.18	49	0.08	0.08	0
2002	Spring	0.01	0	100	0.09	0.08	11
	Summer	1.32	0.19	86	0.30	0.14	53
2003	Spring	0.16	0.15	6	0.13	0.09	31
	Summer	—	—	—	0.08	0.08	0
2004	Spring	1.39	0.19	86	0.29	0.14	52
	Summer	0.47	0.18	62	0.14	0.10	29
2005	Spring	0.75	0.20	73	—	—	—
	Summer	1.36	1.34	1	0.65	0.15	77
2006	Spring	0.93	0.20	78	0.21	0.10	52
2007	Spring	0.52	0.18	65	0.54	0.14	74
	Summer	0.02	0.02	12	0.08	0.08	0
	Summer	0.09	0.06	30	0.21	0.09	57
	Summer	0.08	0.05	33	0.10	0.08	20
	Summer	0.03	0.03	7	0.01	0.01	0
	Summer	0.04	0.03	6	0.11	0.08	27
	Summer	0.15	0.13	13	0.09	0.08	11
Average	Spring	0.43	0.12	72	0.19	0.11	44
	Summer	0.35	0.18	48	0.16	0.09	44

Note: "—" = not recorded.

* Spring events are due to snowmelt-induced runoff, and summer events are due to rainfall-induced runoff events.

† The spring runoff peak represents the maximum annual event for that season (i.e., several peaks could have occurred, but only the maximum peak is shown in this table).

‡ The percent reduction in peak flow was calculated as follows: (inflow – outflow)/inflow x 100%.

Table 4

Summary of the total flow and flow weighted mean concentrations (FWMCs) of total suspended sediment (TSS), total N (TN), suspended N (SUSPN), total dissolved N (TDN), total P (TP), suspended P (SUSPP) and total dissolved P (TDP) at the Steppler and Madill dams/reservoirs between 1999 and 2007.

Sampling period	Station	Flow (m^3 yr^{-1})	TN (mg L^{-1})	SUSPN (mg L^{-1})	TDN (mg L^{-1})	TP (mg L^{-1})	SUSPP (mg L^{-1})	TDP (mg L^{-1})	TSS (mg L^{-1})
Steppler									
Annual	Inflow	286,714 ± 184,771	3.8 ± 0.7	0.5 ± 0.3	3.3 ± 0.6	0.52 ± 0.14	0.09 ± 0.05	0.42 ± 0.10	94 ± 68
	Outflow	268,875 ± 185,117	3.4 ± 0.6	0.4 ± 0.2	2.9 ± 0.5	0.49 ± 0.11	0.09 ± 0.03	0.40 ± 0.09	25 ± 18
	Average reduction	17,839d	0.4a	0.1	0.3a	0.03	0.01	0.02	70b
	Retention	6%	11%	15%	10%	6%	9%	5%	74%
Spring snowmelt	Inflow	122,842 ± 89,115	5.3 ± 1.4	0.6 ± 0.5	4.7 ± 1.0	0.64 ± 0.23	0.12 ± 0.12	0.52 ± 0.1	102 ± 104
	Outflow	113,189 ± 86,741	4.9 ± 1.0	0.5 ± 0.2	4.5 ± 0.9	0.62 ± 0.16	0.09 ± 0.04	0.53 ± 0.15	29 ± 29
	Average reduction	9,653c	0.4a	0.2	0.2	0.02	0.03	−0.01	74
	Retention	8%	7%	28%	4%	3%	24%	−2%	72%
Summer rainfall	Inflow	163,872 ± 115,183	2.8 ± 1.1	0.5 ± 0.4	2.3 ± 0.9	0.43 ± 0.20	0.10 ± 0.07	0.33 ± 0.14	109 ± 125
	Outflow	155,686 ± 115,697	2.4 ± 0.8	0.5 ± 0.2	1.9 ± 0.6	0.41 ± 0.16	0.10 ± 0.04	0.31 ± 0.13	17 ± 11
	Average reduction	8,186c	0.3a	0.02	0.3a	0.02	−0.002	0.02	92
	Retention	5%	12%	4%	14%	5%	−2%	7%	84%
Madill									
Annual	Inflow	306,826 ± 161,769	3.1 ± 0.7	0.4 ± 0.1	2.7 ± 0.7	0.42 ± 0.13	0.07 ± 0.02	0.35 ± 0.12	52 ± 22
	Outflow	306,256 ± 162,270	2.4 ± 0.6	0.4 ± 0.1	2.0 ± 0.7	0.36 ± 0.11	0.08 ± 0.02	0.28 ± 0.10	18 ± 4
	Average reduction	569a	0.7c	0.02	0.7c	0.06a	−0.01	0.07b	33b
	Retention	0.2%	23%	4%	26%	14%	−15%	20%	65%
Spring snowmelt	Inflow	106,094 ± 56,505	4.1 ± 0.8	0.5 ± 0.3	3.6 ± 0.7	0.64 ± 0.16	0.10 ± 0.04	0.54 ± 0.16	89 ± 52
	Outflow	105,547 ± 56,678	3.6 ± 0.6	0.3 ± 0.1	3.4 ± 0.5	0.57 ± 0.18	0.07 ± 0.02	0.50 ± 0.17	21 ± 5
	Average reduction	548a	0.5b	0.2b	0.3a	0.06a	0.03	0.04	68a
	Retention	1%	12%	44%	7%	10%	29%	7%	76%
Summer rainfall	Inflow	213,917 ± 142,151	2.5 ± 0.6	0.5 ± 0.4	2.0 ± 0.5	0.31 ± 0.07	0.08 ± 0.06	0.22 ± 0.04	92 ± 91
	Outflow	213,857 ± 142,282	1.8 ± 0.6	0.4 ± 0.1	1.4 ± 0.6	0.25 ± 0.08	0.09 ± 0.03	0.16 ± 0.06	32 ± 29
	Average reduction	60	0.7b	0.05	0.6b	0.05a	−0.01	0.06b	59a
	Retention	0.03%	27%	10%	31%	17%	−9%	27%	65%

Notes: Sediment data were only collected between 2004 and 2007. No water quality samples were collected in 2003. The annual data for the Madill dry dam do not include any data from 2005 (i.e., a high rainfall year) because of missing snowmelt data. The annual concentration data for the Steppler multipurpose dam do not include any data from 2002 because of little snowmelt and no outflow. Letters represent significance levels: a is for $p < .1$, b is for $p < .05$, c is for $p < .01$, and d is for $p < .001$.

all nine years of the study period varied from slightly below average to below average. As a result, there was considerable yearly and seasonal variability in the size and timing of peak flows (table 3), and quantity and timing of runoff, sediment, and nutrients (tables 4 and 5) generated within the Steppler and Madill subwatersheds.

Seasonally, the spring snowmelt period comprised an average of 43% (range 4% to 67% y^{-1}) of the total annual flow into the Steppler multipurpose dam; while at the Madill dry dam, spring snowmelt runoff accounted for 35% (range 13% to 77% y^{-1}) of the total average annual inflow (table 4). As expected, sediment and nutrient loading into the two dams/reservoirs was strongly related to total inflow, during both the spring snowmelt and summer rainfall events (data not presented). At both dams/reservoirs the majority of sediment loading with inflow runoff waters occurred during the summer months. However, on average, concentrations of TN and TP during the spring snowmelt were nearly double those measured during the summer (especially for dissolved nutrients), and at least half of the nutrient loading into the two dams/reservoirs occurred during the spring snowmelt period (table 5). Seasonally, 60% (range 3% to 86%) and 49% (range 20% to 91%) of the annual load of TN within inflow water at the Steppler multipurpose dam and Madill dry dam, respectively, occurred during the spring snowmelt period. For TP, 53% (range 2% to 86%) and 54% (range 28% to 91%) of the annual load occurred during the spring snowmelt period at the two dams/reservoirs, respectively. Overall, dissolved and suspended N and P loads were fairly evenly split between spring and summer runoff events, but dissolved nutrients were the dominant form of loading for both N and P (72% to 89%) into the two dams/reservoirs, during both the snowmelt and rainfall periods.

Table 5
Summary of the loads of total suspended sediment (TSS), total N (TN), suspended N (SUSPN), total dissolved N (TDN), total P (TP), suspended P (SUSPP), and total dissolved P (TDP) in inflow and outflow waters at the Steppler and Madill dams/reservoirs between 1999 and 2007.

Sampling period	Station	TN (kg y^{-1})	SUSPN (kg y^{-1})	TDN (kg y^{-1})	TP (kg y^{-1})	SUSPP (kg y^{-1})	TDP (kg y^{-1})	TSS (Mg y^{-1})
Steppler								
Annual	Inflow	1,078 ± 684	150 ± 126	929 ± 606	148 ± 98	29 ± 26	119 ± 75	32 ± 29
	Outflow	912 ± 608	114 ± 77	801 ± 541	131 ± 87	24 ± 18	107 ± 70	7 ± 6
	Average reduction	166c	37	128c	17b	5	12c	25a
	Retention	15%	24%	14%	12%	17%	10%	77%
Spring snowmelt	Inflow	643 ± 478	73 ± 67	572 ± 440	78 ± 56	14 ± 14	64 ± 46	13 ± 11
	Outflow	553 ± 426	41 ± 33	514 ± 401	69 ± 52	9 ± 7	61 ± 45	4 ± 5
	Average reduction	90c	31a	57b	9b	5a	3a	9
	Retention	14%	43%	10%	11%	38%	5%	69%
Summer rainfall	Inflow	435 ± 292	78 ± 71	358 ± 235	70 ± 59	15 ± 14	55 ± 45	19 ± 20
	Outflow	358 ± 236	72 ± 52	287 ± 189	62 ± 48	15 ± 13	46 ± 38	3 ± 4
	Average reduction	77b	5	71c	8a	–0.5	9b	16a
	Retention	18%	7%	20%	12%	–3%	16%	83%
Madill								
Annual	Inflow	887 ± 365	107 ± 45	780 ± 327	117 ± 40	21 ± 9	96 ± 33	10 ± 5
	Outflow	706 ± 342	106 ± 50	600 ± 305	107 ± 50	25 ± 14	82 ± 36	3 ± 1
	Average reduction	181c	1	180c	10a	–4	14c	6a
	Retention	20%	1%	23%	9%	–20%	15%	66%
Spring snowmelt	Inflow	437 ± 267	50 ± 33	387 ± 237	63 ± 34	10 ± 6	54 ± 30	6 ± 3
	Outflow	386 ± 224	29 ± 18	356 ± 210	54 ± 26	7 ± 4	47 ± 22	2 ± 1
	Average reduction	51a	20b	30	9a	3	7a	4b
	Retention	12%	41%	8%	15%	27%	13%	68%
Summer rainfall	Inflow	537 ± 383	99 ± 122	438 ± 307	64 ± 43	18 ± 21	46 ± 29	20 ± 32
	Outflow	407 ± 337	89 ± 61	318 ± 280	60 ± 48	21 ± 16	40 ± 32	7 ± 11
	Average reduction	130c	11	119b	4	–3	7b	13
	Retention	24%	11%	27%	6%	–15%	15%	65%

Notes: Sediment data were only collected between 2004 and 2007. No water quality samples were collected in 2003. The annual data for the Madill dry dam do not include any data from 2005 (i.e., a high rainfall year) because of missing snowmelt data. Letters represent significance levels: a is for $p < .1$, b is for $p < .05$, and c is for $p < .01$.

These results are consistent with recent studies in Manitoba (Glozier et al. 2005; Tiessen et al. 2010), but they are different to those reported previously in more humid regions of North America and Europe (e.g., Baker and Laflen 1983; Sharpley and Smith 1994; Uusi-Kamppa et al. 2000; Ulen et al. 2007). Even in regions where snowmelt is a major component of total runoff, particulate nutrients still typically dominated total nutrient loads in these studies.

Impact of Reservoirs on Flow. Between 1999 and 2007, the Steppler multipurpose dam reduced peak flow during the spring snowmelt period by an average of 72% y^{-1} (range 38% to 100% y^{-1}), while peak flow during summer rainfall-generated runoff was reduced by 48% y^{-1} (range 6% to 85% y^{-1}) (table 3). During this same time period, the Madill dry dam reduced both spring snowmelt and summer rainfall peaks by an average of 44% y^{-1} (range 0% to 74% y^{-1} for snowmelt-induced runoff, and 0% to 63% y^{-1} for rainfall-induced runoff). The effectiveness of either dam/reservoir in reducing the peak inflow relative to the outflow is dependent on several factors. The Steppler multipurpose dam was designed to store water up to the drop inlet elevation before spills are made through the drop inlet. Therefore, as inflow into the reservoir continues, water starts rising above the drop inlet elevation until the sill elevation of the earth spillway is reached. Above the sill elevation, water is released from the reservoir at a much greater rate (i.e., 6.0 m^3 s^{-1} [210 cfs]) than that through the drop inlet (i.e., 0.21 m^3 s^{-1} [7.4 cfs]), and the water level would only continue to rise if the inflow rate was greater than the flow rate of the drop inlet and the earth spillway combined. As a result, the impact of the Steppler multipurpose dam in reducing peak inflow is dependent on the volume of water in the reservoir prior to the peak inflow. In turn, the volume of water in the reservoir is dependent on the timing and length of the runoff events. For example, if the runoff prior to the peak flow is significant (i.e., large volume or multiple peaks) the usable storage in the reservoir is filled and the multipurpose dam is much less effective in reducing the outflow peak. Under these conditions in 2005, the rainfall runoff into the Steppler multipurpose dam in 2005 was 1.36 m^3 s^{-1} (48.0 cfs), while the outflow was 1.34 m^3 s^{-1} (47.3 cfs)—a reduction of only 1% in the peak inflow (table 3). Conversely, if a runoff event which occurs quickly (i.e., a steep raising limb on the hydrograph) without much flow preceding the peak flow, outflow will be greatly reduced (i.e., most of the peak flow volume is stored before significant downstream releases are made). An example of this occurred in 1990, when the peak inflow due to a very large rainfall runoff event was 4.1 m^3 s^{-1} (145 cfs), while the outflow was 0.45 m^3 s^{-1} (15.9 cfs)—an 89% reduction in the peak inflow (data not presented). The inflow peak in that year had a frequency greater than a 1:50 year event, while the outflow peak was less than a 1:2 year event.

For the Madill dry dam, the maximum outflow is limited by the capacity of the drop inlet (i.e., 0.18 m^3 s^{-1} [6.4 cfs], unless the road dam were to be overtopped). Therefore, if the inflow is less than 0.18 m^3 s^{-1} (6.4 cfs), the outflow will be equal to, or less than the inflow. A frequency analysis of spring and summer runoff peaks into the Madill dam/reservoir was conducted and indicated that 0.18 m^3 s^{-1} (6.4 cfs) was the median (i.e., 1:2 year runoff peak) flow during the study period (data not presented). Therefore, the reservoir would have typically reduced the outflow (less than the inflow) in approximately half the years. In years where the runoff peak was greater than the median, the reduction could be fairly significant. For example, in 2007, the spring inflow peak was 0.54 m^3 s^{-1} (19.1 cfs) (>1:20 year return period) and the outflow was 0.14 m^3 s^{-1} (4.9 cfs) (<1:2 year return period)—a 74% reduction in the peak inflow (table 3). Similar impacts were also observed for summer runoff events. In 2005, the inflow peak was 0.65 m^3 s^{-1} (23.0 cfs) (>1:20 year return period) and the outflow peak was 0.15 m^3 s^{-1} (5.3 cfs) (<1:2 year return period)—a 78% reduction in the peak inflow.

While the reservoirs successfully attenuated the peak flow as runoff waters were routed through the reservoirs, little of the overall runoff volume was retained during the course of the year. Overall, the Steppler multipurpose dam reduced the annual volume of runoff by an average of 17 839 m^3 y^{-1} (4,712,566 gal yr^{-1}), or 6% y^{-1} (table 4). The Madill dry dam also significantly reduced the annual volume of runoff, however, the overall reduction was only 569 m^3 y^{-1} (150,314 gal yr^{-1}), or 0.2% y^{-1}. At the Steppler multipurpose dam, the volume of runoff during the spring snowmelt and summer rainfall periods were also significantly reduced by an average of 8% and 5% y^{-1}, respectively; while the Madill dry dam significantly reduced the volume of runoff only during the snowmelt period (0.5% y^{-1}). These differences in the reduction in the volume of runoff for the two types dams were expected, because of the inherent differences in storage capacity between dry/flood control dams (i.e., Madill) and multipurpose dams (i.e., Steppler). However, some of the reduction in the volume of water within the two dams/reservoirs (especially during the summer and fall months) is also due to evaporation. We estimate that the evaporation potential within the Steppler multipurpose dam between May and November is ~2% to 3% y^{-1} (using the nomograph of Roberts and Stall (1966), together with the meteorological data for Winnipeg). One other potential exit pathway of water (and dissolved nutrients) in constructed ponds and wetlands is via infiltration or seepage (Larson et al. 2000; Kovacic et al. 2000, 2006; Koskiaho et al. 2003). Based on the low percent reduction of water at each dam/reservoir (and visual observations, including the fact that the two reservoirs never completely empty), seepage does not appear to be a large concern at either the Steppler multipurpose dam or the Madill dry dam. However, a complete analysis of the infiltration potential of the two reservoirs is beyond the scope of the present study.

Impact of Reservoirs on Sediment. Between 2004 and 2007 (recall, sediment data were collected for only the 2004 to 2007 period), the Steppler multipurpose dam reduced annual concentrations of sediment in outflow waters by an average of 70 mg L^{-1} (74%), while the Madill dry dam reduced concentrations of sediment by an average of 33 mg L^{-1} (65%) (table 4). However, there was considerable variability in the dataset. At the Steppler multipurpose dam, reductions in sediment concentration ranged from 21 mg L^{-1} in 2007 to 120 mg L^{-1} in 2005, while at the Madill dry dam, reductions in annual sediment concentration ranged from 14 mg L^{-1} in 2006 to 49 mg L^{-1} in 2004 (data not presented). Similarly, there was considerable inter-year variation in the effectiveness of the dams/reservoirs in reducing annual sediment loads. The average annual reduction in sediment loads ranged from 3 to 50 Mg y^{-1} (3 to 55 tn yr^{-1}) (67% to 83%) at the Steppler multipurpose dam (table 6), and from 2 to 9 Mg y^{-1} (2 to 10 tn yr^{-1}) (49% to 69%) at the Madill dry dam (table 7). Overall, the Steppler and Madill dams/reservoirs retained an average of 25 Mg y^{-1} (28 tn yr^{-1}) (77%) and 6 Mg y^{-1} (7 tn yr^{-1}) (66%) of the total sediment entering each reservoir, respectively (table 5).

The two small headwater storage dams/reservoirs also performed well with respect to reducing suspended sediment when the data were separated into spring snowmelt and summer rainfall periods. The Steppler multipurpose dam appeared to reduce sediment concentrations and loads in outflow water during both hydrologic seasons, but only the differences in sediment loads during the summer (16 Mg y^{-1} [18 tn yr^{-1}] [83%]) were significant (table 5). The Madill dry dam significantly reduced sediment concentrations and loads during the snowmelt period by an average of 68 mg L^{-1} (76%) (table 4) and 4 Mg y^{-1} (4 tn yr^{-1}) (68%) (table 5), respectively. Again, even though the Madill dry dam appeared to reduce sediment concentrations and loads during the summer rainfall period, only the reductions in sediment concentrations (59 mg L^{-1} [65%]) (table 4) were significant.

Overall, the percent retention of suspended sediment in both reservoirs is within the range reported in previous studies. Sharpley et al. (1996) report that a runoff detention pond reduced sediment yield by >80% in Oklahoma. Similarly, Mielke et al. (1985) in Nebraska reported that the sediment trapping efficiency of water and sediment control basins often exceeded 97%, while Kay et al. (2008) in the United Kingdom reported that small dams, constructed on feeder streams immediately before they entered a reservoir (behind which ponds form), reduced sediment concentrations by up to 42%. Differences in sediment retention between studies are likely due to differences in precipitation, flow reduction, vegetation, and the overall length of retention time. In general, the percent retention of suspended sediment at the Steppler multipurpose dam was slightly larger during rainfall events than during the spring snowmelt (table 5) and in years when rainfall-induced runoff dominated annual runoff. However, at the Madill dry dam, the percent retention of sediment was nearly equal during both the spring and summer,

Table 6

The annual and seasonal reduction in total flow and loads of total suspended sediment (TSS), total N (TN), suspended N (SUSPN), total dissolved N (TDN), total P (TP), suspended P (SUSPP) and total dissolved P (TDP) at the Steppler multipurpose dam between 1999 and 2007.

Sampling period	Year	Flow volume (m^3)	TN (kg)	SUSPN (kg)	TDN (kg)	TP (kg)	SUSPP (kg)	TDP (kg)	TSS (Mg)
Annual	1999	18,122 (3%)	255 (13%)	−59 (−34%)	304 (17%)	5 (2%)	−17 (−43%)	22 (10%)	na
	2000	23,620 (27%)	200 (51%)	10 (22%)	186 (54%)	22 (42%)	2 (23%)	20 (45%)	na
	2001	5,584 (1%)	121 (8%)	−11 (−11%)	132 (9%)	1 (1%)	−5 (−26%)	6 (4%)	na
	2002	13,921 (17%)	90 (28%)	46 (47%)	44 (20%)	11 (20%)	7 (39%)	4 (11%)	na
	2003	na	na	na	na	na	na	na	na
	2004	39,130 (12%)	108 (8%)	8 (4%)	100 (8%)	13 (6%)	0.07 (0.2%)	13 (7%)	38 (73%)
	2005	17,979 (4%)	463 (25%)	253 (59%)	212 (15%)	70 (22%)	46 (53%)	24 (10%)	50 (83%)
	2006	8,515 (3%)	44 (5%)	33 (30%)	11 (2%)	8 (8%)	3 (16%)	4 (4%)	7 (67%)
	2007	15,839 (12%)	48 (13%)	12 (25%)	36 (11%)	6 (11%)	2 (27%)	4 (8%)	3 (72%)
Spring snowmelt	1999	10,890 (4%)	200 (15%)	4 (5%)	187 (15%)	−4 (−3%)	2 (13%)	−6 (−5%)	na
	2000	9,626 (99.9%)	54 (99.9%)	3 (99.6%)	50 (99.9%)	5 (99.8%)	1 (99.6%)	4 (99.9%)	na
	2001	2,549 (1%)	18 (2%)	11 (19%)	7 (1%)	1 (1%)	−1 (−9%)	2 (3%)	na
	2002	2,858 (100%)	9 (100%)	1 (100%)	8 (100%)	1 (100%)	0.1 (100%)	1 (100%)	na
	2003	na	na	na	na	na	na	na	na
	2004	29,140 (16%)	128 (13%)	34 (26%)	94 (11%)	18 (12%)	4 (18%)	14 (11%)	1 (11%)
	2005	7,601 (7%)	220 (26%)	145 (74%)	74 (11%)	33 (27%)	30 (71%)	3 (4%)	26 (95%)
	2006	5,667 (3%)	53 (7%)	44 (45%)	9 (1%)	12 (13%)	6 (35%)	4 (6%)	7 (73%)
	2007	8,889 (11%)	35 (13%)	7 (26%)	28 (11%)	3 (8%)	1 (19%)	2 (6%)	1 (62%)
Summer rainfall	1999	7,232 (2%)	55 (8%)	−62 (−62%)	117 (21%)	9 (8%)	−19 (−85%)	28 (29%)	na
	2000	13,994 (18%)	146 (43%)	7 (15%)	136 (46%)	17 (36%)	1 (17%)	16 (39%)	na
	2001	3,035 (1%)	103 (18%)	−22 (−57%)	125 (23%)	−0.1 (−0.2%)	−4 (−51%)	4 (6%)	na
	2002	11,063 (14%)	82 (26%)	45 (46%)	36 (17%)	10 (18%)	7 (39%)	3 (8%)	na
	2003	na	na	na	na	na	na	na	na
	2004	9,990 (7%)	−19 (−5%)	−26 (−34%)	6 (2%)	−5 (−10%)	−4 (−29%)	−1 (−3%)	37 (93%)
	2005	10,378 (3%)	243 (25%)	108 (46%)	138 (19%)	37 (19%)	16 (36%)	21 (14%)	24 (73%)
	2006	2,848 (3%)	−9 (−7%)	−11 (−89%)	2 (2%)	−4 (−27%)	−3 (−163%)	−1 (−7%)	−0.05 (−6%)
	2007	6,950 (12%)	13 (14%)	5 (24%)	8 (11%)	3 (18%)	1 (36%)	2 (13%)	2 (83%)

Notes: The data are presented as annual totals and are also divided into totals for snowmelt and rainfall-induced events. na indicates data not available. Numbers in parentheses denote percent retention for each corresponding period on an annual basis. Sediment data were only collected between 2004 and 2007.

and was typically larger in years when snowmelt-induced runoff dominated. We suspect that seasonal differences in sediment loading into the two reservoirs are due to differences in each watershed's upstream catchment area, flow regimes and morphology.

Due to the process of sediment deposition and buildup after a dam is constructed, small dams and reservoirs, like their larger counterparts, can be threatened by loss of capacity. The rate at which a reservoir fills due to sedimentation is a function of the capacity to inflow ratio; sediment content in the inflow waters; texture and size of sediment; trap efficiency of the reservoir; and the method of reservoir operation (Jothiprakash and Garg 2008). Even though both reservoirs significantly reduced overall sediment concentrations and loads on an annual basis, the quantity of sediment entering the reservoirs was relatively small. An average of 32 and 10 Mg y^{-1} (35 and 11 tn yr^{-1}) of suspended sediment was measured at the inflow to the Steppler and Madill dams/reservoirs, respectively (table 5). On a watershed basis, this is equivalent to <0.15 Mg ha^{-1} y^{-1} (<0.07 tn ac^{-1} yr^{-1}) for each reservoir. To put this into perspective, soil losses >6 Mg ha^{-1} y^{-1} (>2.7 tn ac^{-1} yr^{-1}) are typically considered unsustainable for this region of the Canadian prairies (van Vliet et al. 2005). Within each reservoir, we estimate that an average of ~4 Mg ha^{-1} y^{-1} (~1.8 tn ac^{-1} yr^{-1}) of sediment was retained in the Steppler multipurpose dam during the snowmelt period (using an area = 2.25 ha [5.56 ac], reservoir size if water level is at the spill-way) and ~17 Mg ha^{-1} y^{-1} (~7.6 tn ac^{-1} yr^{-1}) during the rainfall period (using an area = 0.93 ha [2.3 ac] at the drop-inlet). At the Madill dry dam, ~2 Mg ha^{-1} y^{-1} (~0.9 tn ac^{-1} yr^{-1}) of sediment was retained during snowmelt (area = 2.0 ha [4.9 ac]), while ~25 Mg ha^{-1} y^{-1} (~11 tn ac^{-1} yr^{-1}) of sediment was retained during the summer months (area = 0.52 ha [1.3 ac] at drop-inlet). If we assume that 10 Mg ha^{-1} y^{-1} (4.5 tn ac^{-1} yr^{-1}) is equivalent to 1 mm (0.04 in) of sediment (assuming a bulk density of 1,000 kg m^{-3}), then it will take approximately 1,850 years for the Steppler multipurpose dam and 360 years for the Madill dry dam to fill up with sediment to their respective drop inlets. Compare this with Kay et al. (2009) in the United Kingdom who estimated that

Table 7
The annual and seasonal reduction in total flow and loads of total suspended sediment (TSS), total N (TN), suspended N (SUSPN), total dissolved N (TDN), total P (TP), suspended P (SUSPP) and total dissolved P (TDP) at the Madill dry dam between 1999 and 2007.

Sampling period	Year	Flow volume (m^3)	TN (kg)	SUSPN (kg)	TDN (kg)	TP (kg)	SUSPP (kg)	TDP (kg)	TSS (Mg)
Annual	1999	−155 (−0.03%)	33 (3%)	32 (20%)	1 (0.1%)	11 (9%)	4 (12%)	7 (8%)	na
	2000	180 (0.1%)	179 (24%)	21 (16%)	159 (25%)	5 (4%)	−2 (−7%)	7 (7%)	na
	2001	151 (0.03%)	381 (26%)	−46 (−31%)	427 (32%)	−12 (−7%)	−23 (−82%)	12 (8%)	na
	2002	−229 (−0.1%)	132 (19%)	−50 (−62%)	181 (30%)	−11 (−10%)	−11 (−63%)	1 (1%)	na
	2003	na	na	na	na	na	na	na	na
	2004	2,311 (1.2%)	129 (19%)	36 (39%)	93 (16%)	21 (21%)	5 (30%)	15 (19%)	9 (69%)
	2005	na	na	na	na	na	na	na	na
	2006	763 (0.6%)	199 (47%)	−17 (−62%)	216 (55%)	20 (44%)	−4 (−82%)	24 (59%)	2 (49%)
	2007	961 (0.4%)	216 (22%)	33 (27%)	183 (22%)	38 (27%)	2 (8%)	36 (31%)	8 (67%)
Spring snowmelt	1999	328 (0.2%)	−9 (−1%)	53 (67%)	−62 (−11%)	16 (28%)	9 (55%)	6 (16%)	na
	2000	15 (0.01%)	10 (3%)	−16 (−64%)	25 (7%)	−2 (−2%)	−5 (−110%)	3 (4%)	na
	2001	119 (0.1%)	66 (16%)	44 (65%)	22 (6%)	14 (21%)	8 (62%)	6 (11%)	na
	2002	40 (0.1%)	18 (9%)	−1 (−10%)	19 (10%)	−4 (−10%)	−2 (−55%)	−2 (−6%)	na
	2003	na	na	na	na	na	na	na	na
	2004	2,462 (2.5%)	36 (8%)	13 (26%)	23 (6%)	5 (8%)	2 (23%)	3 (6%)	4 (59%)
	2005	na	na	na	na	na	na	na	na
	2006	763 (4.6%)	18 (22%)	11 (70%)	7 (10%)	2 (12%)	2 (62%)	−0.1 (−1%)	2 (87%)
	2007	108 (0.1%)	218 (25%)	39 (40%)	179 (23%)	35 (28%)	3 (16%)	32 (30%)	6 (70%)
Summer rainfall	1999	−482 (−0.2%)	42 (7%)	−21 (−27%)	63 (13%)	−5 (−7%)	−5 (−32%)	1 (1%)	na
	2000	166 (0.1%)	170 (45%)	36 (36%)	133 (49%)	7 (15%)	3 (17%)	4 (13%)	na
	2001	32 (0.01%)	315 (29%)	−90 (−114%)	405 (40%)	−26 (−23%)	−32 (−216%)	6 (6%)	na
	2002	−268 (−0.1%)	114 (24%)	−48 (−73%)	162 (39%)	−7 (−10%)	−10 (−64%)	3 (5%)	na
	2003	na	na	na	na	na	na	na	na
	2004	−151 (−0.2%)	93 (42%)	24 (54%)	69 (39%)	15 (46%)	3 (40%)	12 (48%)	6 (78%)
	2005	332 (0.1%)	124 (11%)	219 (56%)	−95 (−13%)	27 (19%)	26 (39%)	1 (1%)	45 (66%)
	2006	0 (0%)	181 (54%)	−28 (−248%)	210 (64%)	18 (57%)	−6 (−249%)	24 (80%)	−0.4 (−34%)
	2007	853 (1.7%)	−2 (−2%)	−6 (−30%)	5 (7%)	3 (20%)	−1 (−32%)	4 (39%)	2 (59%)

Notes: The data are presented as annual totals and are also divided into totals for snowmelt and rainfall-induced events. na indicates data not available. Numbers in parentheses denote percent retention for each corresponding period on an annual basis. Sediment data were only collected between 2004 and 2007.

the predam tested in their study would take ~12 years to fill up with sediment, and it is clear that the process of sediment deposition and buildup is not a major threat to the performance of the two reservoirs monitored in the current study.

Impact of Reservoirs on Nitrogen. Annually, both the Steppler and the Madill dams/reservoirs significantly reduced the concentration of N in outflow waters (table 4). Between 1999 and 2007, concentrations of TN were reduced by an average of 0.4 mg L^{-1} (11%) at the Steppler multipurpose dam and by 0.7 mg L^{-1} (23%) at the Madill dry dam. Both dams/reservoirs were also effective in reducing average annual concentrations of TDN, but neither was effective in reducing concentrations of SUSPN in outflow water on an annual basis. Concentrations of TDN were reduced an average of 0.3 mg L^{-1} (10%) at the Steppler multipurpose dam and 0.7 mg L^{-1} (26%) at the Madill reservoir. Similarly, when the data were separated into hydrological seasons, both dams/reservoirs significantly reduced the concentration of TN during both spring snowmelt- and rainfall-induced runoff. On average, the Steppler multipurpose dam reduced concentrations of TN by 0.4 mg L^{-1} (7%) and 0.3 mg L^{-1} (12%) within snowmelt- and rainfall-induced runoff, respectively. Concentrations of TDN were also significantly reduced at the Steppler multipurpose dam during the summer rainfall period. However there were no similar reductions in FWMCs of TDN during the spring snowmelt or for SUSPN, annually or seasonally. The Madill dry dam reduced concentrations of TN by 0.5 mg L^{-1} (12%) and by 0.7 mg L^{-1} (27%) during the spring and summer, respectively. In addition, the Madill dry dam significantly reduced concentrations of TDN by 0.3 mg L^{-1} (7%) and by 0.6 mg L^{-1} (31%) during the spring and summer, respectively, while concentrations of SUSPN were reduced by 0.2 mg L^{-1} (44%) during the spring snowmelt.

The Steppler and Madill dams/reservoirs also significantly reduced the annual load of total N discharged from each watershed. Total N was reduced by 15% at the Steppler multipurpose dam and by 20% at the Madill dry dam between 1999 and 2007 (table 5). Similar to sediment, the overall retention of TN was highly variable from year to year,

Table 8
Pearson correlation analysis (*r*-values) between inflow volume (annually and seasonally) and the percent retention of total suspended sediment (TSS), total N (TN), suspended N (SUSPN), total dissolved N (TDN), total P (TP), suspended P (SUSPP), total dissolved P (TDP), and total flow at the Steppler and Madill dams/reservoirs between 1999 and 2007.

Inflow volume	Retention (%)							
	TN	SUSPN	TDN	TP	SUSPP	TDP	TSS	Flow volume
Steppler								
Annual	−0.48	−0.58	−0.39	−0.59	−0.64a	−0.41	0.71	−0.76b
Snowmelt	−0.82b	−0.87c	−0.80b	−0.86c	−0.81b	−0.84c	−0.56	−0.82b
Rainfall	−0.06	−0.19	0.08	0.002	−0.15	0.24	0.25	−0.71b
Madill								
Annual	−0.49	−0.06	−0.37	−0.72a	−0.22	−0.63	0.92	−0.64
Snowmelt	−0.30	0.08	−0.24	0.61	0.07	0.81b	−0.64	−0.68a
Rainfall	−0.19	−0.04	−0.22	−0.74b	−0.26	−0.69a	0.18	0.27

Note: Letters represent significance levels: a is for $p < .1$, b is for $p < .05$, and c is for $p < .01$.

ranging from 5% to 51% at the Steppler multipurpose dam (table 6) and 3 to 47% at the Madill dry dam (table 7). Overall, this resulted in an average reduction of 166 kg N y^{-1} (366 lb N yr^{-1}) at Steppler and 181 kg N y^{-1} (399 lb N yr^{-1}) at Madill (table 5). Loads of TN were also significantly reduced within both reservoirs during both the spring and summer. At the Steppler multipurpose dam, TN loads were reduced by an average of 90 kg y^{-1} (198 lb yr^{-1}), or 14% y^{-1}, during snowmelt runoff and by 77 kg y^{-1} (170 lb yr^{-1}), or 18% y^{-1}, during rainfall runoff. At the Madill dry dam, TN loads were reduced by an average of 51 kg y^{-1} (112 lb yr^{-1}), or 12% y^{-1}, during snowmelt-induced runoff and by 130 kg y^{-1} (287 lb yr^{-1}), or 24% y^{-1}, during rainfall-induced runoff. However, again, the percent retention of TN at the two dams/reservoirs was highly variable, both yearly and seasonally. During the spring snowmelt, the percent retention of TN ranged from 2% to 100% at the Steppler multipurpose dam (table 6). At the Madill dry dam, the percent retention of TN during the spring averaged 12% (table 5), and ranged from −1% to 25% (table 7), indicating that the Madill dry dam was actually a source of nitrogen (rather than a sink) during the snowmelt in one of the years during the study period. During the summer growing season, both reservoirs had at least one year when they released more nitrogen than they retained. At the Steppler multipurpose dam, this occurred in 2004 and 2006, while at the Madill dry dam it occurred in 2007. Overall, the percent retention of TN during rainfall-induced runoff events ranged from −7% to 43% at the Steppler multipurpose dam (table 6) and −2% to 54% at the Madill dry dam (table 7).

Total annual loads of dissolved nitrogen were significantly reduced at the Steppler and Madill reservoirs by 128 kg y^{-1} (282 lb yr^{-1}), or 14% y^{-1}, and 180 kg y^{-1} (397 lb yr^{-1}), or 23% yr^{-1}, respectively (table 5). During the spring snowmelt, the Steppler multipurpose dam was also effective in reducing loads of both SUSPN (31 kg y^{-1} [68 lb yr^{-1}], or 43% y^{-1}) and TDN (57 kg y^{-1} [126 lb yr^{-1}], or 10% y^{-1}). However, only loads of SUSPN (20 kg y^{-1} [44 lb yr^{-1}], or 41% y^{-1}) were significantly reduced at the Madill dry dam during this same period. During the summer, both reservoirs were better at reducing overall loads of dissolved than suspended nitrogen, as only loads of TDN were significantly reduced (Steppler: 71 kg y^{-1} [157 lb yr^{-1}], or 20% y^{-1}; Madill: 119 kg y^{-1} [262 lb yr^{-1}], or 27% y^{-1}). Correlation analyses show that at the Steppler multipurpose dam, the percent retention of TN, SUSPN, and TDN loads were negatively related to snowmelt inflow (table 8). However, this did not necessarily translate in large quantities of N retained. For example, even though 100% of the TN in inflow waters was retained in 2000 and 2002 (i.e., due to very low snowmelt runoff, there was no outflow), very low quantities of TN were retained since there was little TN transported into the reservoir (table 6). At the Steppler multipurpose dam there were no significant relationships between the three N parameters and inflow during the summer rainfall period (table 8). Similarly, at the Madill dry dam there were no significant relationships between the percent retention of TN, SUSPN, or TDN and inflow waters, annually or seasonally.

Previous reviews of natural and constructed wetlands have reported a wide range of removal efficiency for nitrogen. Our results are similar to those reported by Braskerud (2002a) in the cold, temperate climate of Norway, who found that small constructed wetlands retained between 3% and 15% of total N within inflow waters. In Finland, Koskiaho et al. (2003) report that constructed wetlands retained between −7% and 40% of the total nitrogen from agricultural runoff in that region; while in Denmark, Hoffmann and Baattrup-Pederson (2007) report that irrigated and inundated wetlands had N removal efficiency rates 28% and 71%. However, Kay et al. (2008) report no significant impacts of a predam on ammonia or nitrate loads to downstream water, even though sediment loads were significantly reduced in their study. Generally, in studies where dissolved N has been retained, it has been suggested that this retention is due primarily to the removal of nitrate-N via denitrification and/or plant and algal uptake (Woltemade 2000; Paul 2003). This was also apparent in our study as both reservoirs were much more effective in reducing concentrations and loads of nitrate-N than ammonia-N (data not presented). Overall, both reservoirs reduced NO_3, annually and seasonally, but both reservoirs were often a source of NH_3, especially in the summer. However, loads (and reductions) of NO_3 were 10 times larger than NH_3, resulting in a reduction of N overall. The removal of N via nitrification/denitrification processes and plant and algal uptake could also explain why the percent retention of TN and TDN was, on average, greater during the summer than during the spring snowmelt, when plants within the reservoirs are not yet actively growing.

Despite the effectiveness of the two reservoirs in reducing both concentrations and loads of TN, the average annual FWMCs of N in outflow waters were still very high, ranging from 2.7 to 4.6 mg L^{-1} at the Steppler multipurpose dam and 1.7 to 3.5 mg L^{-1} at the Madill dry dam during the study period (data not presented). In Manitoba, there is currently no water quality guideline for total N. However, 1.0 mg L^{-1} is recommended in the neighboring prairie provinces of Alberta and Saskatchewan (Williamson, 2002), which was exceeded in every single sample taken over the course of the project, at both the inflow and outflow sampling locations. However, on a watershed area basis, the average annual load of N entering each reservoir is low, averaging between 4 and 5 kg ha^{-1} y^{-1} (3.6 and 4.5 lb ac^{-1} yr^{-1}). Similarly, the average annual load of nitrogen leaving the Steppler and Madill watersheds is ~4.4 and 2.8 kg ha^{-1} y^{-1} (~3.9 and 2.5 lb ac^{-1} yr^{-1}), respectively.

Impact of Reservoirs on Phosphorus. Numerical values for FWMCs of TP, SUSPP, and TDP at the Steppler multipurpose dam were generally lower in outflow water than in inflow waters (annually and seasonally); however, these reductions were not statistically significant (table 4). At the Madill dry dam, average annual concentrations of TP were significantly reduced by 0.06 mg L^{-1} (14%). In addition, concentrations of TP were reduced by an average of 0.06 mg L^{-1} (10%) and 0.05 mg L^{-1} (17%) during snowmelt and rainfall runoff, respectively. The Madill dry dam also significantly reduced concentrations of TDP annually (0.07 mg L^{-1}) and during the summer (0.06 mg L^{-1}) but not during the spring snowmelt period. The average concentrations of P at both reservoirs, in both inflow and outflow waters, were high and exceeded the recommended water quality guidelines for freshwater in Manitoba (i.e., TP < 0.05 mg L^{-1}; Williamson 2002) in all years of the study. Annually, FWMCs of TP in outflow water at the Steppler and Madill reservoirs were an average of 0.49 and 0.36 mg L^{-1}, respectively (table 3). However, on a watershed area basis, the total annual load of P entering each reservoir was low compared to previously reported studies in more humid regions of the American Midwest (Sharpley et al. 1996), and averaged 0.72 kg ha^{-1} y^{-1} (0.64 lb ac^{-1} yr^{-1}) in the Steppler watershed and 0.56 kg ha^{-1} y^{-1} (0.50 lb ac^{-1} yr^{-1} at the Madill watershed, while the total annual load of P leaving the Steppler and Madill watersheds was 0.64 and 0.51 kg ha^{-1} y^{-1} (0.57 and 0.46 lb ac^{-1} yr^{-1}), respectively.

Although concentrations of P were significantly reduced only at the Madill dry dam, both reservoirs significantly reduced the annual loading of P to downstream water courses (table 5). Loads of TP were reduced by an average of 17 kg y^{-1} (37 lb yr^{-1}) or 12% at the Steppler multipurpose dam and by 10 kg y^{-1} (22 lb yr^{-1}) or 9% at the Madill dry dam. Overall, the average annual percent retention of P loads at the Steppler and Madill reservoirs were comparable to that reported by Uusi-Kamppa et al. (2000) in Scandinavia, where small ponds (>1 m [3.3 ft] deep, vegetated only on the banks) similar to those in the current study retained ~14% of the inflow P. However, again, there was considerable interannual variability in our results. At the Steppler multipurpose dam, the percent retention of TP ranged from a high of 42% in 2000 to a low of 1% in 2001 (table 6). At the Madill dry dam, the percent retention of TP was largest in 2006 (44%), but negative in 2001 (–7%) and 2002 (–10%) (table 7). Seasonally, loads of TP were also significantly reduced during both the spring snowmelt (9 kg y^{-1} [20 lb yr^{-1}], or 11%) and summer rainfall (8 kg y^{-1} [18 lb yr^{-1}], or 12%) periods at the Steppler multipurpose dam (table 5), while at the Madill dry dam, TP was reduced by an average of 9 kg y^{-1} (20 lb yr^{-1}), or 15%, during snowmelt runoff, but the retention during rainfall runoff was not statistically significant. The range in percent retention of TP in our study is similar to that reported by Braskerud (2002b) in Norway, where small constructed wetlands retained between 24% and 44% of TP inputs.

In both dams/reservoirs, annual TDP loads were significantly reduced between inflow and outflow samples, but there were no significant differences in either the Steppler or Madill reservoirs for SUSPP on an annual basis (table 5). Annually, the Steppler multipurpose dam reduced loads of TDP by 12 kg y^{-1} (26 lb yr^{-1}), or 10%, while the Madill dry dam reduced loads of TDP by 14 kg y^{-1} (31 lb yr^{-1}), or 15%. Seasonally, the Steppler multipurpose dam was effective in reducing loads of both SUSPP (5 kg y^{-1} [11 lb yr^{-1}], or 38%) and TDP (3 kg y^{-1} [7 lb yr^{-1}], or 5%) during the spring snowmelt. However, at the Madill dry dam, only loads of TDP (7 kg y^{-1} [15 lb yr^{-1}], or 13%) were significantly reduced in the spring. Similar to the results for nitrogen, both the Steppler and Madill dams/reservoirs were more effective at removing dissolved P than suspended P during rainfall-induced runoff events. During the summer, loads of TDP were reduced at both reservoirs (Steppler: 9 kg y^{-1} [20 lb yr^{-1}], or 16%; Madill: 7 kg y^{-1} [15 lb yr^{-1}], or 15%), but there were no significant effects on SUSPP at either reservoir. In fact, in both reservoirs, more SUSPP was released, on average, during the summer than retained (tables 5, 6, and 7). We suspect that this was a combination of relatively low concentrations of particulates within inflow water (especially in comparison to total dissolved nutrients) and algal growth during the summer. The percent retention of TP, SUSPP, and TDP loads was also significantly related (negatively) to snowmelt inflow at the Steppler multipurpose dam (table 8). The correlation analysis also suggests that loads of SUSPP were negatively related to total inflow on an annual basis. At the Madill dry dam, loads of TP were also negatively related to annual inflow. However, TP and TDP were positively related to inflow during the snowmelt period, and negatively related to inflow during the summer (table 8).

Overall, our results are similar to those of Braskerud et al. (2005), who report that the average total P and dissolved reactive P retention within constructed wetlands in cold temperate regions (i.e., Sweden, Norway, Finland, Switzerland, and Illinois, United States) ranged from 1% to 88% and –19% to 89%, respectively. They also report that retention varied from site to site, and suggest that site-specific factors within each catchment and wetland greatly influenced P removal. Previous studies have suggested that retention time and location are critical elements in effectively treating agricultural runoff water. If the overall retention time within a reservoir is too short, few nutrients will settle, sorb, or be incorporated into plant biomass. For example, in Switzerland, Reinhardt et al. (2005) report that a typical constructed nutrient retention wetland was able to retain >50% of the incoming TDP, provided that the water residence time was >7 to 10 days. In Germany, Paul (2003) also report that nutrient elimination in predams during the summer was largely controlled by the overall retention time of water and biological processes (e.g., phytoplankton growth) within the dams. However, in cold climates, P incorporation into the plant biomass may not be as important, since the growing season is short and typically does not include the peak runoff period in the spring. In Finland, Koskiaho et al. (2003)

suggested that under their cold, boreal conditions, where most nutrient loading occurs during seasons when biological activity is low, constructed wetlands functioned primarily as sedimentation traps (i.e., retained nutrients more efficiently in particulate than in dissolved form) and those with the longest water residence times worked best within their environment. Previous studies have also reported that in addition to sedimentation of particles and biological uptake, P is removed from wetlands and ponds by the sorption of dissolved reactive P by soil within the reservoir (Uusi-Kamppa et al. 2000). In fact, Liikanen et al. (2004) in Finland (where the constructed wetland tested reduced TP and TDP loads by 68% and 49%, respectively), suggest that before the construction of any wetland, the surface soil should be removed to increase the sorption capacity of the reservoir, especially if it is to be constructed on P rich agricultural land. Without the removal of surface soil, there is a greater risk of the wetland being a source of P, rather than a sink. Similarly, continued monitoring of the small dams/reservoirs in the South Tobacco Creek watershed is important to ensure that they do not eventually become net exporters of P (and nitrogen). However, over the course of the study there were no apparent trends in sediment and/or nutrient retention within either dam/reservoir and the two reservoirs do not appear to be losing efficiency even though they are ~20 years old, likely due to the fact that very little sediment is actually entering either of the reservoir ponds under these environmental conditions.

While the two reservoirs studied in the current project were successful in reducing the loads of total P to downstream water bodies, the exact reason (i.e., settling, sorbing or incorporation of P) for this reduction is unclear. Also, although loads of TP were significantly reduced at the Steppler multipurpose dam, concentrations were not. This suggests that the observed reduction in loads of TP in outflow waters at this site was due (in part at least) to the reduction or losses of P containing water, rather than retention of TP alone within the reservoir. For example, P retention within the reservoir may have been partially offset by evaporation losses of water, resulting in no significant difference between inflow and outflow concentrations of P. It is apparent that additional research is needed to determine the environmental processes that affect the overall capacities of all conservation retention structures (i.e., small dams and/or reservoirs, constructed wetlands, WASCOBs) to retain sediment and nutrients in cold-climate regions.

Summary and Conclusions

After nine years of collecting water samples and monitoring the inflow and outflow of water, our results show that small-scale headwater storage dams/reservoirs constructed in the South Tobacco Creek are effective in reducing peak flows and rapid runoff from agricultural land at the top of the Manitoba Escarpment. However, while the reservoirs successfully attenuated the peak flow as runoff waters were routed through the reservoirs, little of the overall runoff volume was retained during the course of the year. Our results also show that these dams/reservoirs are capable of reducing agricultural nutrient loads by amounts in excess of the targets of 13% for N and 10% for P set by the Manitoba government. Both reservoirs significantly reduced annual loads of sediment, total nitrogen and total P, which resulted in an average annual retention of 25 Mg y^{-1} (28 tn yr^{-1}) (77%) of sediment, 166 kg y^{-1} (366 lb yr^{-1}) or 15% of N, and 17 kg y^{-1} (37 lb yr^{-1}) or 12% of P from the Steppler multipurpose dam, and 6 Mg y^{-1} (7 tn yr^{-1}) (66%) of sediment, 181 kg y^{-1} (37 lb yr^{-1}) or 20% of N, and 10 kg y^{-1} (22 lb yr^{-1}) or 9% of P from the Madill dry dam. In addition, the two reservoirs reduced annual concentrations of sediment and N to downstream receiving waters. However, only the Madill dry dam significantly reduced concentrations of P, and the average concentrations of N and P within both inflow and outflow water samples still exceeded the current recommended guidelines for freshwater in the Canadian Prairies, in all years of the study. The Steppler and Madill reservoirs were also effective in reducing annual loads of dissolved N and P and during both snowmelt and rainfall runoff, with the retention of dissolved nutrients being slightly higher during the summer than the spring. Surprisingly, both reservoirs were much less effective in significantly reducing annual loads of suspended nutrients than dissolved nutrients to downstream water bodies. While the reservoirs were effective in removing particulates during snowmelt runoff, they were often sources (rather than sinks) of suspended nutrients during rainfall-generated events. We suspect that this was due to the limited amount of particulate material entering the reservoirs—especially in comparison to total dissolved nutrients—and algal growth during the summer. However, since dissolved nutrients were the dominant form of both N and P (in both snowmelt and rainfall runoff events), both reservoirs were successful in reducing overall nutrient loads to downstream water bodies.

Admittedly, small headwater storage dams and reservoirs may not be the universal solution for reducing nutrient loading in the Lake Winnipeg watershed (e.g., they may be less practical in landscapes with minimal relief, such as the Red River Valley). Nonetheless, the data show that these small headwater storage dams and reservoirs result in a significant reduction in downstream nutrient loading from runoff water, adding to the overall economic benefit of building them. Additional reductions in nutrient loading could be achieved if the water and nutrients in the reservoirs were used locally (e.g. irrigation of agricultural crops during moisture deficient periods), further reducing overall nutrient loading downstream. In combination with improved flood and erosion control for the region, it is clear that small headwater storage dams and reservoirs are an effective conservation tool to reduce downstream nutrient loading into rivers and downstream water bodies, and have sufficient value that deserves consideration when developing watershed management plans, especially for undulating and hummocky landscapes on the Great Plains.

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