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MARGINAL VALUE OF IRRIGATION WATER USE IN THE SOUTH SASKATCHEWAN RIVER BASIN, CANADA

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ABSTRACT—The allocation of water is part of water management. In order to achieve maximum benefits to society, water should be allocated toward uses that have the highest value, followed, as an alternative, by the next highest level or one with equal value. Such decisions require knowledge of water value at the last unit of use. Within agriculture, irrigation is important. Irrigation water must be allocated to various crops; therefore, producers require knowledge of the marginal value of water among alternative crops. This study estimates marginal value product for irrigation water within the southern areas of the Canadian Prairie Provinces using a crop-response model. Marginal values were estimated under the present and a future climate scenario. Cash crops such as potatoes and dry beans had higher marginal values of water, around \$1,000 per 1,000 m^3. Cereals and oilseed crops lagged behind (close to \$200 per 1,000 m^3). Results show modest increases in marginal value under climate change, compared to the volatility resulting from commodity market price changes seen today.

Key Words: Canada, crops, irrigation water, marginal value, South Saskatchewan River Basin

INTRODUCTION

Water is integral to all economic, social, and environmental processes. Although water is a renewable resource, it must be distributed efficiently, not only because almost all available water in many jurisdictions is allocated, but also because water sources are expected to become scarce due to climate change. For all allocation decisions, decision makers require knowledge of the trade-offs created from reallocating a given quantity of water from one use to another. If economic growth is an important objective of a water management decision, consideration of resulting economic change is important. In other words, decision makers require knowledge of economic consequences that result from not using a certain quantity of water in a given situation. If such valuation is done at the last unit of water used for a given economic activity, values are typically called marginal values.

Knowledge of water's marginal values is very important for both short-term and long-term management of water projects and resources in the region. These values are crucial for allocating water for competing uses. Furthermore, these values may also guide the decision maker in selecting the best adaptation option in situations of water scarcity.

Agricultural producers and agricultural water supply project managers face similar decisions involving the allocation and reallocation of water. At the farm level, irrigation can be applied to many crops and subject to rotational and other agronomic considerations. Knowledge of water's value at the margin (last drop or unit) would be helpful when reallocating a given quantity of water among various crops, particularly when water supplies are limited. Although the economic value of water has been addressed (see Kulshreshtha and Tewari 1991; Groenfeldt 2006; Mueller 1985; ADI Nolan Davis and

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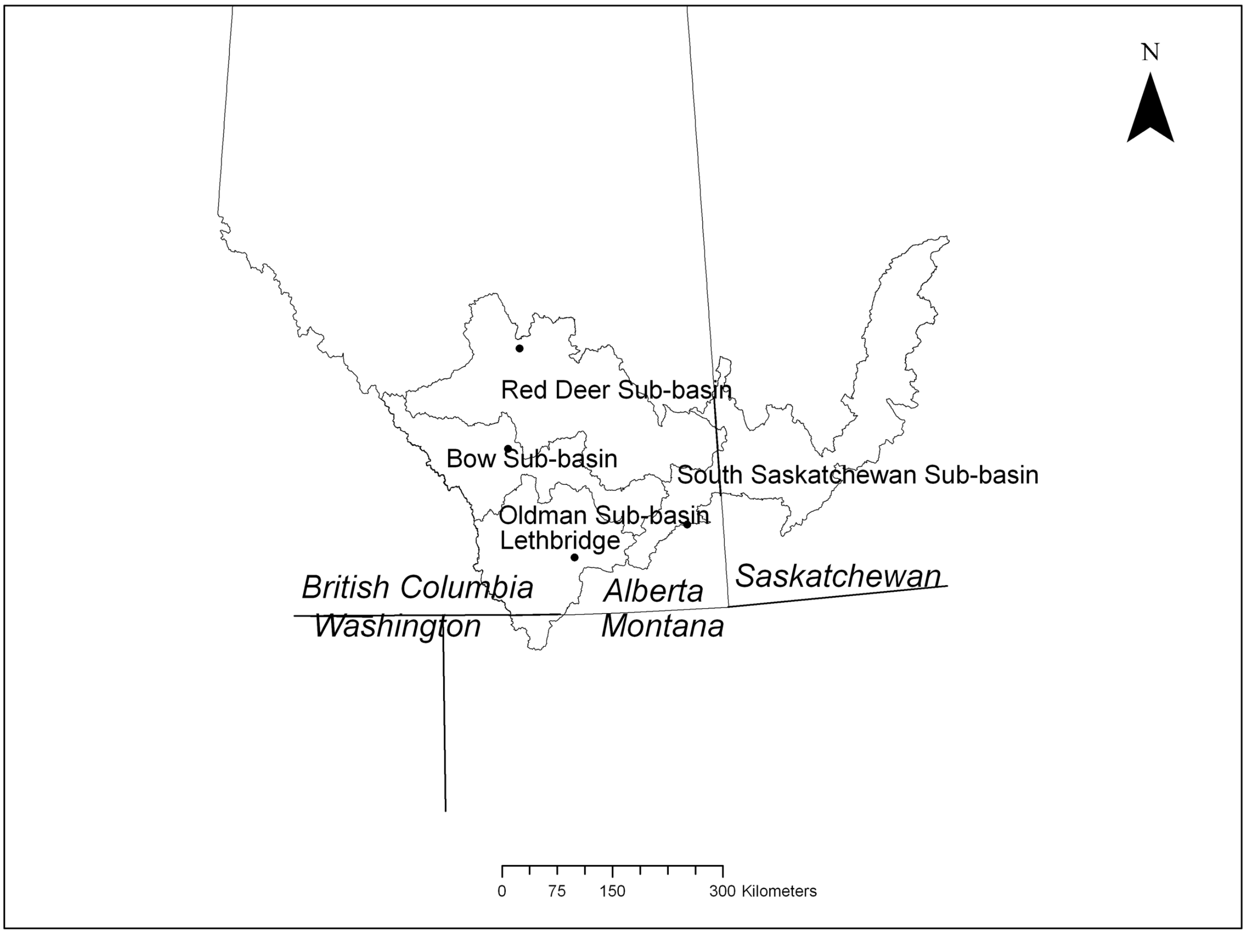

Figure 1. Sub-basins and cities of the South Saskatchewan River Basin.

Gardner Pinfold 1996), these studies have limited the valuation to gain in economic efficiency using the concept of producer surplus. These values are more appropriate for decisions involving development of new irrigation projects in a region. On the other hand, once irrigation is in place, reallocating this water requires knowledge of a different set of values. A more appropriate concept in this context is the marginal value of water, which shows the costs and benefits of reducing the water usage by a small amount to a given crop. The marginal value of water may be useful knowledge in times of water shortages, during periods, for example, of hydrologic droughts in the short run, or of climate change in the long run.

Irrigation is required in the Canadian Prairies, particularly in the provinces of Alberta and Saskatchewan (Fig. 1), where the annual precipitation ranges between 300 and 500 mm (Environment Canada 2004). The largest irrigated area is in the southern portion of Alberta and Saskatchewan. In 2005, Alberta had a total of approximately 537,000 ha (5,366 km^2) of irrigated land, while Saskatchewan had a total of approximately 69,000 ha (686 km^2) of irrigated land (Statistics Canada 2005). Much of Alberta's irrigation is concentrated in the South Saskatchewan River Basin (SSRB), as an estimated 493,000 ha (4,927 km^2) of irrigated lands are within this basin (Sobool and Kulshreshtha 2003). The Saskatchewan portion of the SSRB has an irrigated area of approximately 35,000 ha (350 km^2). Thus, the SSRB contributes more than half the irrigated area in the two provinces.

Agricultural production in Canada consumes water for irrigation (85%) and livestock watering (15%) (Brandes and Ferguson 2004). Agriculture also requires a large quantity of water because of high evapotranspiration (Brandes and Ferguson 2004). Without irrigation, the seasonally drier regions of Canada, including the sub-basins in Figure 1, could not be agriculturally productive. Most irrigation water in the SSRB is obtained as meltwater from the Canadian Rockies. However, supplies of meltwater are expected to be lower under climate change due to receding glaciers in the region from which these rivers originate. In the four sub-basins of Alberta, allocation has already reached a limit. Further irrigation development may be very costly.

The Saskatchewan government has noted the potential to increase irrigation along with efficiency and productivity. Irrigation districts in both Saskatchewan and Alberta, especially the larger ones, have taken measures to promote water conservation and efficient use. These measures include improved scheduling, distribution technologies, and consideration of expansion of storage (among some sectors) (Rush et al. 2004). Alberta's Water for Life strategy is designed to ensure reliable, quality water supplies for a sustainable economy. Institutional reforms being considered include economic instruments, best management practices, and watershed management plans involving local communities to achieve efficiency and productivity of water use while securing social, economic, and environmental outcomes (Sauchyn and Kulshreshtha 2008). The potential for conflict also extends across state borders. For instance, water use in the Oldman River sub-basin has come under scrutiny from the United States (Rush et al. 2004).

By finding the marginal value product of irrigation water use, we attempt in this study to contribute to the information needed to prioritize water use. This study only contributes information on the marginal value of surface water. It is predicted that surface water supply sources, under climate change, will be reduced, thereby creating a situation of increasing water scarcity (Sauchyn and Kulshreshtha 2008).

OBJECTIVES OF THE STUDY

Our major objective in this paper is to estimate the marginal value of surface water in irrigation use in the South Saskatchewan River Basin. Valuation is done on a disaggregated basis for the five various sub-basins within the SSRB. Our second objective is to simulate the marginal value of water in irrigation under the future scenario of climate change, and further, to estimate any changes to the demand for irrigation water use.

Each of the five sub-basins of the SSRB has a different crop mix. Thus, it is conceivable that each sub-basin may have a different marginal value of irrigation water. A spatially disaggregated analysis is therefore preferable to an aggregate one.

Description of the South Saskatchewan River Basin. The SSRB extends from the eastern slopes of the Alberta Rockies in an easterly direction until the South Saskatchewan River joins the North Saskatchewan River in Saskatchewan and drains into the Hudson Bay. The SSRB is a conglomerate of five sub-basins (Fig. 1). Using sub-basin-provincial boundaries, these sub-basins are as follows: The Bow River sub-basin; the Red Deer River sub-basin; the Oldman River sub-basin; the South Saskatchewan River sub-basin (Alberta province); and the South Saskatchewan River sub-basin (Saskatchewan province). The Bow River serves the city of Calgary, which, with a population of over 1 million, is the largest city in Alberta. The Red Deer River serves the city of Red Deer, the Oldman River the city of Lethbridge, and the South Saskatchewan River the city of Medicine Hat. The latter three sub-basins are mainly agricultural, having a demand for irrigation and stock watering. The SSRB is an area that is particularly susceptible to agricultural droughts. Droughts of longer duration have occurred in the past (St. George and Sauchyn 2006). In fact, when John Palliser surveyed the region for inhabitation, he declared it to be totally unfit, partly because of the dry conditions (Lemmen and Dale-Burnett 1999). The region south and east of Red Deer, as seen in Figure 1, could be considered to fall within the triangle.

The SSRB's surface water resources are important from the point of view of sustaining biological, social, and economic activities in the basin, an important region of the Canadian Prairie Provinces because of its share of economic activity (two of those provinces, Alberta and Saskatchewan, are shown in Figure 1, and the third province, Manitoba, which is not shown in Figure 1, lies east of Saskatchewan). In 2001, the Alberta portion of the SSRB had a population of 1,582,981 and the Saskatchewan portion, 324,356 (Sobool and Kulshreshtha 2003). This population residing within the boundaries of the SSRB represents 53.2% and 33.1% of the total populations of Alberta and Saskatchewan, respectively (based on data provided in Statistics Canada 2002). Besides serving the needs for major cities located in it, the SSRB also provides water for mining, manufacturing, and waste assimilation, along with power generation.

Allocation of surface water in the region is administered through two types of institutions: district (or group) irrigation projects, and private irrigation. While the entire allocation or portion of it may actually be withdrawn, only a portion of the withdrawn amount is used, with the rest considered as return flow to the river. For a description of irrigation allocation, withdrawal, use and return flow, see Amec (2007).

In this study, only the value of surface water is estimated. In the Alberta SSRB sub-basins, there are

13 irrigation districts. In the Saskatchewan portion of the SSRB, irrigation is in two regions: the Lake Diefenbaker Development Area (LDDA) and the Southwest Development Area (SWDA). These areas also have a distinctly different type of irrigation in terms of both water delivery and crop mix. In the LDDA, irrigation is organized under irrigation districts, although some private irrigation does exist. Furthermore, farms in this region have both irrigated and dryland areas; however, a wider set of crop choices is available to them on irrigated lands. In the SWDA, irrigation is practiced as a small-plot irrigation system. Forages are the major crops on these irrigated lands. However, much of the information for this sub-basin was poor, which is why this area was excluded from the present analysis. The excluded portion is estimated at 4,500 ha, or only 13% of the total district irrigation area in the SSRB.

STUDY DESIGN

The conceptual framework for this study is presented in two major parts: (1) a description of the marginal value of water under present conditions; and (2) a depiction of the marginal value of water under climate change.

Concept of Marginal Value of Water. Marginal value of water in this study was measured as its marginal value product (MVP). MVP reflects the benefits of applying an additional unit of water to a given crop, and is estimated as the difference between an additional gain in gross revenue through the value of increased yield, and the additional cost of the application of the marginal unit of water to the crop. The additional costs may include a variety of agricultural inputs, such as fertilizer, chemicals, and energy for water application, among others. This additional cost is typically called the marginal cost (MC) of water. The difference between a change in the gross revenue associated with a given quantity of water and a change in the marginal cost results in the marginal value product of water in a given crop (use) at a given location (sub-basin).

Impact of Climate Change on Value of Water in Irrigation. Climate change not only affects water resources but also water demand. In many countries, food security will depend, among other factors, on the impact of climate change on water availability (and its use) for irrigation. According to Doll (2002), two-thirds of the world area equipped for irrigation in 1995 will possibly suffer from increased water requirements. However, other studies have reported different results. For example, Izaurralde et al. (2003) report that in the United States, irrigation demand for corn and alfalfa production under different climate change scenarios and CO_2 fertilization would decline. Conversely, a composite model by Peterson and Keller (1990) predicted a rise in irrigation in part because of decreases in the total area cultivated due to a loss of rainfall, accompanied by warmer climate. In the eastern part of the United States, the same study also predicted an increase in irrigation, accompanied by some decrease in cultivated areas. However, Wayland and Tornil (1999) have shown that the coupled effects of decreases in runoff and increases in irrigation may be devastating to the streams of Illinois and other midwestern states.

The impact of climate change, in its widest sense, on crop water requirements requires us to consider change at three levels. First, we need to take into account impact via changes in local weather, particularly rainfall and evapotranspiration (ET). These impacts would affect soil water balance and hence irrigation needs. These impacts would result in changes in yield and quality, and consequently would affect the economics of growing and irrigating particular crops. Changes in temperature and the occurrence of frost can also alter the geographical area in which each crop can best be grown.

Second, changes in atmospheric CO_2 levels have a direct impact on plant physiology, directly affecting how plants grow and how much water they transpire. Changes in atmospheric CO_2 that directly impact a crop's physiology could be a potentially significant factor in irrigation water demand. Although the impacts of atmospheric CO_2 change are still under dispute, Gallaher (2001) identified a range of impacts as diverse as leaf growth and structure, stomatal resistance, transpiration rates (and hence leaf cooling), transpiration efficiency, photosynthesis, growth-stage durations, root-to-shoot ratios, rooting depth, plant growth, yield, and crop quality. However, most experiments have been carried out within controlled laboratory environments over short periods of time (i.e., as used commercially in glasshouses). Few studies have examined the effect of long-term continuous elevated CO_2 exposure on plant adaptation. Very few studies have simulated field conditions, where wind can be an important factor in determining water use, and where water stress can become a limiting factor (Downing et al. 2003). The literature review suggests that the interactions between the many direct and indirect impacts make modeling difficult and potentially unreliable.

Third, climate change could alter the differences in productivity, in terms of trade among nations, which in turn could alter the extent of crops grown locally (Downing et al. 2003). Fischer et al. (1996) estimates that these changes will be less adverse in mid- to high-latitude regions than in low-latitude regions. Mendelsohn (2003) has also reported that the United States will tend to benefit in every sector from global warming.

Although some studies on irrigation demand that use precipitation (P) and evapotranspiration (ET) have been reported (see Downing et al. 2003), such studies for the Canadian irrigation regions are not available. Furthermore, even fewer studies have addressed the issue of marginal value of water in irrigation. One study that reported such values was Hurd et al. (1988), which was based on the work started by Vaux and Howitt (1984). A report on water valuation by the Food and Agriculture Organization mentions climate change only anecdotally as a driver in the valuation of water (Turner et al. 2004).

Given the nature of linkages between water use and climate change, one can imagine a multitude of impacts. These can be categorized as first-, second-, and third-generation effects. First-generation effects include the direct effects of climate change on water use levels, which in turn affect various water users. Several general circulation models have demonstrated the difficulty of forecasting precipitation change for the larger region encompassing the Canadian Prairies, with some showing increases and others decreases, due to the wide uncertainty associated with projecting precipitation. Barrow and Yew (2005) derived several regional climate models for Alberta (increasing the resolution of global climate models, or GCMs). Among them, the drier models or scenarios show that warming would increase moisture demand among crops and hence irrigation demand. To irrigators, this may translate into altered profitability of irrigated crops and may even lead in some regions to a decision not to irrigate. Cohen (1991) reported an increase of between 83% and 200% in irrigation in the Saskatchewan River sub-basin under various global warming scenarios. The second-generation effects of climate change follow the first-generation effects. Increase in the water needs of various crops may result in higher outlay for water, which may then trigger innovations in water-saving technologies. Some of these water-saving technologies may be capital-intensive. Both higher outlay and greater innovations would have implications for the economics of farming in the region. Livestock production may also require altered feed and water levels under the changed climate, which would translate into change in the relative competitive position of livestock production, particularly in colder and harsher climates. Third-generation effects would be a culmination of the previous two types of impacts. These would be felt more at the aggregate levels, regional or national, and in some cases, at the international level. Adjustments in food supply could also trigger a variety of socioeconomic and political problems. Climate-change mitigation policies adopted by some regions, such as programs promoting crops for biofuels, may change competitiveness or terms of trade among countries. Trade patterns among countries and among regions would likely be altered, which would ultimately affect both the inflation rate and also the balance of payment. Increased use of water would result in increased competition for water, which may lead to greater conflicts among water users regionally and internationally. They are all examples of challenges such models face in this type of analysis.

In any study of the marginal value of water under climate change, these three types of effects need to be taken into account. However, most studies are, according to Hurd et al. (1988), "divorced from that of economic response" and are mere "back of the envelope estimates."

Methodology of Estimating MVP under Current Conditions. Given that the marginal value of water is related to a change in the total value of a product (as measured through gross revenue) associated with various levels of water application, our knowledge of the crop response model, further translated into gross marginal value of production, is central. Under the assumption that producers are price takers, the physical product function can be translated into a total value function by simply multiplying the physical product by the market price.

In arid and semiarid climates, crop water requirements are typically met through two sources: natural precipitation (net amount available to the crop) and supplementary irrigation. The relevant section of a value of production function is shown in the top graph in Figure 2. As water is added to the crop, production will increase until some maximum value of production is reached. Beyond this point, no irrigation needs to be provided. The approximate shape of this function is considered nonlinear in nature, although it is subject to empirical testing.

In order to operationalize the concept of marginal value of water in irrigation in this study, we undertook (1) a disaggregation of the total irrigated cropping extent of the SSRB among its sub-basins; (2) an estimation of crop mix, or crop extent, of individual crop types on irrigated farms among the various sub-basins; and (3) an estimation of irrigation technologies used in various sub-basins. Another task, important since it determines irrigation efficiency and marginal irrigation costs, is (4) an estimation of the change in gross revenue and marginal

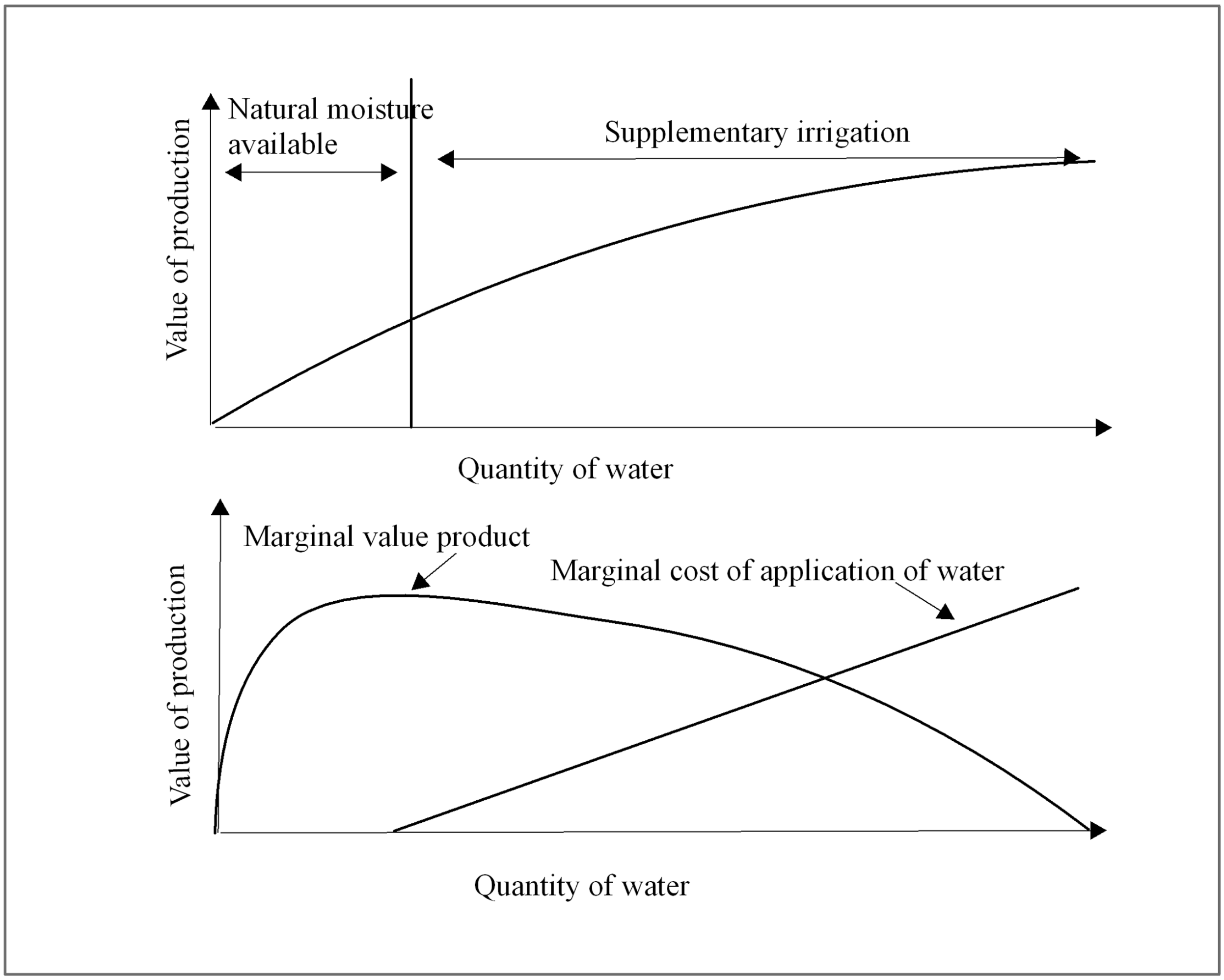

Figure 2. Concept of marginal valve of irrigation water.

cost associated with a marginal unit of water as applied to a given crop in a sub-basin.

In this study, valuation of MVP was undertaken for 10 major crops grown in the SSRB. These crops together made up 82% of total area in the Alberta SSRB sub-basins and 84% of the total area in the LDDA region of Saskatchewan. The crops included alfalfa, barley for grain and for silage, canola, dry beans, tame grass, hard red spring wheat, soft white spring wheat, potatoes, and sugar beets. The selection of these crops was guided by the data available on the relationship between water use and crop yields (water production function).

With this data taken into account, we estimated the MVP as follows: (1) we selected a crop response model relating water application level and crop yield; (2) using this model, we calculated the standard irrigation requirements (to bring soil moisture to field capacity) for various crops; (3) we estimated crop yields associated with standard irrigation requirement and also yields under gradually declining levels of application of water at intervals of 25 mm (one inch); (4) we estimated gross revenue under each successively declining level of irrigation water application; and (5) we estimated marginal irrigation cost and net revenue for each level of irrigation water application.

The production function (a crop-response model) used in this study was based on a review of literature relevant to the Canadian prairies. Only one model (one by Heikkila et al. 2002) was deemed to be applicable to the SSRB; this model demonstrated the relationship between crop yield and climatic variables (translated into ET). Since no models were found for Saskatchewan, it was assumed that the model, when adjusted to local climatic conditions, was applicable to Saskatchewan as well. This model is shown in equation 1:

$$Y_a = K_{ay} . [A_0 + \{A_1 . (ET_a / ET_p)\} + \{A_2 . (ET_a / ET_p)^2\}] . Y_m \quad (1)$$

where Y_a = actual yield from each crop under prevailing water supply conditions (kg/ha), Y_m = maximum yield attainable from each crop where no inputs are limiting (kg/ha), ET_a = actual evapotranspiration (mm), ET_p = potential evapotranspiration (mm), and $K_{ay}, A_0, A_1, and A_2$ are crop-specific coefficients (no units).

In order to estimate the crop yields under different levels of water application, values of above crop-specific parameters (K_{ay}, A_0, A_1, and A_2) were needed. These were obtained from Heikkila et al. (2002).

The first step in determining the marginal value of water is to determine moisture availability by precipitation and irrigation for optimal crop growth. This required climatic data on effective precipitation and reference or potential evapotranspiration (ET_p), and actual evapotranspiration (ET_a) . ET_p is the potential evapotranspiration when moisture is not a constraint, ET_a is the actual evapotranspiration when moisture is constrained and the physiology of the crop adjusts to conserve water. ET_p needs to be multiplied by a crop-specific coefficient and scaling factor to be converted to ET_a. This, along with effective precipitation, is used in reference to a particular crop and location. This means that spring wheat, for example, would have different effective precipitation and ET_a values when grown in different sub-basins and would also differ from those of a barley crop growing next to it on the same sub-basin, because barley will have a different growth period. Historic average, maximum and minimum ET_p, and effective precipitation (along with coefficients and scaling factors to convert to ET_a) were obtained by personal communication with Chinn (Irrigation Branch, Alberta Agriculture, Food, and Rural Development, 2005) and Heikkila et al. (2002) for each crop in the sub-basin. They are summarized in Table 1.

Having gathered all parameters for the crop-response model (equation 1), crop yields and gross revenue were estimated using commodity prices. These prices were mean 10-year nominal crop prices extending over the period 1994-2003, obtained from Saskatchewan Agriculture, Food, and Rural Revitalization (2005) and Alberta Agriculture, Food, and Rural Development (2003). Where sources could not provide historic prices, crop price indices from Statistics Canada were used to adjust crop prices for the same historic period and derive a mean. Yields from irrigation at standard crop water requirement levels are shown in Table 2.

Since estimation of the MVP is the net of any additional costs incurred in connection with application of water, an estimation of these costs was also included. Conceptually, these costs include labor, repair and maintenance, and energy costs. According to Heikkila et al. (2002), these costs differ only by irrigation technology, and not necessarily by crops grown. Once a crop is planted, the only costs that vary by level of irrigation are labor, repair and maintenance, and energy costs associated application of water. These costs are shown in Table 3.

When irrigation was applied across a sub-basin, the marginal cost was estimated by first weighting the costs in Table 3 by the respective proportion of irrigation technologies adopted in the sub-basin, and then multiplying this figure by the incremental change in the volume of irrigation water applied. The respective proportions of irrigation technologies adopted in the sub-basin were obtained from Chinn (pers. comm. 2005). The marginal cost shown in Table 3 was assumed to remain constant across the entire range of water application.

In order to assess the marginal value of water for various crops in a sub-basin of the SSRB, water application was reduced in an incremental fashion by one-hectare inch (or 254 m^3) from the level at which maximum yield is obtained. From this, the cost of water application (discussed above) was netted out. These values were subsequently converted into marginal value of water per thousand cubic meters.

Methodology of Estimating MVP under Climate Change. Although a comprehensive study of marginal value of water should include all three generational impacts of climate change on irrigation water use (as noted above), because of resource limitations, only the first-generation impacts were captured in this study. These impacts were estimated using regional precipitation and evapotranspiration projections for the years 2040-69, which were based on Nyirfa and Harron (2000) using the Canadian Global Circulation Model 1 (CGCM1). Under these projections, the ratio of evapotranspiration in years 2040-69 to the present day (baseline) would be between 1.0573, 1.1780, 1.0257, 1.0932, and 1.13846 for the Oldman River, Bow River, Red Deer River, South Saskatchewan River (Alberta), and South Saskatchewan River (Saskatchewan) sub-basins, respectively. The ratio of projected precipitation to baseline would be between 1.0389, 1.0724, 1.0730, 1.02953, and 1.0709 for the same sub-basins, respectively. When we multiply the ratio of future (2040-69) to present-day evapotranspiration by the present day's effective evapotranspiration we obtain a value for the future effective evapotranspiration. When we multiply the ratio of future to present-day precipitation by the present day's precipitation we obtain a value for the

TABLE 1
BASELINE AND PROJECTED CLIMATIC PARAMETERS (MILLIMETERS/GROWING SEASON)

Particulars	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potatoes	Sugar beets
Bow River Basin—Baseline										
ET_p	896	591	518	635	601	896	635	635	837	721
ET_a	573	344	319	369	297	296	404	404	520	484
Precipitation	259	168	149	178	165	259	178	178	237	206
Bow River Basin—Climate change										
ET_p	1,055	696	611	748	708	1,055	748	748	986	850
ET_a	675	406	376	434	349	348	476	476	613	570
Precipitation	278	180	160	190	177	278	190	190	255	221
Oldman River Basin—Baseline										
ET_p	881	578	505	622	591	880	622	622	821	710
ET_a	563	338	312	362	294	290	398	398	513	479
Precipitation	271	173	159	182	169	182	182	182	251	214
Oldman River Basin—Climate change										
ET_p	932	611	534	658	625	930	658	658	868	750
ET_a	596	357	330	383	311	306	421	421	543	507
Precipitation	282	179	165	189	176	189	189	189	261	223
Red Deer River Basin—Baseline										
ET_p	880	584	513	628	594	880	628	628	824	711
ET_a	565	341	316	365	293	291	400	400	513	476
Precipitation	250	164	143	175	173	250	175	175	230	209
Red Deer River Basin—Climate change										
ET_p	1,061	704	618	757	717	1,061	757	757	994	858
ET_a	681	411	381	440	353	351	482	482	619	574
Precipitation	268	176	154	188	186	268	188	188	247	225
SSRB (Alberta Basin)—Baseline										
ET_p	904	596	521	641	610	904	641	641	845	731
ET_a	579	349	323	374	303	299	411	411	528	492
Precipitation	232	147	134	155	144	232	155	155	211	184
SSRB (Alberta Basin)—Climate change										
ET_p	988	651	570	701	667	989	701	701	924	799
ET_a	633	381	353	409	331	326	449	449	578	538
Precipitation	238	152	138	160	148	239	160	160	217	189
SSRB (Saskatchewan Basin)—Baseline										
ET_p	906	644	570	690	641	973	690	690	912	NA
ET_a	617	369	344	394	312	320	432	432	558	NA
Precipitation	378	204	191	204	207	232	205	210	211	NA
SSRB (Saskatchewan Basin)—Climate change										
ET_p	1,013	668	586	719	682	1,013	719	719	947	NA
ET_a	649	361	361	418	338	334	459	459	591	NA
Precipitation	271	175	157	185	174	247	185	185	249	NA

Sources: Baseline values are from 1928 to 2003, credited to Agriculture Canada's Gridded Prairie Climate Database. Projected values (climate change) are our own calculations using CGCM1 scenarios from Nyirfa and Harron (2002).
Note: NA = not applicable.

TABLE 2
BASELINE CROP YIELDS UNDER STANDARD IRRIGATION REQUIREMENT (TONNES/HA)

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potatoes	Sugar beets
Bow	13.08	5.45	25.16	2.96	2.30	4.25	3.72	5.38	34.43	57.94
Oldman	12.83	5.32	24.54	2.92	2.28	4.20	3.65	5.28	34.12	57.51
Red Deer	12.88	5.38	24.88	2.94	2.25	4.24	3.67	5.31	34.06	57.13
SSRB Alberta	13.21	5.53	25.49	2.99	2.38	4.28	3.78	5.47	35.00	58.85
SSRB Saskatchewan	13.00	4.94	25.02	2.95	2.31	4.24	3.71	5.36	34.41	NA

Note: NA = not applicable.

TABLE 3
MARGINAL COST OF IRRIGATION

System	Labor cost ($/mm/ha)	Repair and maintenance ($/mm/ha)	Energy cost ($/mm/ha)
Sprinkler, hand-move, solid set, or wheel move	0.067	0.057	0.195
Sprinkler, pivot, high pressure	0.022	0.109	0.220
Sprinkler, pivot, low pressure	0.022	0.111	0.160

Source: Heikkila et al. (2002).

TABLE 4
BASELINE MARGINAL VALUE PRODUCT ($/HA/1000 M^3 IRRIGATION WATER)

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potato	Sugar beets
Bow	196	128	111	112	644	160	93	147	1,114	282
Oldman	189	131	114	116	658	169	94	151	1,153	290
Red Deer	185	129	113	114	656	165	94	149	1,141	290
SSRB Alberta	185	129	113	113	662	163	94	149	1,133	286
SSRB Saskatchewan	141	181	118	140	661	159	96	151	1,094	NA

Notes: SSRB Saskatchewan does not have any sugar beet cultivation at the time of analysis; NA = not applicable.

future precipitation. These values are shown in Table 1. Even though five new regional climate projections were made by Barrow and Yu (2005) for Alberta, we did not find any values on projected evapotranspiration in Barrow and Yu's study.

The above data were used to construct parameters for the yield model shown in equation 1, based on the assumption that the marginal value of water would change only as a result of the direct effect of climate change on precipitation and evapotranspiration. Indirect effects such as the change in irrigation efficiency and crop mix were assumed to be negligible. This methodology also ignores the CO_2 fertilization effect, partly because of both inherent uncertainty and intra-year variability in precipitation and evapotranspiration. Similarly, changes to growing period and pest and disease incidence were also excluded. Finally, sensitivity of MVP to change in market prices was simulated by simulating scenarios with the lowest and highest prices for each crop within the last 10 years and comparing them with the baseline and climate change scenarios, both of which use 10-year average prices.

RESULTS: ESTIMATED MARGINAL VALUE OF WATER USED FOR IRRIGATION

Estimated MVP of Irrigation Water under Current Conditions. The estimated values of MVP for various crops and sub-basins are shown in Table 4. The estimated

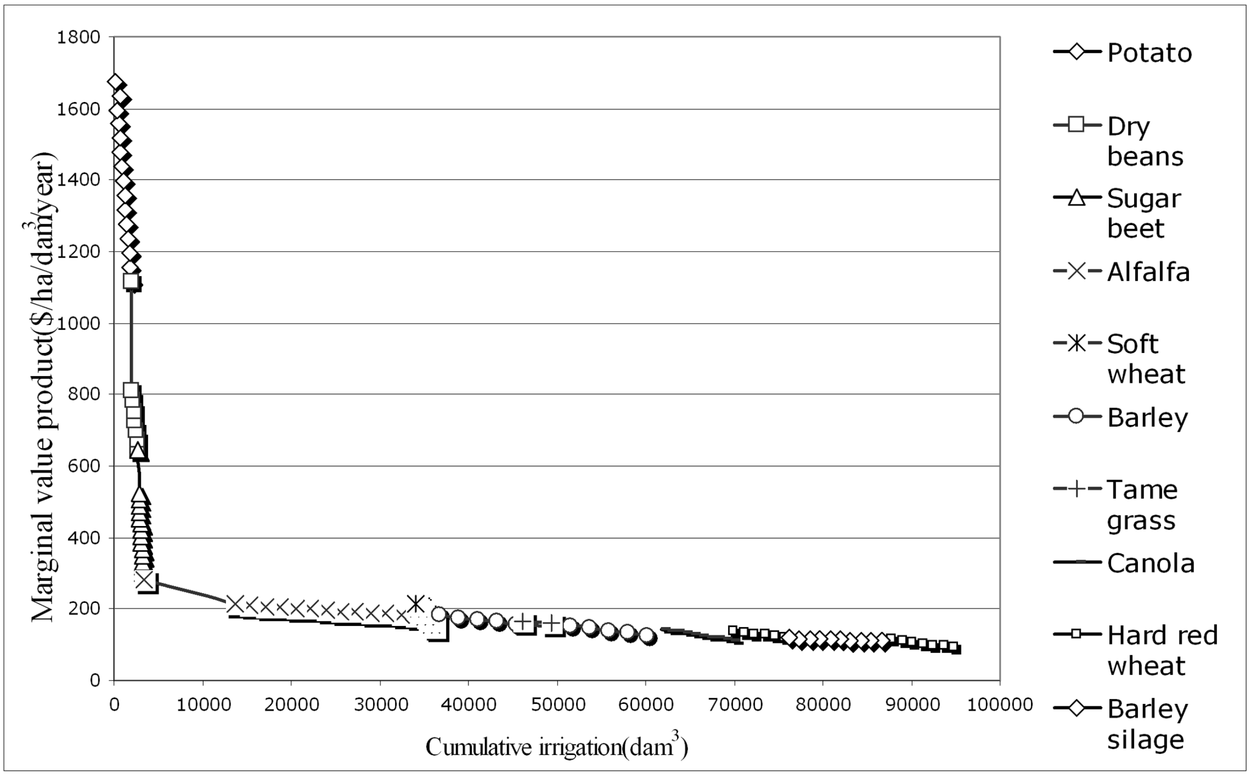

Figure 3. Marginal value of irrigation water, Bow river sub-basin.

values are for the last inch of water applied at standard irrigation requirement (i.e., when soil is at field capacity). Generally speaking, the marginal value of water for specialty crops, such as potatoes, dry beans, and sugar beets, was higher than the values for other, more traditional crops. The three highest MVP values were for potatoes, dry beans, and sugar beets in the order of \$1,100/dam^3, \$700/dam^3 and \$300/dam^3, respectively. Forage such as alfalfa had a relatively higher marginal value than hard red spring wheat but was still lower than the specialty crops. One must note that the value of water for alfalfa is only for forage production. Since reduced forage production may have implications for livestock production, these values may be underestimated. Two striking features of these estimates are (1) marginal values of water in various sub-basins are fairly close, which is to be expected since all changes in yield are based on similar climatic conditions and since irrigation practices are fairly uniform across sub-basins; and (2) the marginal value product of water varies significantly across crops. Cash crops such as potatoes and sugar beets score higher MVP of water than traditional crops.

These values reflect the cost to producers if the water application rate is reduced on account of water shortages, and no other production-related adaptation is undertaken. Again, caution is advised since this a short-run situation and the producers do not have choice of making adaptations.

In order to represent short-run costs of water shortages, we needed to compare the marginal values over the entire range of irrigation application. This entailed reducing the water application in small amounts to the point where no irrigation was provided to that crop. When reducing the water application, the marginal value kept increasing for each crop, which provided us a marginal value curve. It should be noted that the marginal value curve is based on the physiology of crop growth—water demand—and does not convey farmer utility or demand. Crops were then ranked in order by their marginal value of water. After ranking, water demand was estimated by multiplying each crop by their respective extent (in hectares). Marginal values that were ranked were plotted against water demand to derive an irrigation demand curve. Figure 3 shows only the plot for the Bow River sub-basin, but the shape of the plot for other sub-basins was very similar. In most cases, the marginal value order among crops was clearly separable (potatoes first, dry beans second, for example). However, in some cases, an overlap was seen. Such an overlap was noted between barley and tame grass, for example, as seen in Figure 3.

Under water shortages, it appears that hard wheat and barley silage are the crops least preferred for irrigation. However, this reasoning needs to be adjusted if rotational and disease considerations dictate their inclusion in the irrigation priority scheme. The sharp drop after the irrigation of cash crops (i.e., potatoes, dry beans, sugar beets) suggests that the first 5 million m^3 of water for irrigation in the sub-basin has a very high marginal value. Beyond this point, the marginal value of irrigating other crops becomes lower than $200 per ha per 1,000 m^3. This suggests that much of the water shortage impacts production of cereals and oilseed, and perhaps some forages. The latter may not be affected if irrigation farms have beef cattle as well, because these values are for crop production only, and do not consider any forward linkages through cattle production.

Estimated MVP of Irrigation Water under Climate Change. Using the values of greater precipitation and even greater evapotranspiration as provided by the CGCM1 scenarios, the results show a need for irrigation water to meet crops' standard water requirement (Table 5) and higher crop yields as a result shown in Table 6. If we assume today's irrigation equipment efficiencies and present irrigated crop extent, and then multiply the latter by the greater level of water in irrigation withdrawal at standard application, the volume of water withdrawn increases by 1.5 million dam^3. Our assumptions make this an overestimate of what may actually be withdrawn. More realistically, irrigation equipment efficiencies would likely improve to conserve water, while at the same time, less water-consuming crops may be introduced. Furthermore, under climate it is also conceivable that producers may not irrigate to meet the total water deficit for the crop.

Since marginal value product is highly sensitive to assumption regarding future prices, simulations of MVP were made under average, low, and high product prices. The increased crop production did not change the MVP of the last unit of water applied as much as cyclical market prices did. MVP at the last unit of water applied increased for several crops. However, canola, tame grass, potatoes, and sugar beets showed a small decline as the incremental yield from greater ET, with climate change, did not justify the incremental irrigation costs. Tables 7 and 8 illustrate this point. It should be noted that these values are at or near the point of maximum yield, and require larger quantity of irrigation water.

The MVP curve was drawn at gradually declining levels of irrigation applied. Because more water is required after climate change than before to meet the same MVP points along the curve, Figure 4 shows a small schematic shift in the MVP curve, which was produced for the Bow River sub-basin. A rightward shift occurred in the value of water for cash crops (potatoes and sugar beets), as well as for grains and oilseed.

The MVP curve could be interpreted as the measure of the producer water demand curve. The integral of the area below the MVP curve and above a supply curve (marginal cost curve) measures producer surplus. When demand shifts right under climate change, it increases producer welfare from irrigation water use, assuming markets and technology remain unchanged. However, market price changes may have greater impacts on welfare than climate change alone. Although water supply from the SSRB meets current irrigation and municipal needs, future population growth and climate change both increases demand and reduces supply (Martz and Pietroniro 2006). Then irrigation would be discontinued for crops with the smallest MVP, like wheat and barley silage, for example. The remaining higher value crops such as potatoes and dry beans would require more water.

SUMMARY AND CONCLUSIONS

Without water for irrigation in arid and semiarid climates of Saskatchewan and Alberta, much arable land may not be economically viable. Irrigation is almost essential, particularly in light of the region's frequent droughts. In order to ensure efficient water allocation, one needs to understand the economic value of water at the margin.

Although several researchers have addressed the economic value of water, they have limited the valuation to gain in economic efficiency using the concept of producer surplus. These values are more appropriate for decisions involving development of new irrigation projects in a region. On the other hand, once irrigation is in place, reallocating this water requires knowledge of a different set of values. Knowledge of water's value at the margin (last drop or unit) would be helpful when reallocating a given quantity of water among various crops, particularly when water supplies are limited.

In the four sub-basins of Alberta, allocation has already reached a limit. Further irrigation development may be very costly. The Saskatchewan government has noted the potential to increase irrigation along with efficiency and productivity. Irrigation districts, especially

TABLE 5
IRRIGATION REQUIREMENT (MM) UNDER BASELINE AND CLIMATE CHANGE SCENARIOS

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potatoes	Sugar beets
Bow										
Baseline	478	256	258	291	184	55	329	329	397	390
Climate change	604	327	328	371	242	107	415	415	503	490
Oldman										
Baseline	417	228	219	257	169	154	298	298	355	358
Climate change	449	245	236	277	183	167	319	319	382	384
Red Deer										
Baseline	463	249	254	279	164	60	317	317	388	366
Climate change	607	331	334	370	229	121	415	415	510	479
SSRB Alberta										
Baseline	510	284	279	323	218	98	360	360	436	423
Climate change	580	324	317	367	251	129	408	408	495	478
SSRB Saskatchewan										
Baseline	452	220	244	278	191	89	329	329	409	NA
Climate change	539	266	292	333	233	124	391	391	488	NA

Note: NA = not applicable.

TABLE 6
CROP YIELDS (TONNES/KM^2)

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potato	Sugar beets
Bow										
Baseline	1,308	545	2,516	296	230	425	372	538	3,443	5,794
Climate change	1,541	649	3,012	331	289	453	441	639	3,873	6,541
Oldman										
Baseline	1,283	532	2,454	292	228	420	365	528	3,412	5,751
Climate change	1,361	567	2,611	304	249	431	388	562	3,579	6,031
Red Deer										
Baseline	1,288	538	2,488	294	225	424	367	531	3,406	5,713
Climate change	1,555	657	3,055	334	292	457	447	646	3,901	6,566
SSRB Alberta										
Baseline	1,321	553	2,549	299	238	428	378	547	3,500	5,885
Climate change	1,448	610	2,813	318	271	444	416	602	3,749	6,310
SSRB Saskatchewan										
Baseline	1,300	494	2,502	295	231	424	371	536	3,441	NA
Climate change	1,484	569	2,887	323	278	448	426	616	3,799	NA

Note: NA = not applicable.

TABLE 7

MARGINAL VALUE PRODUCT UNDER IRRIGATION ($/1000 M^3)

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potato	Sugar beets
Bow										
Baseline	196	128	111	112	644	160	93	147	1,114	282
Climate change	181	129	113	105	686	142	93	148	1,060	268
Low price	158	99	86	74	497	106	63	104	990	254
High price	234	174	135	140	869	266	127	197	1,222	322
Oldman										
Baseline	189	131	114	116	658	169	94	151	1,153	290
Climate change	189	131	115	115	669	166	95	151	1,149	288
Low price	151	101	87	76	507	111	64	106	1,025	261
High price	227	179	140	147	888	282	130	203	1,265	331
Red Deer										
Baseline	185	129	113	114	656	165	94	149	1,141	290
Climate change	185	131	115	106	705	144	95	150	1,079	273
Low price	148	101	87	75	506	109	64	106	1,014	261
High price	221	177	138	144	885	275	129	201	1,252	332
SSRB Alberta										
Baseline	185	129	113	113	662	163	94	149	1,133	286
Climate change	186	131	114	109	689	153	94	150	1,108	279
Low price	149	101	87	74	510	107	64	106	1,006	257
High price	222	177	138	142	893	271	129	200	1,242	327
SSRB Saskatchewan										
Baseline	141	181	118	140	661	159	96	151	1,094	NA
Climate change	146	190	118	136	669	154	94	149	1,059	NA
Low price	109	112	90	98	510	104	65	108	972	NA
High price	171	258	144	175	891	266	131	203	1,200	NA

Note: NA = not applicable.

TABLE 8

DIRECTION OF CHANGE IN MARGINAL VALUE PRODUCT BY CROP AND SUB-BASIN DUE TO CLIMATE CHANGE ($/1000 M^3)

Sub-Basin	Alfalfa	Barley	Barley silage	Canola	Dry beans	Tame grass	Hard red spring wheat	Soft white spring wheat	Potatoes	Sugar beets
Bow	-15	+1	+2	-7	+42	-18	0	+1	-54	-14
Oldman	0	0	+1	-1	+11	-3	+1	0	-4	-2
Red Deer	0	+2	+2	-8	+49	-21	+1	+1	-62	-17
SSRB Alberta	+1	+2	+1	-4	+27	-10	0	+1	-25	-7
SSRB Saskatchewan	+5	+9	+0	-7	+8	-5	-2	-2	-35	NA

Notes: Plus (+) symbolizes increase in marginal value product as a result of climate change; minus (-) symbolizes a decrease in marginal value product as a result of climate change; zero (0) symbolizes no change; NA = not applicable.

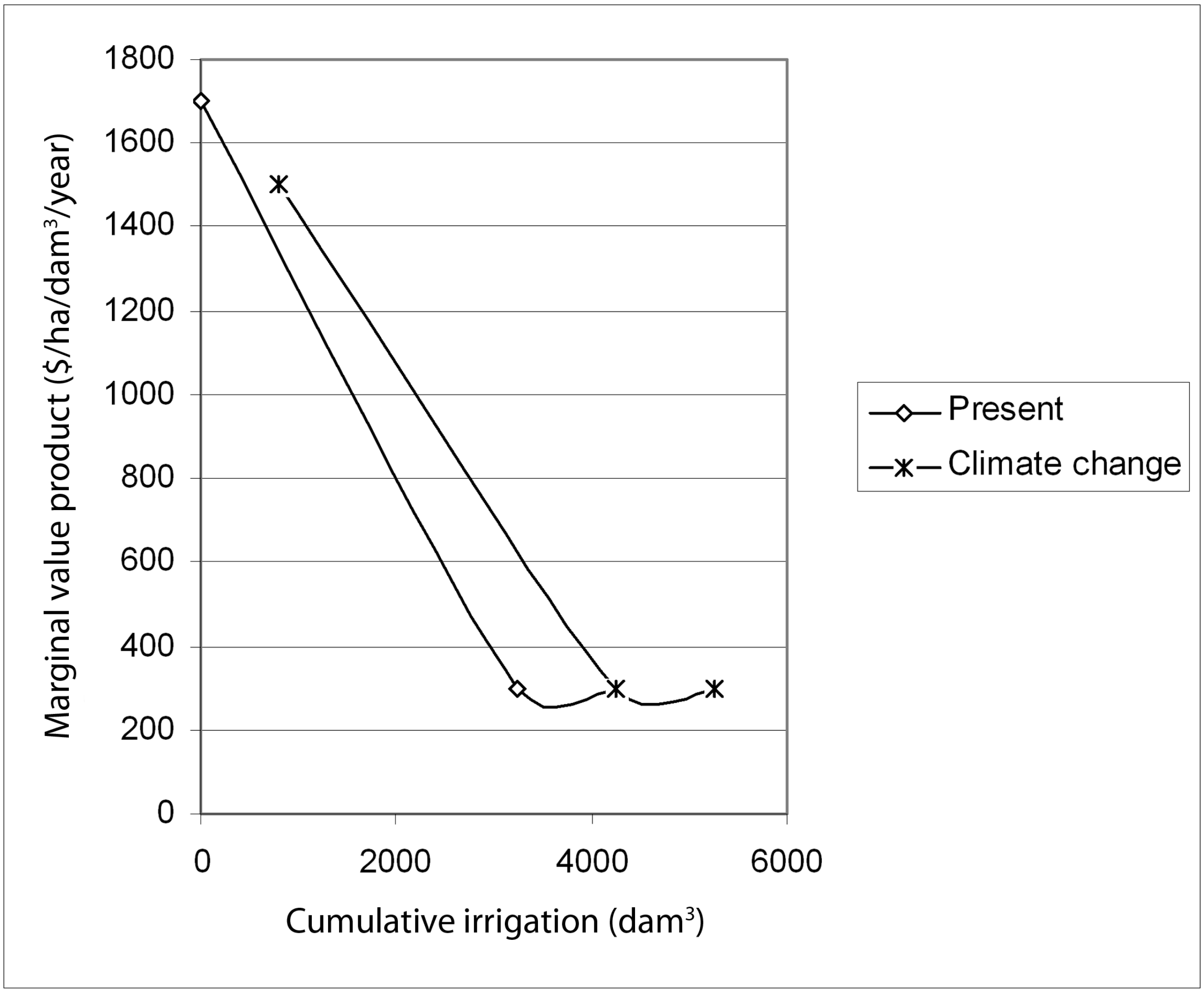

Figure 4. Bow River sub-basin.

the larger ones, in both Saskatchewan and Alberta are considering institutional reform and policies to promote water conservation and efficient use.

The objective of this paper was to estimate such marginal value of water for various crops in the SSRB for the present and future under a climate change scenario. Over and above costs incurred associated with that unit of water, the marginal value product (MVP) of water measures the contribution made by a small quantity of water when applied to a given crop in successive units. In this study these values were estimated for the South Saskatchewan River Basin in the southwestern part of the Canadian Prairies. This basin, which extends over Alberta and Saskatchewan, is the major region for economic activity and population concentration. Under the hypothesis that these values were not uniform for the entire basin, the MVP values were estimated for each of the five sub-basins within the SSRB. However, the result did not support this hypothesis, as most values were found to be very close. Still, these values varied significantly across crops. Cash crops, such as potatoes, dry beans, and sugar beets, scored the higher MVP of water. For these crops, irrigation is highly desirable from an economic point of view. At the same time, one should also note that crops such as potatoes can be also be grown under dryland conditions. In order to represent short-run costs of water shortages, estimates were made of the entire range of water application by small intervals. Many similarities were seen in all regions. Under water shortages, hard wheat and barley silage are not the preferred crops for irrigation, unless rotational and disease considerations dictate their inclusion in the irrigation production system. In all five sub-basins, the marginal value of water fairly soon becomes lower than \$200 per hectare per 1,000 m^3. The above values are not very different from those reported by Madariaga and McConnell (1984), who found that the marginal value of irrigation water was between \$622 and \$2,789 per 1,000 m^3; their results were price-indexed to 2005 Canadian dollar values.

The first-generation effects of climate change would be greater demand for irrigation water and an increase in crop production yields. These result in a small rightward shift in the MVP. This shift in MVP due to climate change is modest compared to cyclical market price fluctuations. Market impacts were modeled as the sensitivity of MVP to the lowest and highest commodity prices seen in the last 10 years. Under climate change, estimated water withdrawal may increase by 1.5 million dam^3. This estimate is 2.6 times greater than Martz and Pietroniro's (2006) estimate under medium population growth. Our value could be an upper bound, because we assume that irrigation meets the full standard water requirement, with no improvement in water-conserving irrigation technologies and with no adoption of water-conserving crops.

The MVP curve is a measure of the producer water-demand curve. Each irrigation district is typically allocated a limit on the volume of water, which they do not exceed. The water-supply curve is therefore constant within the allocated limit of water; it is, in other words, elastic. Although the water supply for the SSRB meets current irrigation and municipal needs, future population growth and climate change would increase demands and reduce supply. Irrigation could be curtailed for crops with the smallest MVP, such as wheat and barley silage, while higher-value crops would require more water. Assumptions of a change in second- and third-generation effects of climate change (improvement in irrigation efficiency, greater retention of winter precipitation, changes in the productivity of Canadian agriculture relative to the rest of the world, changes in global price for our crops, as well as changes in crop mix) have not been accounted for in the analysis. An estimation of these effects is left for future studies in this area.

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