An economic assessment of local farm multi-purpose surface water retention systems in a Canadian Prairie setting

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Online Resource 1. Detailed description of the parameters and equations used in the model

The first flow within the dynamic model is *inflow*. Refer to Figure 3 in the main text for a stock flow diagram of the model. Daily discharge values (in m^3/day) are input in graphical format into this flow for the growing season of one year, 154 days (April 15 – September 15). Each time a new year is simulated, new discharge values from MESH are input. *Inflow* flows into the *reservoir* stock. An initial reservoir volume (in m^3) is set based on the MESH cumulative flow values from March – April 15th of each year. For example, for the year 2005 simulation initial reservoir volume is set at 3.4 million m^3. Two flows are drawn from the *reservoir* stock, *outflow* and *irrigation abstraction*. The emergency spillway and gates for the dike are included in the model to enable calculation of outflows under flood conditions and release of reservoir water, respectively. Values were obtained from the provided engineering drawings for the dike. *Outflow* is determined by the following equation for outflow over a rectangular weir:

$$Outflow = ((3)(Weir_{Coefficient})(L)(H)^{1.5}(86400)) - ((Evaporation)(Reservoir\ Area)) \quad (1)$$

where the $weir_{Coefficient}$ is a converter set at 0.6 based on standard engineering convention, length (L) a converter with a value of 12 meters to indicate the length of the weir, 86,400 is a converter to adjust the outflow value from m^3/s to m^3/day, and height (H) is determined in a converter by the following formula:

$$H = if\ (Reservoir_{Elevation} - Spillway_{Elevation}) > 0\ then\ (Reservoir_{Elevation} - Spillway_{Elevation})\ else\ 0 \quad (2)$$

$Reservoir_{Elevation}$ is another converter holding the following equation derived from the engineering storage rating curve:

$$Reservoir_{Elevation} = (9\ x\ 10^{-7})(Reservoir) + 378.23 \quad (3)$$

with reservoir values coming from the *reservoir* stock in m^3/day. The spillway elevation converter is set to 379.1 meters. Returning to Equation 1, the *reservoir area* converter is set at 85,867,480 m^2. *Evaporation* values are from the 1981-2010 mean monthly evaporation values at Brandon, Manitoba. These values were provided by the Government of Manitoba (2015). The mean monthly values were divided by the number of days in the month to give an average daily evaporation value in meters that was input into the evaporation converter graphically. Evaporation values drawn from these mean values were applied to all years within the study period. This method of determining evaporation was used due to lack of information available to calculate daily evaporation at the study site.

To model the effects of irrigation of crops on reservoir water levels, a variable allowing for water abstraction from the reservoir stock, *IrrigationAbstraction,* was included in the model. Water abstracted from the reservoir for crop irrigation, in combination with rain depth, provides the water available for crops (Belcher et al., 2004). For the purposes of this model, available water is applied to the four most common crops produced in the watershed. The total crop area of the watershed is 6,698 hectares. The four most prevalent crops within the local Victoria and Lorne census areas as of 2011 are canola, spring wheat, alfalfa, and barley (Government of Canada 2011). Due to the low moisture deficits experienced in Manitoba, primarily dryland crops such as cereals and oilseed, which are also lower value crops, often do not provide enough financial benefit to merit irrigation (Gaia Consulting Limited 2007). As potato is the most commonly irrigated crop in Manitoba, but was not present in the study watershed, the model was also run replacing barley crops with potato crops for the 2006 year to determine the changes to economic benefits (Gaia Consulting Limited 2007; Government of Manitoba 2016). The model was adjusted to determine how much of the study cropland would need to be converted to potatoes in order to receive a positive net revenue from irrigation. The year 2006 was chosen for this simulation as it was a driest year within the study time period. The highest recorded, with recording beginning in 1991, application of irrigation to potato also occurred in 2006 (Gaia Consulting Limited 2007). With potato crops replacing barley, the percentage of crop allocated to potato was set to 5%, 20%, 30%, 50%, and 100%. Simulations were run with no irrigation, irrigation distributed across all four crops, as well as irrigation isolated to only the potato crops. The equation for *IrrigationAbstraction* is:

$$IrrigationAbstraction = abstraction_{canola} + abstraction_{wheat} + abstraction_{barley} + abstraction_{alfalfa} \qquad (4)$$

Where:

$$Abstraction_{crop} = (max\ abstraction\ amount)(fractionAbstraction) \qquad (5)$$

Max abstraction amount is set at 15,000 m^3/day. This value was found via calibration to allow the reservoir to drain slowly while still providing sufficient water for irrigation until the end of the growing season. *FractionAbstraction* is explained in Equation 6. Irrigation is applied (*Switch = 1*) if the available water for a crop (*Crop = Canola, Wheat, Barley or Alfalfa*) is only sufficient to provide 80% of that crop's optimum yield at a point in time during the growing season. A value of 80% was chosen for *gap* (Equation 7) as water stress causing yield reduction happens when water available for plants falls below 60% of optimum (Grinder 2000). To ensure water available for plants does not reach that level, irrigation would begin once a threshold for available water enabling 80% yield was met on or after May 15th (day 30, included in Equation 7. This ensures water is only applied to a crop when sufficient water for optimal growth is not being met without irrigation. A feedback loop within the model between actual yield and the switch used to initiate the withdrawal of irrigation was thus included. The withdrawn irrigation water created a feedback to water available for crops, impacting actual yield. As water available to plants was increased, actual yield could be optimized to improve net revenue. The algorithm for the fraction of the amount available for irrigating each crop $fractionAbstraction_{Crop}$ becomes:

$$
\begin{aligned}
& if \sum_{Crop} Switch_{Crop} > 0 \\
then \quad & denominator = \sum_{Crop} Switch_{Crop} * fractionArea_{Crop} \\
& fractionAbstraction_{Crop} = \frac{Switch_{Crop} * fractionArea_{Crop}}{denominator} \\
& else \quad (0)
\end{aligned}
\tag{6}
$$

This algorithm serves to direct the water to each crop as needed and to ensure water is not applied to a crop when sufficient water for optimal growth is being met without irrigation. $FractionArea_{Crop}$ is determined based on the fraction of each crop in the crop area. Canola comprises .46 of the crop area, wheat comprises .38, barley comprises .05, and alfalfa comprises .11 of the crop area. These values are based on historical patterns within the study area (Government of Manitoba 2014b; Government of Canada 2015b). Switch for each crop is determined by the following equation:

$$Switch_{crop} = if\ Actual_{yield} < (gap * Optimum_{Yield})and\ time > 30\ then\ 1\ else\ 0 \tag{7}$$

$Optimum_{yield}$ represents the maximum, or optimal yield of each crop based on optimal water requirements being met and is constant for each crop and simulation year. Once the model has abstracted water for irrigation it is linked to an *irrigation* function that takes the crop area stored and converts the irrigation abstraction into a mm/day value using the following equation:

$$Irrigation = (Irrigation\ Abstraction/Crop\ Area) * 1000 \tag{8}$$

Each crop has a unique optimal water requirement that is represented in the model as crop specific sufficiency curves. These curves determine yield based on $WaterAvailable_{Crop}$, which is calculated as the sum of precipitation and irrigation water (Belcher et al. 2004). Rain depth is a graphical input (mm/day) based on values from Environment Canada (Government of Canada 2015c). The $WaterAvailable_{Crop}$ flow uses the following equation to provide the amount of water available to each crop in mm/day:

$$WaterAvailable_{Crop} = Rain\ Depth + Irrigation * fraction\ abstraction \tag{9}$$

See Equation 6 for the $fractionAbstraction_{Crop}$ converter equation. 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 is recharged with precipitation and/or irrigation water. All other factors affecting growth, such as nitrogen and phosphorus levels, and pesticides were assumed to be applied at the optimal level such that water was the only limiting factor to crop yield. Irrigation amounts were optimized to provide the highest crop yield.

$WaterAvailable_{Crop}$ flows into the stock, *AvailableWaterDepth*. This stock acts to hold the inflowing available water and uses it to calculate actual yield. Each crop has a unique optimal water requirement that is represented in the model as crop specific sufficiency curves, which determines yield based on water availability (Figure 1)(Belcher et al., 2004). The water sufficiency curves for each crop inform the actual yield in combination with the max yield converter. Maximum yield is constant for each crop and each simulation year.

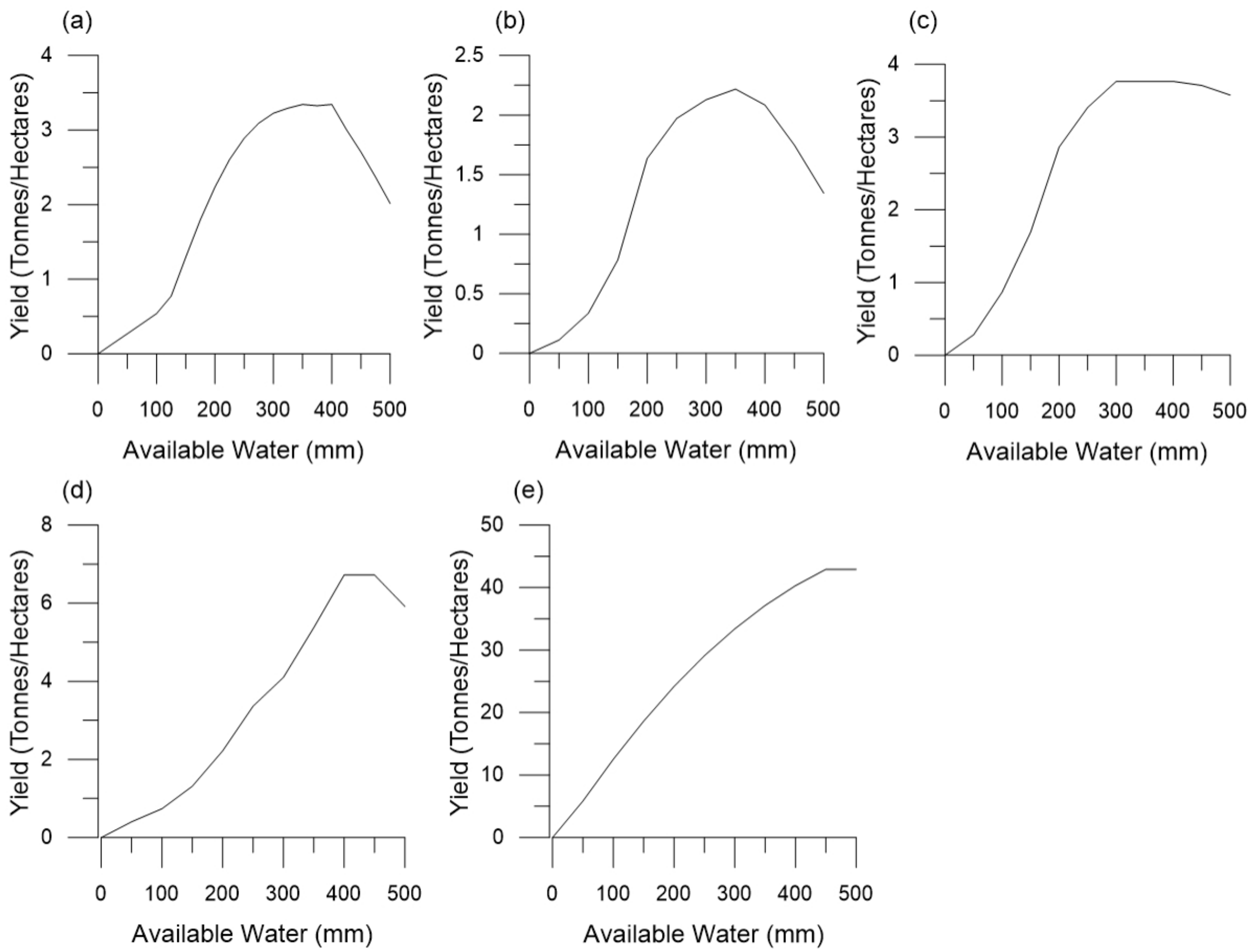

Fig. 1 Water sufficiency curves for (a) wheat (b) canola (c) barley and (d) alfalfa and (e) potato

The equation for $ActualYield_{Crop}$ is:

$$ActualYield_{Crop} = Max\ Yield * Water\ Sufficiency\ Curve * 10{,}000 \qquad (10)$$

which provides the actual yield for each crop in tonnes/m^2. The $ActualYield_{Crop}$ converter then creates a feedback to the converter, $Switch_{Crop}$ (refer to Equation 7). Irrigation is triggered when available water drops below the level that provides 80% of optimal yield. $ActualYield_{Crop}$ is also used to estimate landscape level gross revenue. The formula for the $GrossRevenue_{Crop}$ converter is:

$$GrossRevenue_{Crop} = Actual\ Yield * Price * Crop\ Area * Fraction\ Crop\ Area/10{,}000 \qquad (11)$$

Crop prices were assumed to be fixed throughout the simulations and are from the Government of Manitoba estimated crop production costs for 2015 (Government of Manitoba 2015a). Commodity prices for earlier years were not available, thus the 2015 prices were applied to all scenarios. The resultant gross revenue for each crop were used in combination with crop production costs and input costs to determine the net economic revenue under irrigation. A list of parameters used within the model are summarized in Table 1.

Table 1 Parameter values, units, and sources for the system dynamic model.

Parameters	Value	Units	Source
Daily discharge values (inflow)	Daily flow values for April 15th – September 15th each year	m^3/day	MESH (Côté et al., 1998; Kouwen et al., 1993; Mahfouf et al., 2007; Pietroniro et al., 2007; Verseghy 1991; Verseghy et al. 1993)
Initial reservoir volume	Cumulative flow values from March to April 15th each year	m^3	MESH (Côté et al., 1998; Kouwen et al., 1993; Mahfouf et al., 2007; Pietroniro et al., 2007; Verseghy 1991; Verseghy et al. 1993)
Outflow	Equation (2)	m	Established engineering equation for outflow over a rectangular weir
Weir coefficient	0.6	dimensionless	Established engineering value
Length (L)	12	m	Engineering drawings
Height (H)	Equation (3)	m	Established engineering equation
Reservoir elevation	Equation (4)	m	Engineering storage rating curve
Spillway elevation	379.1	m	Engineering drawings
Evaporation	April (0.00182) May (0.00422) June (0.00460) July (0.00454) August (0.00469)	m/day	1981-2010 mean monthly evaporation values converted to daily values at Brandon, MB (Government of Manitoba, 2015)

	September (0.00346)		
Reservoir Area	85,867,480	m^2	ArcGIS
Total crop area	66,976,634	m^2	ArcGIS; (Government of Manitoba 2014b)
Max irrigation abstraction amount	15,000	m^3	calibration
Rain depth	Variable	mm/day	Environment Canada (Government of Canada, 2015b)
Max Yield	Alfalfa (0.000672126) Barley (0.000376588) Canola (0.000224124) Spring Wheat (0.000336063) Potato (0.004)	tonnes/ m^2	Government of Manitoba, 2015a
Crop Prices	Alfalfa (132.28) Barley (173.23) Canola (418.87) Spring Wheat (238.83)	$/tonne	Government of Manitoba, 2015a
Fraction Crop Area	Alfalfa (.11) Barley (.05) Canola (.46) Spring Wheat (.38)	dimensionless	CANSIM
Fraction Crop Area for 2006 Potato	Potato (.05, .20, .30, .50, 1) Alfalfa	dimensionless	CANSIM

Simulation (as crop area allocated to potato increases)	(.11, .06, .033, 0, 0) Canola (.46, .41, .377, .30, 0) Spring Wheat (.38, .33, .29, .30, 0)		