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An Economic Assessment of Local Farm Multi-Purpose Surface Water Retention Systems under Future Climate Uncertainty

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Abstract: Regions dependent on agricultural production are concerned about the uncertainty associated with climate change. Extreme drought and flooding events are predicted to occur with greater frequency, requiring mitigation strategies to reduce their negative impacts. Multi-purpose local farm water retention systems can reduce water stress during drought periods by supporting irrigation. The retention systems' capture of excess spring runoff and extreme rainfall events also reduces flood potential downstream. Retention systems may also be used for biomass production and nutrient retention. A sub-watershed scale retention system was analysed using a dynamic simulation model to predict the economic advantages in the future. Irrigated crops using water from the downstream reservoir at Pelly's Lake, Manitoba, Canada, experienced a net decrease in gross margin in the future due to the associated irrigation and reservoir infrastructure costs. However, the multi-purpose benefits of the retention system at Pelly's Lake of avoided flood damages, nutrient retention, carbon sequestration, and biomass production provide an economic benefit of $25,507.00/hectare of retention system/year. Multi-purpose retention systems under future climate uncertainty provide economic and environmental gains when used to avoid flood damages, for nutrient retention and carbon sequestration, and biomass production. The revenue gained from these functions can support farmers willing to invest in irrigation while providing economic and environmental benefits to the region.

Keywords: climate change; multi-purpose retention systems; agriculture; irrigation

1. Introduction

Across Canada, annual mean temperature has increased since the 1950s. As of 2010, Canada has experienced an annual average surface air temperature warming of 1.5 °C. Stronger warming trends have been found for the north and west of Canada, with the greatest warming occurring in winter and spring [1,2]. These climatic changes are expected to increase potential evapotranspiration and lead to moisture deficits [3]. Changes in precipitation timing are also expected, resulting in less snow-cover, shorter snow-cover duration, increased winter river flows, and decreased summer flood events [3–5]. If the timing of seasonal precipitation begins to change and temperatures continue to rise under climate change, there will be severe effects on agriculture, ecosystems, water runoff rates and quantities, as well as groundwater storage. On the Canadian Prairies, where 80 percent of Canada's farmland is situated, strategic water management solutions are needed to deal with the uncertainty associated with climate change and its impact on agricultural production [4,6,7]. Changes in temperature and precipitation expected with climate change will impact a wide range of variables, affecting the productivity of annual crops. Alterations in the growing season length, frost timing, heat waves, precipitation, and moisture availability will be witnessed with temperature and precipitation increases. This will require farmers to be ready to adapt to new climatic patterns [8]. The uncertainty associated with climate also increases risk for farmers, requiring water management solutions that will provide benefits to farmers under all conditions, while reducing agricultural risk [8,9]. Economic consequences of drought or flooding events will depend on the agricultural and water management sectors success in preparing and adapting for climatic extremes [4]. The chosen water management strategy needs to be economically viable, benefitting the farmer and the provincial economy, while reducing risk in agricultural production systems [10].

Climate change is predicted to increase the frequency of extreme drought and flooding events which will impact agricultural sectors, such as southern Manitoba, Canada [4,7,9,11]. Historically, the trend within Manitoba has been to remove excess water from agricultural land as quickly as possible in spring using a series of ditches and drains [3,12]. This strategy to deal with flooding in the province is common throughout the landscape [3,13]. While drainage systems are meant to remove excess water from inundated land quickly, they can actually increase the negative effects of floods by amplifying flood peaks, which then have greater force to cause damage [3]. Drainage also increases the amount of nutrients being removed from the landscape, subsequently impacting water quality as they flow into Manitoba's water bodies [3]. Quickly removing water from the landscape may also leave agricultural lands vulnerable to soil moisture deficits under future climate uncertainty as evapotranspiration quickly removes summer precipitation from the soil [3]. The province of Manitoba aims to increase their adaptive capacity to prepare for future climate uncertainties [9,14,15]. Increasing the adaptive capacity of southern Manitoba communities will require the development of techniques allowing farmers to drought proof their crops as well as to limit damages caused by floods in non-drought years. Strategies should also allow for sustainable water management by providing multiple benefits when possible, such as bio production and nutrient retention [14]. Strategies currently being used on the Prairies include crop insurance, soil and water conservation, improved irrigation (where applicable), exploration of groundwater supplies, as well as introduction of new infrastructure [4,7,9]. Infrastructure implementations range from new wells and pipelines to dugouts [4]. Dryland farmers look to decrease drought risk by conserving soil moisture and nutrients through crop rotation and minimizing tillage practices [9].

The creation of multi-purpose local farm water retention systems, designed to capture and store surface water, may be a viable option that would reduce water stress during droughts by providing water for irrigation [16]. Additionally, the retention systems would serve to capture excess runoff in spring and during extreme rainfall events to help mitigate flood events. The stored water can be used for biomass production and nutrient retention [14,17]. Retention systems also serve to reduce downstream peak flow and aid in retaining flood waters which reduces associated flood risks downstream [16,18]. If water is released from reservoirs, they serve to replenish groundwater stores downstream [16]. Researchers have found these systems to be effective for increasing and stabilizing crop yields via irrigation in locations such as Texas, Kansas, Kentucky, India, and Thailand [19]. Berry [20] reported an average increase in crop yield of $13.00/hectare/year when irrigation was applied to canola, alfalfa, barley, and spring wheat using water from a local farm retention system in Manitoba. However, there is limited pre-existing irrigation infrastructure in Manitoba, so adopting irrigation as a management strategy would require the costly installation of irrigation infrastructure. This would require farmers to earn incremental gross margins of $147.00/hectare of crop land/year to cover the cost of irrigation infrastructure and a surface water retention system as a water source [20]. While irrigation did not provide an increase in gross margins under present day conditions, future climate change scenario predictions of increased temperatures and precipitations may result in more economically advantageous conditions in the future.

Surface water retention systems additionally aid in improving water quality. Retention systems have shown success in reducing nutrient and sediment loading in various locations worldwide. Several examples from the literature provided by [21] on retention systems in America and Europe have shown effectively reduced nutrient loading. A runoff detention pond in Oklahoma, USA reduced sediment discharge downstream by 82%, total nitrogen by 56%, and total phosphorus by 60% [22]. A reduction in total nitrogen of 38%, and 56% in total phosphorus loading from a constructed wetland (a detention basin formed by berms adjacent to a stream) in Illinois, USA was reported by [23]. A shallow predam, a small reservoir aimed at improving water quality of a larger main reservoir downstream, in Luxembourg, was found to retain total phosphorus up to 60%, and a deep predam retained up to 82% [21,24]. A small dam in Spain reduced total phosphorus loads downstream by over 25% [25]. Small ponds in Finland and Sweden reduced total phosphorus loading by 17% and constructed wetlands in Norway and Finland reduced total phosphorus loading by 41% [21,26].

In Manitoba, small on-farm surface water retention systems are scattered throughout agricultural watersheds. The South Tobacco Creek Watershed, in south central Manitoba, is home to twenty-six dams providing management of almost 30% of the watersheds drainage area [18]. The watershed is now home to five dry dams, six back-flood dams, and fifteen multipurpose dams. Each dam was designed to retain 20–25 mm of runoff at full capacity from their catchment area [21]. These dams' capacity to reduce flood risk has been under study since the 1990s. The Watershed Evaluation of Beneficial Management Practices (WEBs) program, an Agriculture and Agri-Food Canada (AAFC) research program, began in 2004 to expand the research on the South Tobacco Creek Watershed dams to include sediment, nitrogen, and phosphorus loadings downstream [18]. Both the dry flood control dam and the multi-purpose dam were effective in reducing total suspended sediment (65%–85% reduction), particulate nitrogen (41%–43% reduction during snowmelt, 7%–11% reduction from summer rainfall events), and particulate phosphorus (27%–38% reduction in snowmelt runoff) [18]. The entire system of dams within the watershed provided a reduction in peak flow of 9%–19% from spring snowmelt runoff and 13%–25% from rainfall runoff [18]. Another on-farm retention pond in Saint-Samuel, Quebec was found to reduce peak flows by 38%, on average, from rainfall runoff events [27]. The pond was also effective at removing total suspended sediment, total nitrogen, and total phosphorus with mean removal efficiency ratios of 50%–56%, 42%–52%, and 48%–59%, respectively.

The ecosystem benefits of reduced nutrient and sediment loading downstream, carbon sequestration, and avoided flood damages downstream have been monetized for surface water retention systems on the Prairie landscape. Berry [20] reported retention system's ability to reduce downstream phosphorus and nutrient loading, sequester carbon, and contribute to avoided flood damages downstream can provide $17,600/hectare of retention basin/year. This estimate used a carbon credit value of $25.00/tonne of carbon dioxide equivalent, which the Manitoba Liquor and Lotteries Corporation is currently offering in Manitoba [28]. Benefit transfer methodology was used to estimate monetary values for reductions in nutrient loading and avoided flood damages downstream [20,29–33]. Cattail harvest from surface water retention systems as a biomass crop has recently been commercialized in Manitoba. Multi-purpose surface water retention systems gain additional ecosystem benefits of biomass production, increased nutrient management, and carbon dioxide emission offsets when cattail harvest is introduced [14,34]. Berry [20] reported that harvesting cattail for biomass production, nutrient removal, and carbon credits from multi-purpose retention systems can provide an additional $7657.00/hectare of retention basin/year. This estimate included monetary compensation for nitrogen and phosphorus removal from the ecosystem from cattail harvest, carbon credit production from biomass replacing coal with a value of $25.00/tonne of carbon dioxide equivalent, and a net value of dry cattail biomass of $16.59/tonne [17,28,34,35].

The purpose of this study is to determine the economic feasibility of the adoption of a multi-purpose local farm surface water retention system as a water management strategy in southern Manitoba to reduce the increased agricultural risks to farmers under future climate uncertainty [9,16,36]. Future climatic conditions will be modelled for the study area to determine the economic and environmental benefits water retention systems can offer as a water management strategy under climate change.

Study Site

The study site for this analysis is a pre-existing water retention system at Pelly's Lake in southern Manitoba (Figure 1). Prime agricultural lands surround the lake, with the lake's watershed currently used to produce a range of crops [6]. The four main crops in the watershed are canola, spring wheat, alfalfa, and barley [37]. Landowners in the area had historically attempted to drain the area of Pelly's Lake to increase hay production. However, these efforts ultimately failed due to the presence of an underground spring, poor drainage, poor water retention potential, and widespread flooding during times of excess water [6,13]. This led to an agreement with the La Salle Redboine Conservation District (LSRCD) to create a back flood system offering multiple benefits [38]. Conservation districts in Manitoba promote sustainable development in working to protect their districts natural resources [39]. The frequently saturated land at Pelly's Lake, MB now provides flood water retention, capturing the spring freshet along with rain runoff, and nutrient retention [17,40,41]. The retained water is released in mid-June to maintain baseflow downstream. Hay production can then occur on the drained land. A water storage capacity of 2,100,000 m^3 additionally provides a large water source if irrigation development in the area is pursued.

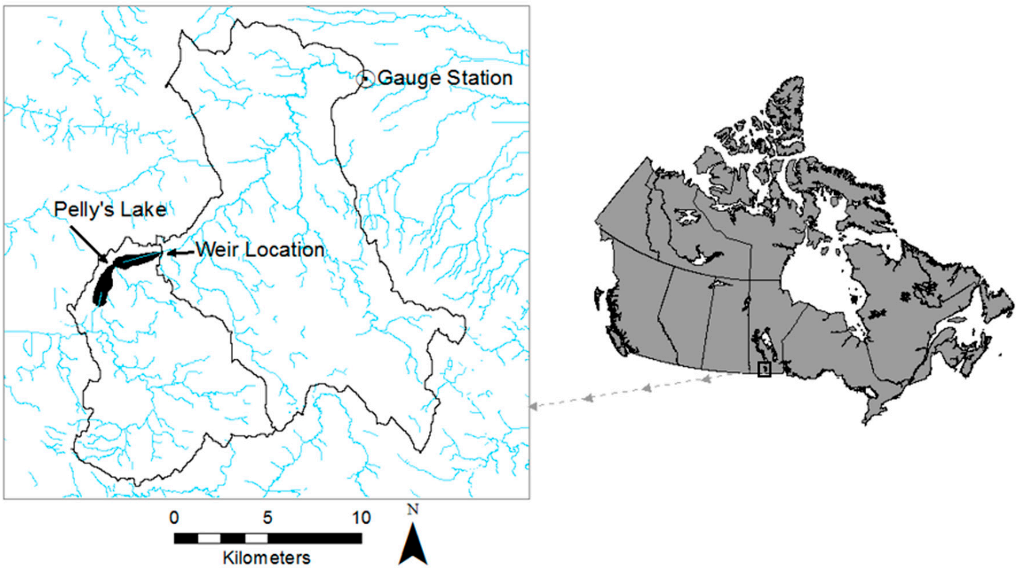

Figure 1. Pelly's Lake, Manitoba, Canada, situated within its watershed. To the right of this is the downstream gauge station and adjacent watershed boundary.

2. Materials and Methods

In order to explore the potential economic advantages of retention ponds under future climate conditions, a hydrologic model was parameterized using future precipitation and temperature data at a fine resolution for the study site. The output from the hydrologic model was input into a modeling system to provide projections of how water storage at the Pelly's Lake multi-purpose retention system would be affected by climate change. Stella modeling software, a program designed specifically for modeling complex system dynamics, allowed for an integrated hydrologic, reservoir, irrigation, plant growth, and economic model to be created [42]. The modeling system was developed based on a daily time step using a growing season simulation period running from April through September. The daily time step captured short-term components of the system while allowing for multiple years to be analyzed for a long-term analysis of the problem [10]. Spatially, study simulations were confined to the

Pelly's Lake watershed as the multi-purpose retention system would collect runoff and precipitation within this boundary (Figure 1).

2.1. Modeling System

2.1.1. Hydrologic Model and Reservoir Module

To model the hydrologic component of the target watershed, the Environment and Climate Change Canada environmental modeling system Modélisation Environnementale Communautaire—Surface and Hydrology (MESH) was chosen. MESH is a distributed land surface model commonly used in Canada for medium to large scale simulations [43,44]. Environment and Climate Change Canada uses MESH as part of an operational forecasting tool and the modeling system is currently being used within research projects such as the Drought Research Initiative (DRI) [45]. MESH requires multiple inputs to provide a complete distributed land surface model. The energy and water balance requirements for the model were determined using the Canadian Land Surface Scheme (CLASS) 1 [44] and CLASS 2 [46]. CLASS 1 is a physically based land surface model which calculates heat and moisture transfer at the surface, while CLASS 2 calculates energy and moisture fluxes at the canopy level [43,46]. Precipitation data for MESH were taken from the Canadian Precipitation Analysis (CaPA) project which produces rainfall accumulations at a six-hour time step and resolution of 15 km over North America in real-time [47]. Further required climatic data such as long wave and short wave radiation, humidity, pressure, and wind speed was acquired from the Global Environmental Multiscale (GEM) Model [43,48]. Routing of water within the study area was performed within the MESH model using a storage-routing technique which applies the continuity equation as outlined in [49]. Optimization of the MESH model was performed. Streamflow outputs from the MESH model were summed for 1 January to 14 April each year to provide an initial reservoir volume from spring freshet. Streamflow values for 15 April to 15 September each year were input into the model (Figure 2). Reservoir outflow considered the height of the emergency spillway, outflow over a rectangular weir, evaporation rates, and withdrawals taken for irrigation purposes (Figure 2). Table 1 provides detailed input parameters and equations for the modeling system.

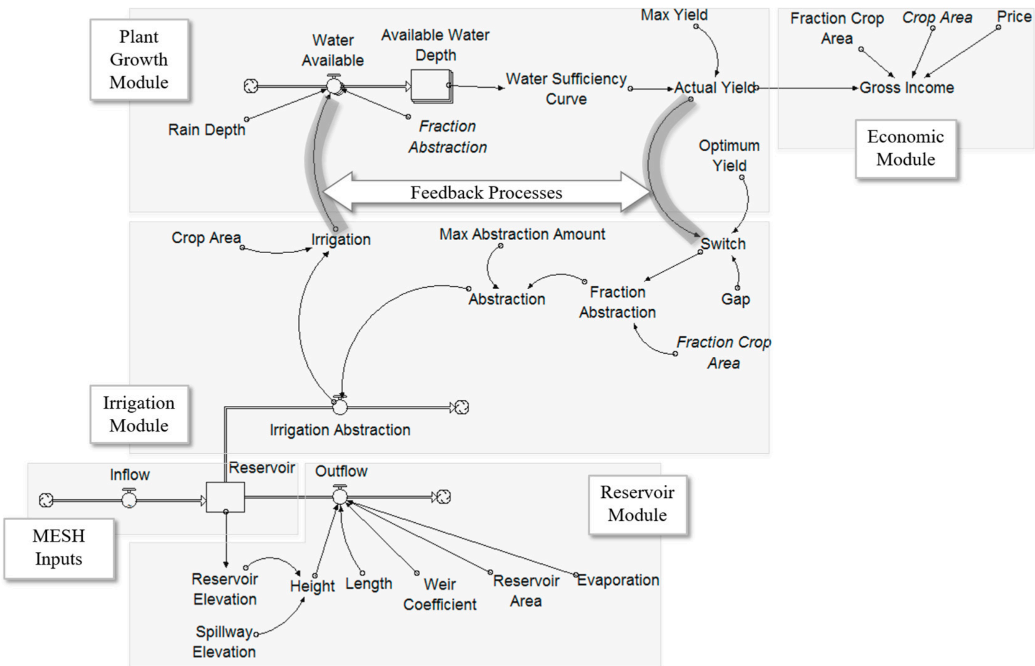

Figure 2. A stock-flow diagram of the modeling system, visually divided into its five component modules.

2.1.2. Irrigation and Plant Growth Module

The irrigation module consisted of irrigation withdrawals and precipitation during the growing season informing soil water volume available for crops (Figure 2). The four most prevalent crops in the study watershed as of 2011, canola, spring wheat, alfalfa, and barley, were modelled with a crop area of 6697 hectares [40]. On average within the study area, there is some initial spring soil moisture associated with snowmelt, however for the purposes of this model, soil moisture was recharged with precipitation and/or irrigation water. Soil moisture was recharged with precipitation and/or irrigation water. With the primary focus of the analysis on water as a crop production input and to maintain the tractability of the model, we assumed that all other production inputs, including nitrogen and phosphorus fertilizer and pesticides, were applied at rates which met crop growth requirements such that water was the only limiting factor to crop yield. This assumption was supported by our use of Government of Manitoba estimated, region specific, production costs including input and insurance cost. These costs are estimated based on the assumption that production inputs are used at rates to meet all crop growth requirements. The resultant crop yields were used in combination with crop prices to determine gross income (Table 1). Crop production costs and input costs were subtracted from gross income in Microsoft Excel to estimate gross margins under irrigation.

2.1.3. Economic Module

Crop prices, production costs, and insurance costs used in the economic module were 2015 values, provided by the Government of Manitoba, and were held constant for all future simulations (Figure 2, Table 1) [50]. Production costs refer to costs for seed and seed treatment, fertilizer, fungicide, herbicide, and insecticide application, machinery operation, fuel, leases, land taxes, and interest costs. Agricultural input costs and crop prices will fluctuate over time due to changes in food demand, changes in crop varieties and production technology, as well as changes in energy prices and climate. However, analysis of Canadian agriculture suggests that the ratios between farm expenses and receipt have been relatively stable over time [51]. As a result, we adopt the relatively strong assumption that input costs including reservoir and irrigation installation and upkeep costs as well as production costs and output prices associated with each crop type were constant for all simulations with the model. The total adjusted cost of the retention system at Pelly's Lake, which included upkeep and accrued interest for a twenty-year time horizon, was $45,167/year ($5.26/ha/year) [35,52]. A twenty-year time horizon was chosen as this represents reservoir infrastructure's typical serviceable life [52]. Centre-pivot irrigation infrastructure installation, labour, and maintenance over a twenty-year time horizon totalled $966,010 ($112.50/ha/year) [53].

Table 1. Parameter values and equation inputs for each module within the modeling system.

Parameters/Units	Inputs and Equations with Descriptions
Reservoir Module	
Inflow (m^3/day)	Input graphically using output data from the MESH hydrologic model on a daily time step.
Reservoir (m^3)	Initial reservoir volume calculated based on cumulative output from the MESH hydrologic model from 1 January–14 April.
Outflow (m^3/day)	$=(3 \times \text{Weir\_Coefficient} \times \text{Length} \times \text{Height}^{1.5} \times 86{,}400) - (\text{Evaporation} \times \text{Reservoir\_Area})$
	The established engineering equation for discharge over a rectangular weir was multiplied by 86,400 to convert from m^3/s to m^3/day. Evaporation over the reservoir area was subtracted from the discharge equation [54].
Weir Coefficient (dimensionless)	=0.6, An established engineering value was used.
Length (m)	=12, Spillway length was taken from the engineering drawings for the Pelly's Lake weir.
Height (m)	=IF (Reservoir Elevation − Spillway Elevation) > 0 THEN (Reservoir Elevation − Spillway Elevation) ELSE 0, An established engineering equation.

Table 1. *Cont.*

Parameters/Units	Inputs and Equations with Descriptions	
Reservoir Elevation (m)	$=9 \times 10^{-7} \times$ Reservoir + 378.23	
	This equation was determined from the engineering storage rating curve for the Pelly's Lake weir.	
Spillway Elevation (m)	=379.1, This value was provided on the engineering drawings for the Pelly's Lake weir.	
Evaporation (m^3/day)	=0.00182 (April) =0.00422 (May) =0.00460 (June)	=0.00454 (July) =0.00469 (August) =0.00346 (September)
	Mean monthly evaporation values from 1981–2010 were converted to daily values at Brandon, MB [54]. These values were used due to insufficient data available to calculate evaporation at the study site.	
Reservoir Area (m^2)	=85,867,480, calculated in ArcGIS.	
Irrigation Module		
Irrigation Abstraction (m^3/day)	=Abstraction[Canola] + Abstraction[Wheat] + Abstraction[Barley] + Abstraction[Alfalfa], This variable calculated the total water abstraction volume abstracted from the reservoir.	
Abstraction [Crop]	=Max Abstraction Amount × Fraction Abstraction This equation calculated irrigation withdrawal volumes for each crop.	
Max Abstraction Amount (m^3)	=15,000, this amount was calibrated to allow the reservoir to drain at a rate to provide sufficient water for irrigation for the entire growing season.	
Fraction Abstraction [Crop](dimensionless)	=IF ((Switch[Canola] + Switch[Wheat] + Switch[Barley] + Switch[Alfalfa]) > 0) THEN(Switch[Crop] × Fraction_Crop_Area[Crop]/(Switch[Canola] × Fraction_Crop_Area[Canola] + Switch[Wheat] × Fraction_Crop_Area[Wheat] + Switch[Barley] × Fraction_Crop_Area[Barley] + Switch[Alfalfa] × Fraction_Crop_Area[Alfalfa])) ELSE (0)	
	When water requirements were not being met by a specific crop, this algorithm directed water withdrawals to the crop requiring irrigation. It also ensured water was not applied unless required to optimize crop growth.	
Fraction Crop Area	=0.46 (Canola) =0.38 (Wheat)	=0.11 (Alfalfa) =0.05 (Barley)
	Historical patterns of crop production in Manitoba were used to determine the fraction of total crop area each crop comprised [37,55].	
Switch[Crop]	=IF (Actual Yield < Gap × Optimum Yield AND TIME > 30 THEN 1 ELSE 0	
	Irrigation was triggered for a specific crop if the crop's actual yield fell below 80% of optimum yield on day 30 (15 May).	
Gap	=0.8, Irrigation application occurred when available water only allowed for 80% or less of optimum yield growth. Yield reductions due to water stress occur when available water falls below 60% of optimum plant requirements. The threshold of 80% ensured there was always sufficient water available to the plant [53].	
Irrigation (mm/day)	=(Irrigation Abstraction/Crop Area) × 1000	
	This equation served to convert irrigation from a volume to a depth.	
Crop Area (m^2)	=66,976,634, This was calculated in ArcGIS using data on land use downloaded from the Manitoba Land Initiative [55].	
Plant Growth Module		
Rain Depth (mm/day)	Input graphically using values from Environment and Climate Change Canada for Holland, MB [56].	
Water Available [Crop] (mm/day)	=Rain Depth + Irrigation × Fraction Abstraction	
	Daily water available for crop growth [57].	
Available Water Depth [Crop] (mm)	Initial value set at 0. Snowmelt would contribute to initial spring soil moisture, however for the purposes of the model soil moisture was assumed to be recharged solely from precipitation and/or irrigation water.	
Water Sufficiency Curve [Crop]	These curves were input graphically and represented the unique optimal water requirements of each crop. They allowed for crop yield to be calculated based on water availability [57].	
Max Yield [Crop](tonnes/m^2)	= 0.000224124 (Canola) = 0.000336063 (Wheat)	=0.000376588 (Barley) =0.000672126 (Alfalfa)
	Max yield values were held constant for all simulations [50].	

Table 1. *Cont.*

Parameters/Units	Inputs and Equations with Descriptions	
Actual Yield [Crop] (tonnes/hectare)	=Max Yield × Water Sufficiency Curve × 10,000	
	Crop yield was calculated based on water availability. Each crop's water sufficiency curve provided a proportion of maximum growth based on water availability. This proportion was multiplied by max yield and 10,000 to convert from m^2 to hectares.	
Optimum Yield [Crop]	For each crop, values were input graphically. The variable represented the maximum yield of each crop over time when its water requirements were being met. Values were constant for all simulations.	
Economic Module		
Gross Income [Crop] ($)	=Actual Yield × Price × Crop Area × Fraction Crop Area/10,000 Calculated landscape level gross income.	
Price [Crop] ($/tonne)	=418.87 (Canola) =238.83 (Wheat)	=173.23 (Barley) =132.28 (Alfalfa)
	Crop prices were not available for years before 2015. Thus, 2015 crop prices were used in all simulations [50].	

2.2. Climate Change

Statistically downscaled climate data for the study area were acquired from the Pacific Climate Impacts Consortium (PCIC) for the present study [58,59]. Climate scenarios are available across Canada from PCIC. Data are produced at a gridded resolution of roughly 10 km or 300 arc-seconds for 1950–2100. Three output variables on a daily time step are available from PCIC: precipitation, minimum temperature, and maximum temperature [59]. Scenarios for all four representative concentration pathways (RCPs) (Table 2) are available and multi-model ensemble tables are provided to aid the researcher in climate model selection with the widest breadth of future climate simulations. Due to constraints on time and resources, the model ensemble list was narrowed down to contain only four models for this study (Table 3). Historical daily gridded climate data for Canada were used in combination with General Circulation Model (GCM) projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [59]. The chosen GCMs have been studied and shown to model climate change most effectively for regional applications over North America [58,60,61]. Of the two downscaling methods provided by PCIC [59], Bias Corrected Spatial Disaggregation (BSCD) was chosen for this study due to its extensive application in previous hydrologic modeling research across North America, its ease of use, daily time series output of gridded temperature and precipitation, and its ability to capture emission scenario transience effectively [58,61–64]. The BSCD method bias-corrects monthly GCM data against GCM gridded observed data. BSCD also downscales monthly GCM data to allow for regional analysis at a daily time step [58,62,63]. Further description of the application of BSCD to PCIC scenarios can be found in Werner [58]. The second downscaling option, Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ), is a recently developed method. As such, at the time of this study its application and accuracy in modeling climate change effects had not been extensively tested and was thus not suitable for this application [63].

Table 2. Representative concentration pathways (RCPs) overview.

RCP	Description
RCP2.6	Radiative forcing will peak at approximately 3 W/m^2 before 2100 and then levels will decline.
RCP4.5	Radiative forcing will stabilize at 4.5 W/m^2 after 2100.
RCP6	Radiative forcing will stabilize at 6 W/m^2 after 2100.
RCP8.5	Radiative forcing will rise resulting in 8.5 W/m^2 in 2100.

Table 3. Selected models used in multi-model ensemble of future climate scenarios.

Modeling Center	Institute ID	Model Name
Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2
Meteorological Office Hadley Centre	MOHC	HadGEM2-ES
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G

Emission scenarios RCP2.6, RCP4.5, and RCP8.5 were used for this study. The emission scenario RCP6 was excluded due to time constraints. The RCP4.5 emission scenario represented a median radiative forcing scenario in place of simulating RCP4.5 and RCP6 as median scenarios. Outputs from the four chosen climate models were downloaded for the study area. As the downscaled models have a grid resolution of approximately 10 km, outputs were spatially constrained over the study area between latitudes 49° N and 50° N and longitudes 98° W and 97° W.

The multi-model ensemble mean historical climate data were validated against observed climate data for the 2005–2014 (present day) study period to confirm its representation of observed values. As shown in Figure 3 there is some discrepancy between modelled and observed precipitation. This is due to the downscaling method application to the GCMs introducing bias. However, it does appear that the multi-model ensemble mean is capturing the annual and monthly cycle of precipitation. Figure 4 illustrated the multi-model ensemble mean's capacity to simulate observed temperature at the study location. These figures provided validation that the GCMs are suitable for simulating future climate change at this location.

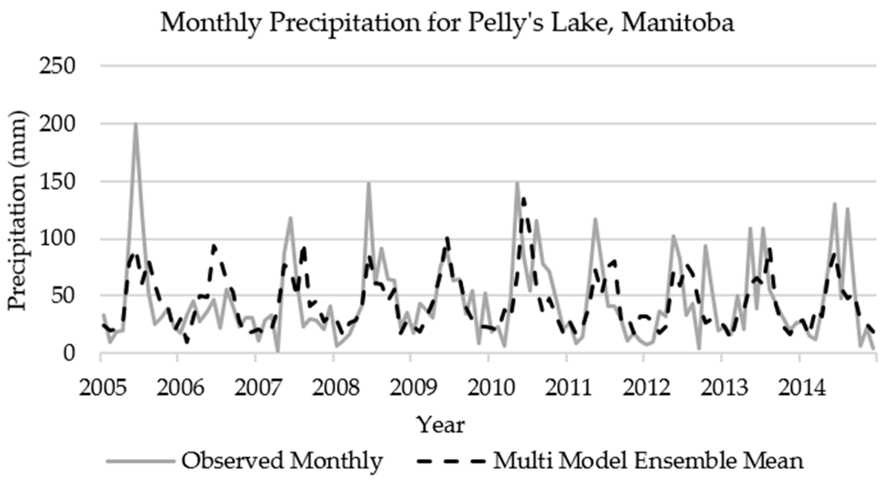

Figure 3. Comparison of observed and modelled monthly precipitation at Pelly's Lake, Manitoba for 2005–2014.

Climate trends at Pelly's Lake for the median emission scenario, RCP4.5, along with the two extreme emission scenarios, RCP2.6 and RCP8.5, were graphed to provide a comparison (Figures 5 and 6). The data were divided into summer and winter to determine multi-model ensemble mean increment changes in precipitation and temperature for the two seasons. These plots indicate a consensus in future climate precipitation trends between the four different models, increasing confidence that the climate models are performing as desired. Confidence in the model's abilities to simulate future climate conditions was further increased by the clear trends between models for each RCP. Outputs from the PCIC downscaled models support the findings published by Warren and Lemmon [1] that precipitation is projected to increase for all seasons across Canada in the future. Future precipitation simulation outputs in the same report also indicated precipitation increases will be greater in the winter than the summer [1].

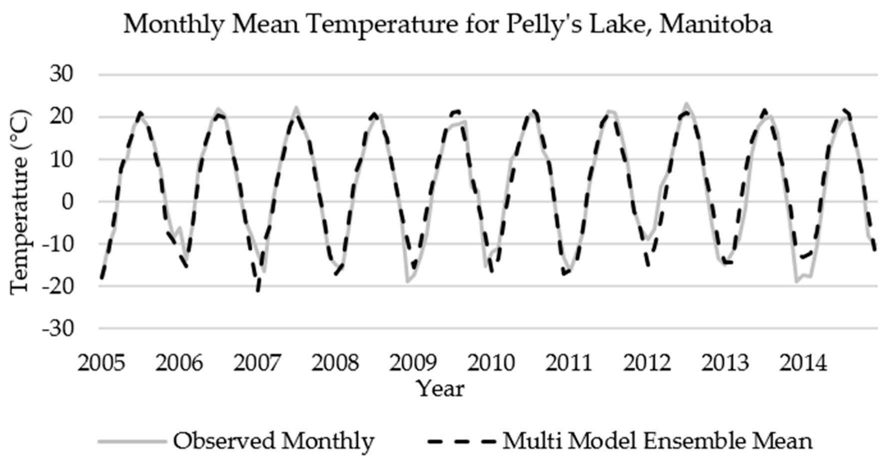

Figure 4. Comparison of observed and modelled monthly mean temperature at Pelly's Lake, Manitoba for 2005–2014.

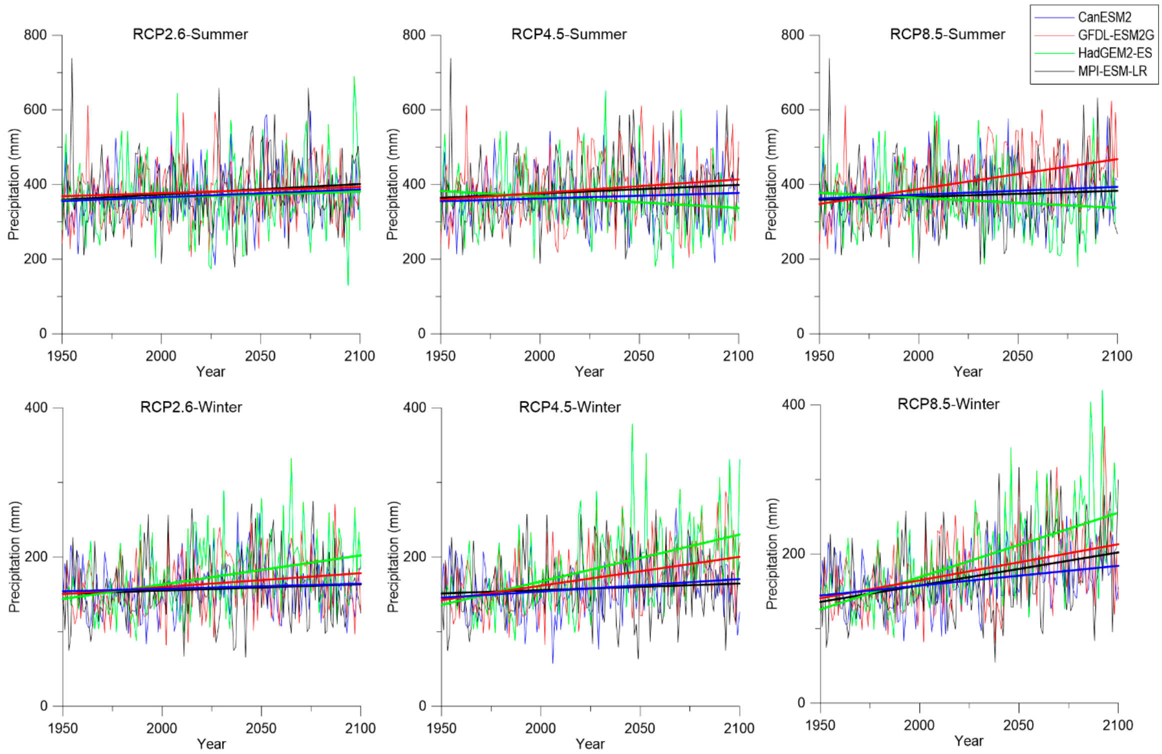

Figure 5. Multi-model ensembles for each representative concentration pathway (RCP) showing summer and winter precipitation with lines representing mean precipitation for each climate model. The spread between model simulations illustrates uncertainty.

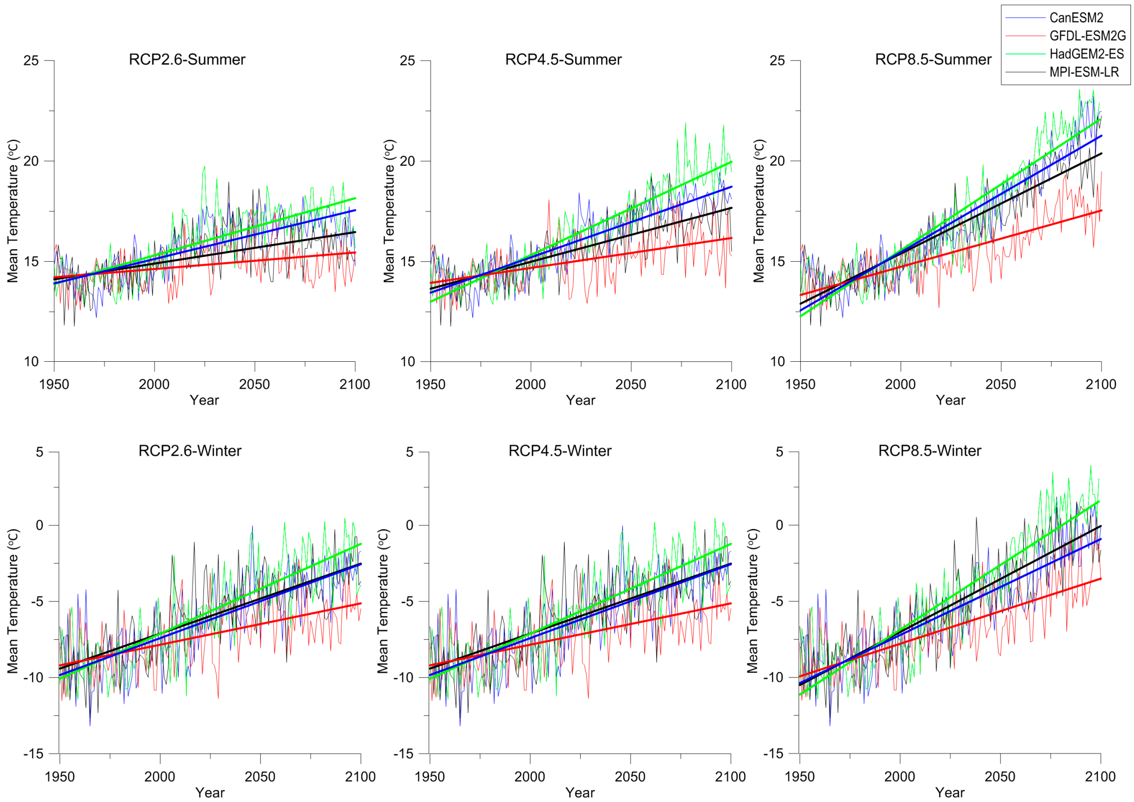

Figure 6. Multi-model ensembles for each representative concentration pathway (RCP) showing summer and winter temperature with lines representing mean temperature for each climate model. The spread between model simulations illustrates uncertainty.

2.2.1. Delta Method

As this study deals with the benefits of retention basins under future climate uncertainty, climate data were required to provide long term trends in future climate change that will impact the retention system's water volume. For this reason, a simple delta method application was chosen to simulate the two future climate periods. This method has been extensively used for studies that aim to provide a sensitivity analysis of future climate uncertainty [52,65–68]. The delta method applies changes in climate variables extracted from GCMs or Regional Climate Models (RCMs) for the study area to a baseline observed climatology [66,68]. Precipitation is adjusted multiplicatively and temperature is adjusted additively [62,66,68]. Spatial variability of the climate variables within the observed time series are preserved in any future climate simulations [62,66,68]. This assumption is a key limitation of the delta method [62,68]. However, for this study, it is more important to have accurate representation of future spring runoff volumes and precipitation volumes for the growing season [68].

Using the downscaled GCMs, climate outputs taken from PCIC future climate conditions were extracted for two ten-year time periods, 2050–2059 and 2090–2099. This allowed for representation of the middle (2050–2059) and end of the century (2090–2099). Multi-model ensemble means were used to calculate incremental changes in temperature and precipitation for the two future study periods based on the present-day time period (2005–2014). An ensemble mean value was used for this calculation as research has determined that ensemble means reduce bias within individual models, providing a more robust output than any individual GCM output [60]. Incremental changes in precipitation and temperature from the three RCP4.5 multi-model ensemble means were applied to 2005–2014 present day climate data within the hydrologic model (Table 4). Precipitation changes were applied to the baseline time period multiplicatively while temperature changes were applied additively. All other parameters within the modeling system remained the same as for the 2005–2014 time period.

Streamflow outputs from the hydrologic model provided the 2050s and 2090s hydrologic input for the modeling system.

Table 4. Mean season precipitation totals, mean season temperature increases and increases between study periods based on the multi-model ensemble means for representative concentration pathways (RCP)2.6, RCP4.5, and RCP8.5.

Decade	Mean Precipitation Total (mm)			Incremental Increase %			Mean Temperature (°C)			Temperature Increase (°C)		
	RCP			RCP			RCP			RCP		
	2.6	4.5	8.5	2.6	4.5	8.5	2.6	4.5	8.5	2.6	4.5	8.5
Summer (May–October)												
2005–2014	371.9	371.9	371.9	-	-	-	15.29	15.44	15.25	-	-	-
2050–2059	413.3	376.8	377.7	11.1	1.3	1.56	16.17	16.86	17.56	0.9	1.4	2.3
2090–2099	382.2	381.2	408.9	2.77	2.5	9.95	16.00	17.82	20.51	0.7	2.4	5.3
Winter (November–April)												
2005–2014	162.7	162.7	162.7	-	-	-	−6.867	−6.525	−6.857	-	-	-
2050–2059	174.5	176.9	199.3	7.25	8.8	22.5	−5.786	−4.489	−4.241	1.1	2.0	2.6
2090–2099	159.6	189.6	218.7	−1.91	16.6	34.4	−6.158	−3.178	−0.430	0.7	3.4	6.4

2.2.2. Uncertainty

It is important to note uncertainties associated with climate projections from GCMs as well as downscaled methods [69,70]. Future anthropogenic emission levels involve uncertainty. Models used for simulating future climate scenarios have uncertainties linked to imperfect representation of climate processes. Current understanding of climate conditions is imperfect leading to imperfect knowledge being fed into projections [69,70]. Finally, variability at the interannual and decadal level is difficult to represent accurately in long-term projections. However, this does not mean future climate projections are false as uncertainty can be quantified [69]. Each GCM and downscaling method has a unique set of parameters as initial conditions within the model. By using future climate scenario results for as many models as possible and producing a multi-model ensemble mean or median, a more probable future climate scenario can be determined. The spread in results between models illustrates the level of uncertainty in the obtained multi-model ensemble results [58,69,71].

3. Results

Annual gross margin was estimated from model simulations with and without irrigation for the middle of the century, 2050 to 2059, and the end of the century, 2090 to 2099 for three radiative forcing scenarios. The simulation results indicated that irrigated crops using water abstractions from the reservoir experienced a decrease in gross margin when compared to gross margins without irrigation and associated infrastructure for both study simulation periods. Results for the three radiative forcing scenarios, RCP2.6, RCP4.5, and RCP8.5 using incremental percentage increases to the 2005–2014 MESH climate data for the 2050s and 2090s are provided in Tables 5 and 6, respectively. The differences in gross margin when irrigation and associated infrastructure costs were considered are provided in the second column of Tables 5 and 6. The estimated yearly cost of the retention pond and irrigation infrastructure was $160.00/hectare. Any gross margin value above −$160.00 reflects that the increased crop yield enabled by irrigation water offset the yearly cost of the retention pond and irrigation infrastructure. A value above zero would indicate all retention pond and irrigation infrastructure costs are being offset by increased crop yield under irrigation application.

Table 5. Difference in crop gross margins without irrigation and crop gross margins with irrigation and associated variable and infrastructure costs, and increase in crop gross income under irrigation for the 2050s using three different radiative forcing scenarios.

Year	Difference in Crop Gross Margins without Irrigation and Crop Gross Margins with Irrigation and Associated Variable and Infrastructure Costs ($/hectare)			Increase in Crop Gross Margins under Irrigation ($/hectare)		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2050	−174.00	−172.00	−173.00	−13.60	−11.80	−12.30
2051	−145.00	−151.00	−150.00	15.10	9.42	10.60
2052	−155.00	−153.00	−153.00	4.79	7.31	6.94
2053	−150.00	−146.00	−147.00	9.99	14.50	12.80
2054	−146.00	−143.00	−144.00	14.01	17.40	16.50
2055	−159.00	−159.00	−159.00	0.83	1.53	1.53
2056	−157.00	−146.00	−147.00	3.60	14.00	13.50
2057	−143.00	−136.00	−142.00	17.40	24.50	17.90
2058	−125.00	−127.00	−127.00	35.40	33.10	33.70
2059	−126.00	−126.00	−126.00	33.90	33.90	33.90
Average	−148.00	−146.00	−147.00	12.10	14.40	13.50

Note: Difference = Gross margin with retention pond used for irrigation - Gross margin without retention pond installation and associated irrigation.

Table 6. Difference in crop gross margins without irrigation and crop gross margins with irrigation and associated variable and infrastructure costs, and increase in crop gross income under irrigation for the 2090s using three different radiative forcing scenarios.

Year	Difference in Crop Gross Margins without Irrigation and Crop Gross Margins with Irrigation and Associated Variable and Infrastructure Costs ($/hectare)			Increase in Crop Gross Margins under Irrigation ($/hectare)		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2090	−173.00	−173.00	−174.00	−13.10	−13.20	−13.50
2091	−151.00	−150.00	−142.00	9.42	10.10	18.00
2092	−154.00	−154.00	−155.00	6.39	6.35	4.86
2093	−146.00	−147.00	−153.00	14.30	12.80	7.15
2094	−143.00	−144.00	−146.00	17.00	16.30	14.00
2095	−159.00	−159.00	−159.00	1.53	1.53	0.82
2096	−147.00	−147.00	−157.00	13.30	13.00	3.60
2097	−135.00	−142.00	−144.00	25.20	17.90	16.30
2098	−125.00	−125.00	−125.00	35.30	35.30	35.40
2099	−126.00	−126.00	−129.00	34.10	33.90	30.90
Average	−146.00	−147.00	−148.00	14.30	13.40	11.80

Note: Difference = Gross margin with retention pond used for irrigation - Gross margin without retention pond installation and associated irrigation.

All years, with the exceptions of 2050 and 2090, under all radiative forcing scenarios, within the two study time periods would experience increased crop yields from irrigation water (Tables 5 and 6). The years 2050 and 2090 experienced the highest growing season precipitation amounts of the simulation periods (497–546 mm and 503–541 mm, respectively). A rainfall event on 14 July overwhelmed canola and wheat crops, reducing yields and subsequently triggering more irrigation water to be applied until the end of the growing season. This additional irrigation application after the crops had already received excess water was detrimental to crop yields. It is important to note that the model does not account for the dynamic decision making of farmers regarding irrigation application. In a high precipitation year, the farmer would recognize crop yield reductions were due to an excess of water and would abstain from irrigation application.

The average impact of irrigation application for the 2050s simulations was an increase in annual average gross income of $12.10 to $14.40/hectare, depending on the radiative forcing scenario (Tables 5 and 6). However, due to the cost of irrigation and reservoir installation this left the farmer with an average gross margin of $146.00 to $148.00/hectare, dependent on radiative forcing scenario, each year to cover the reservoir and irrigation infrastructure and operation costs. For the 2090s simulations, the average impact of irrigation application was an increase in annual average gross income of $11.80 to $14.40/hectare, decreasing as radiative forcing increased. This left the farmer with an average net cost of $146.00 to $148.00/hectare each year, increasing as radiative forcing increased, to cover the reservoir and irrigation infrastructure and operation costs. Therefore, although the availability of irrigation water did increase crop production, the increased gross income was insufficient to offset the costs of the irrigation water.

Yearly gross margins with and without irrigation, yearly precipitation amounts, and reservoir volumes are provided in Figures 7 and 8 for the 2050s and 2090s, respectively. There was one year under all radiative forcing scenarios in each simulation period, 2057 and 2097, which required the total reservoir storage volume for irrigation application. In addition, 2091 under RCP2.6 required the total reservoir storage volume for irrigation application. This year experienced the lowest precipitation levels of all years and radiative forcing simulations, which required substantial irrigation application to optimize crop yield. While initial reservoir volumes and irrigation withdrawal volumes varied between radiative forcing scenarios, during the course of the growing seasons the reservoir always filled to capacity, allowing for irrigation withdrawals. As the MESH simulations used climate data from 2005 to 2014, variability in precipitation and temperature reflected that time period.

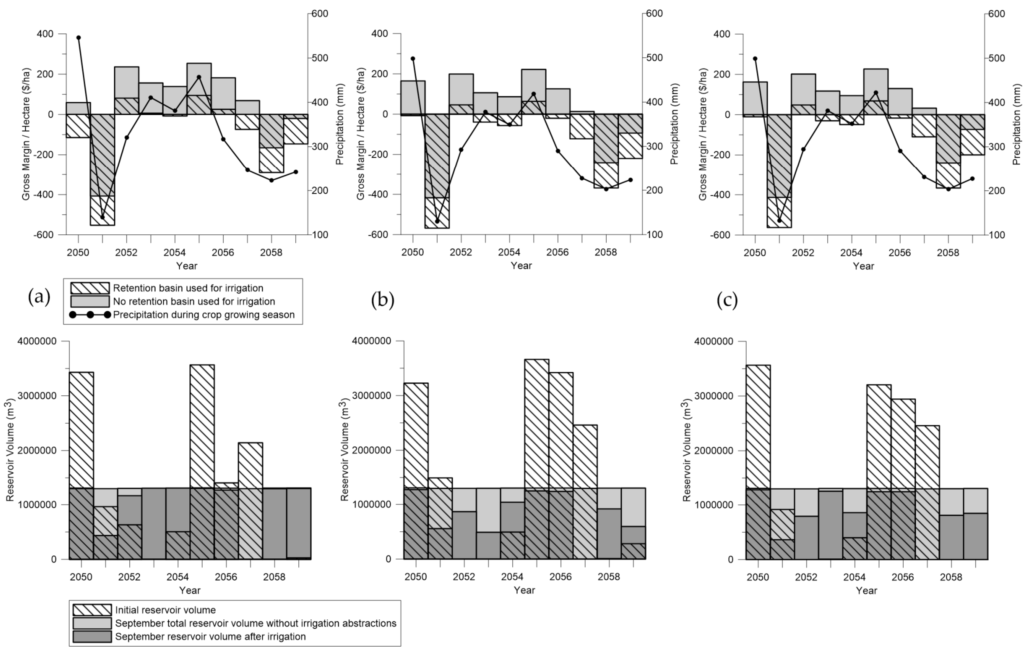

Figure 7. Yearly 2050–2059 crop gross margins with and without irrigation application and yearly water availability using incremental precipitation and temperature increases for: (**a**) Representative concentration pathway (RCP)2.6; (**b**) RCP4.5; and (**c**) RCP8.5. Reservoir levels for: (**a**) RCP2.6; (**b**) RCP4.5; and (**c**) RCP8.5 are also provided.

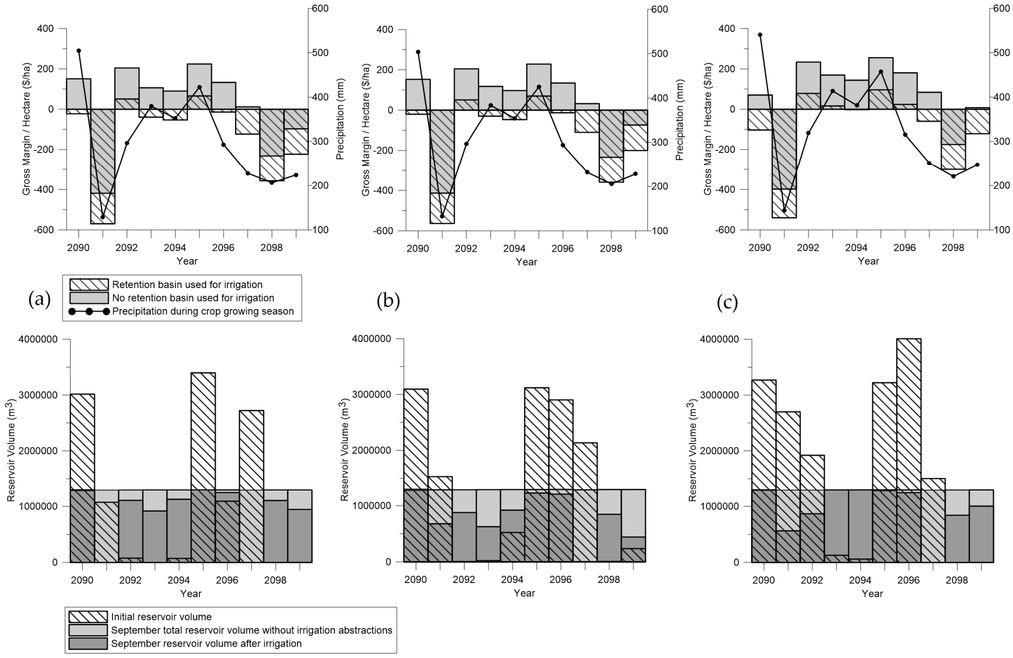

Figure 8. Yearly 2090–2099 crop gross margins with and without irrigation application and yearly water availability using incremental precipitation and temperature increases for: (**a**) Representative concentration pathway (RCP)2.6; (**b**) RCP4.5; and (**c**) RCP8.5. Reservoir levels for: (**a**) RCP2.6; (**b**) RCP4.5; and (**c**) RCP8.5 are also provided.

Results of this study can be explained by the precipitation and temperature increases experienced in the 2050s and 2090s. Incremental increases in temperature and precipitation during the 2090s increased from RCP2.6 to RCP8.5. These changes to temperature and precipitation caused crop gross income under irrigation to decrease from RCP2.6 to RCP8.5 and excess water overwhelmed the water capacity of the crops. Precipitation changes during the 2050s were less consistent with increases in radiative forcing. The 2050s experienced the largest increase in summer precipitation and smallest increase to winter precipitation under RCP2.6. Subsequently, the pattern of crop gross income increases does not align with increases in radiative forcing scenarios. Instead, RCP4.5 provided the highest gross income under irrigation and RCP2.6 provided the smallest increase to crop gross income under irrigation. Winter precipitation, which impacts initial reservoir volumes, increased for all scenarios except RCP2.6 for the 2090s. This however, did not provide enough water to fill the reservoir in all years. The increased summer precipitation levels did ensure the reservoir always filled to capacity by the end of the growing season. The variation in temperature and precipitation under different radiative forcing scenarios and time periods were not significant enough to have a significant impact on gross margins. Based on these simulation results, irrigation and reservoir installation at Pelly's Lake are not economically viable and do not generate positive crop gross margins in the middle or end of the century.

4. Discussion

The economic advantages of multi-purpose local farm retention pond systems and their use for irrigation under future climatic conditions were investigated using a dynamic modeling system. The middle of the century, 2050–2059, and the end of the century, 2090–2099, were simulated under three radiative forcing scenarios, RCP2.6, RCP4.5, and RCP8.5. The multi model ensemble future climate scenarios indicated precipitation increases will occur in the 2050s and 2090s under each RCP scenario, with the exception of winter precipitation under RCP2.6 for the 2090s, which decreased. Precipitation increases were higher for winter than summer. These results are supported by several studies which have predicted a general trend of increasing precipitation over Canada with higher projected increases to precipitation for winter months [1,3–5,72,73].

Using the delta method, incremental changes to temperature and precipitation from the present day period (2005–2014) were used to simulate future climate conditions. This method allowed for comparison of how changes in water volumes will impact irrigation water availability and subsequent crop gross margin. Due to the high costs of irrigation infrastructure and maintenance, irrigated cropping systems utilizing water abstractions from the reservoir experienced a decrease in gross margin when compared to gross margins without irrigation for both simulation periods under all RCP scenarios. To cover the costs of the irrigation and reservoir infrastructure, the farmer would have to earn incremental gross margins of $146.00 to $148.00/hectare of crop land/year in the 2050s and 2090s. Compared to present day simulations, the cost of irrigation and reservoir infrastructure to the farmer did not change under predicted future climate conditions [20]. However, increases in crop yield under irrigation were more consistent and increases in spring runoff and precipitation provided more stable reservoir water volumes which increased irrigation water availability.

The predicted increases in reservoir water volumes indicates that flooding may become more severe in the future, increasing multi-purpose surface water retention systems importance and value for flood reduction. However, this increase in reservoir water volumes also points to an opportunity for water storage for irrigation application. As future climate change is predicted to increase the severity and duration of floods and droughts [4,7,9,11], the ability to capture surface runoff in times of flood also provides water stores to draw on during times of drought. While irrigation installation remains costly, it is still an important adaptation strategy to reduce agricultural risk during times of drought. Policy providing irrigation subsidization may be implemented in the future to increase its adoption, in which case knowledge of strategies that provide sufficient water sources to utilize for irrigation application will be important.

Based on the findings of this research, multi-purpose retention basins are not economically justified when considering only the irrigation benefits provided to the participating farmers. However, a range of other benefits may be provided by the water retention system. As illustrated by Berry [20], Grosshans [17], and Dion and McCandless [35], multi-purpose retention systems provide significant economic benefits when you consider the ecosystem services they provide. Multi-purpose retention systems provide avoided flood damages downstream, sequester carbon, and reduce downstream nutrient and sediment runoff. There was substantial flow produced from spring melt that exceeded the capacity of the modelled reservoir under climate simulations for the middle and end of this century (Figure 7). A network of several multi-purpose retention systems, similar to the installed network in the South Tobacco Creek Watershed, may be required to deal with the future increases in spring runoff volumes. As part of the retention system network in the South Tobacco Creek Watershed in Manitoba, a multi-purpose dam reduced peak flow caused by spring snowmelt by an average of 72% per year, with a range of 38% to 100% peak flow reduction/year. Summer rainfall generated peak flow was reduced an average of 48% per year by the same multi-purpose dam. There is discussion regarding the construction of a second upstream reservoir at the Pelly's Lake retention site. This would increase the systems storage capacity by 1,600,000 m^3. As a result, the retention system would retain the predicted future volumes of spring melt runoff (Figure 9).

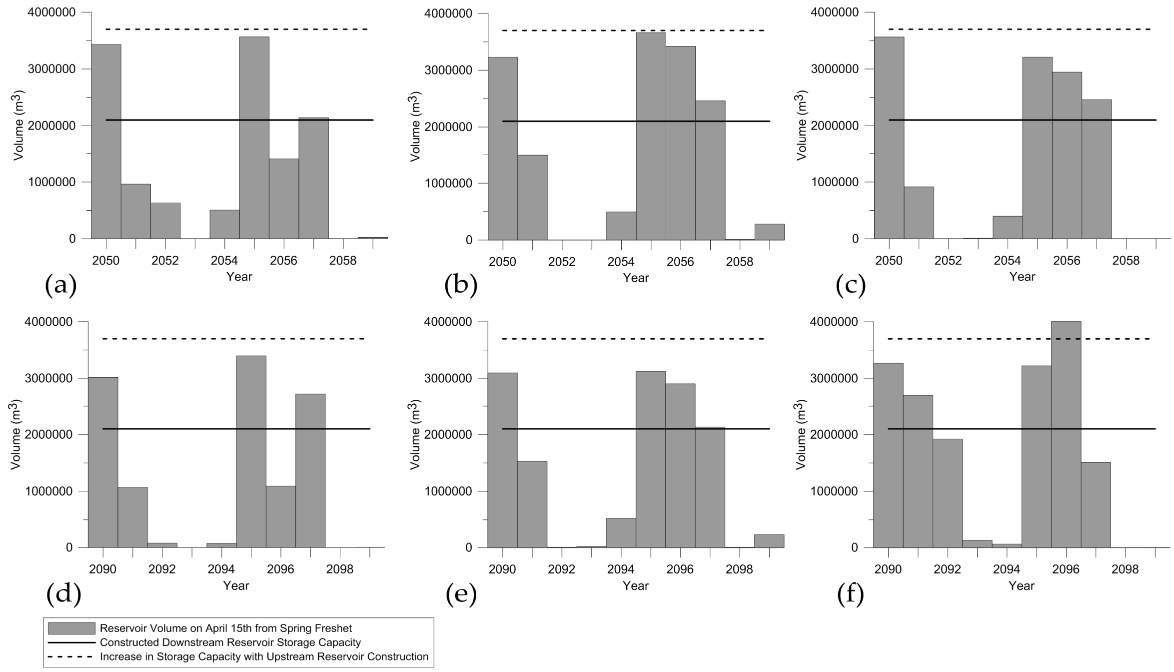

Figure 9. Reservoir capacities and initial reservoir volumes for future radiative forcing scenarios for the 2050s time period: (**a**) Representative concentration pathway (RCP)2.6; (**b**) RCP4.5; (**c**) RCP8.5; and the 2090s time period: (**d**) RCP2.6; (**e**) RCP4.5; (**f**) RCP8.5.

In additional to the economic benefits associated with avoided flood damages downstream, multi-purpose surface water retention systems can provide a biomass source. Harvesting cattail for biomass production and nutrient removal from the flooded area of multi-purpose retention systems is being commercialized in Manitoba and can provide monetary benefits from the production of carbon credits and bio products [17,28,34]. These ecosystem benefits of multi-purpose retention systems can provide additional economic revenue to compensate for the cost of the reservoir and irrigation infrastructure.

Using multi-purpose retention basins for avoided flood damages, nutrient retention, and biomass production also allows the public to benefit from these systems. The province of Manitoba has expressed interest in retention basins as a nutrient abatement option as part of their commitment to reducing downstream nutrient loading. The Manitoba Surface Water Management Strategy [14] states that water storage and associated release strategies should optimize production and harvest of biomass resources to remove phosphorus from the aquatic environment. As the South Tobacco Creek Watershed in Manitoba has illustrated, a series of retention systems on the Manitoba landscape has the potential to reduce downstream loading of phosphorus and nitrogen. Over a nine year period from 1999–2007, the retention system network decreased downstream nutrient loading above the Manitoba government's targets of 10% and 13% for phosphorus and nitrogen, respectively [21]. As the average phosphorus and nitrogen concentrations in the watershed were still in excess of recommended levels in the Canadian Prairies, Tiessen et al. [21] suggested using the reservoirs for local benefits, such as irrigation, to reduce downstream nutrient loading further. With the addition of cattail harvest, downstream loading of phosphorus and nitrogen would be further reduced [14,34,74,75]. Additionally, the removal of phosphorus during cattail harvest increases the wetlands ability to store more phosphorus, reducing downstream loading. This is essential for combating algal blooms and increasing water quality in aquatic environments such as Lake Winnipeg, Manitoba [34].

The current strategy for quickly removing water from the Manitoba landscape, via a series of ditches and drains, increases downstream flood peaks and decreases water quality. This method is only sustainable when there is adequate access to water and land use practices do not create nutrient pollution issues [3]. This quick drainage is already proving problematic for downstream nutrient loading into Lake Winnipeg in Manitoba. Future predictions of increased spring runoff volumes indicate increased issues with this strategy due to increased downstream flood peaks and increased nutrient loading. Moving forward, investing in multi-purpose local farm retention systems decreases flood peaks, increases water quality, while also providing water security during times of drought, as well as opportunities for biomass production and irrigation development. The reductions in phosphorus and nitrogen multi-purpose local farm retention systems can provide aid in Manitoba's goal of reducing nitrogen and phosphorus concentrations by 50% to Lake Winnipeg [14]. Rural municipalities and landowners benefit from the savings associated with avoided flooding damages while the province of Manitoba and its population benefit from the reduction to downstream nutrient loading and carbon storage providing climate regulation. Due to the economic and environmental gains multi-purpose retention systems provide to the province, subsidies could also be provided to incentivize widespread adoption.

Future Directions

The modelling system developed for this research could easily be adapted to include additional reservoirs within the catchment area, enabling an analysis of the regional impacts. As the current study is localized, it is difficult to state how well retention systems would work throughout the Red River Valley landscape. Regionalization of the study would also allow for the calculation of flow reductions over a larger area due to the installation of multiple retention systems. Comparisons could then be drawn between the effectiveness of water retention systems vs. current drainage systems on the Red River Valley landscape. The modelling system could also be easily expanded to include additional modules of interest to the researcher. Water samples are being collected for Pelly's Lake, upstream and downstream of the reservoir. Inclusion of a module on sediment and nutrient levels would allow for a more accurate economic assessment based on the amount of phosphorus and nitrogen loading the retention system at Pelly's Lake is reducing.

5. Conclusions

This paper aimed to estimate the monetary benefits of multi-purpose local farm retention systems under future climate scenarios. When there was insufficient precipitation to allow for maximum crop growth during the study time periods, irrigation using water stored from spring runoff and rainfall events in the water retention system provided increased annual crop gross income. However, a loss in gross margin was estimated due to the costs of developing the retention and irrigation systems. Retention basins' additional capacity for avoided flood damages, nutrient retention, biomass production, and carbon sequestration provide substantial economic and environmental gains. The addition of a second reservoir basin to the Pelly's Lake retention system would accommodate the predicted increases to future spring runoff, reducing downstream flood damage. The value multi-purpose retention basins can provide provincially supports the adoption of multi-purpose local farm surface water retention systems as an effective water management strategy. The recommended use of multi-purpose local farm retention systems is for avoided flood damages, nutrient retention, and biomass production to support farmers wanting to invest in irrigation. This use will subsequently provide economic and environmental benefits for the government of Manitoba.

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