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# **Implications of Current and Alternative Water Allocation Policies in the Bow River Sub Basin of Southern Alberta**

by

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## Abstract

In this study, economic implications of allocating surface water with the existing policy (seniority rule) and three other alternative (People First, proportional reduction, and trading) policies are investigated to address potential water scarcities in the Bow River Sub Basin (BRSB) of Southern Alberta using a mathematical programming model. The model used an improved calibration technique and 2008 data for three irrigation and three non-irrigation sector users in the BRSB. Results indicate that while the seniority rule favours senior license holding irrigation users and the People First policy favors municipal sector users, irrigation users are better off with the proportional allocation policy even though it affects all users across-the-board. Moreover, if the users can participate in a costless trade, then non-irrigation users tend to buy water as they place high value of water at the margin. Some irrigation users find selling water more profitable than utilizing their allocations for crop production.

**Keywords:** positive mathematical programming, allocative efficiency, seniority rule, proportional allocation, trading.

JEL classification: C61, Q15, Q25.

## 1. Introduction

Surface water in three of the four sub basins in the South Saskatchewan River Basin of Southern Alberta has been fully or over allocated and are closed for new allocations (AMEC, 2009, p1). In those closed sub basins, which includes the Bow River Sub Basin (BRSB), new users can get water only through savings and reallocation of water among the existing users. In this backdrop, growing demands for water from population, economy and environmental needs and potential scarcity in future supply have prompted the Government of Alberta to declare *Water for Life* strategy in 2003, under which an ambitious goal is set to improve conservation, efficiency and productivity of water use in the province by 30% between 2005 and 2015 (Alberta Environment, 2003). To achieve this goal, the Conservation, Efficiency and Productivity (CEP) Project team has identified seven major water using sectors in the province (irrigation, oil & gas, mining/oil sands, power generation, municipality use, chemical & petrochemical, and forestry), where major improvements can lead to substantial water savings (Alberta Water Council, 2008). For example, a recent estimate by Alberta Irrigation Projects Association (2010) shows that a

4.6% improvement in the efficiency of water use in the irrigation sector alone could save enough water to meet the annual demand of all municipalities in the South Saskatchewan River Basin. It is also believed that allocative efficiency of water use can be improved through voluntary transfer and trading of water within and between sectors.

Historically, water allocation system in Alberta has been governed by a priority rights principle called, ‘first-in-time, first-in-right’ (FITFIR), (Government of Alberta, 2010). It is also popularly known as the ‘seniority’ rule since it entails priority access to the allocations of senior license holders during shortage years regardless of the purpose of use – the implication being that junior license holders might be denied access to water in such shortage years. Some irrigation districts in Southern Alberta hold the most senior organizational large scale water allocation licenses while municipalities, industries, commercial units, and other users usually hold junior licenses.

A recent alternative suggestion is to reduce allocations proportionally to all users during shortage years instead of the current seniority based allocations (Droitsch and Robinson, 2009). In this report, Recommendation 3 states, “. . . water licences should be converted to water ‘shares’ that entitle the holder to a portion of the water available for diversion in each time period. While water licences currently provide the right to withdraw a fixed volume of water, a water share would provide the right to withdraw a percentage of water available on a seasonal basis up to a specified maximum volume limit” (p. 23). Proportional sharing strategy has been practiced in other jurisdictions such as in Colorado, Mexico, Chile, and Australia with varying degree of success. A more detailed account of the operational definitions of proportional allocation system and its applications in other parts of the world could be found in He et al. (2012).

In a joint declaration, the thirteen irrigation districts in Southern Alberta that manage bulk of the surface water have recently proposed another allocation system dubbed as the ‘People First’ policy to ensure water availability for municipalities during acute shortage years. Specifically the press release states, “Alberta's thirteen irrigation districts approved a declaration ensuring that in times of drought in Southern Alberta, human and livestock needs will be met before those of irrigated agriculture (News Wire, 2011, March 22)”. This declaration is an attempt to mitigate fears that people and livestock operations might be denied water during severe drought years as municipalities generally possess junior licenses with lower priority than the irrigation water licenses in Alberta. Unlike the proportional shortage sharing system, this declaration therefore tries to address the potential water shortage problem through voluntary cooperation keeping the historical priority licensing system in force.

This study focuses on comparing and contrasting economic implications of the current water allocation policy (FITFIR or ‘seniority’ rule) in the Bow River Sub-Basin (BRSB) of Southern Alberta against the two proposed alternative allocation mechanisms described above (proportional shortage sharing and ‘People First’) through the application of a positive mathematical programming model. The results are further contrasted against the outcomes of a short-term seasonal trading policy that allows users to buy or sell water for the irrigation season depending on their marginal value of water. Economic benefits of these four different policies are investigated for three potential water shortage scenarios.

A review of the computational models available for analyzing water allocation issues in general and for Southern Alberta in particular is provided in Section 2. Specific model used in this study is presented in Section 3 followed by a description of the study area and data in Section 4. Results and discussions are in Sections 5 and 6 respectively.

## **2. Water allocation models**

A comprehensive review of models available for analyzing water allocation policies in Southern Alberta and other parts of the world could be found in He et al. (2012). The models reviewed in that study include both physical allocation models as well as economic optimization models. Physical allocation models are not particularly relevant for the present study and therefore are not repeated here.

Past studies that used economic optimization models of water allocation policies in Southern Alberta include Horbulyk and Lo (1998), Mahan et al. (2002), He and Horbulyk (2010), and He et al. (2012) among others. The earlier two studies employed sub-basin scale models to analyze allocative efficiency gains from within and across sub-basin transfers of water among users in the four sub-basins (Red Deer River, Bow River, Oldman River, and South Saskatchewan River) of the South Saskatchewan River Basin (SSRB). The study by Mahan et al. (2002) expanded the scope and coverage of the earlier study by Horbulyk and Lo (1998) by adding six different water user groups including a detail irrigation sector sub-model of six major crops produced in the region. Results from trading of water showed a 3% efficiency gain for the water surplus season, 6% for an average flow season, and 15% for a drought season.

The latter two studies used irrigation district scale models to analyze the impact on agricultural producers' surpluses of alternative water allocation and pricing policies for moderate to severe water shortage scenarios in the Bow River Sub-Basin (BRSB) of Southern Alberta. The study by He and Horbulyk (2010) specifically investigated water pricing and short-term trading policies as a substitute for the existing first-in-time, first-in-right (FITFIR) based water allocation policy while the study by He et al. (2012) investigated three mechanisms of proportional shortage sharing policies in comparison to the FITFIR and short-term trading policies for three

irrigation districts (Western Irrigation District (WID), Eastern Irrigation District (EID), and Bow River Irrigation District (BRID)) in the BRSB. Both studies used a mathematical programming model with positive mathematical programming (PMP) calibration technique introduced by Howitt (1995a, 1995b) which involves estimating a non-linear (quadratic) cost function from the dual values of the calibration constraints in order to maximize a modified non-linear objective function subject to a set of physical, economic, and regulatory constraints.

Of course, there have been many other economic optimization models in other jurisdictions to achieve different objectives. Two large scale models – California Value Integrated Network (CALVIN) model by Draper et al. (2003) and California water resource simulation (CALSIM) model by California Department of Water Resources (2002) – have been used to analyze a range of economic issues in California. Booker and Young (1991, 1994) developed an economic-hydrologic optimization model for Colorado to analyze within and between state trading of water for 14 different user groups. Chakravorty and Umetsu (2003) developed a spatial model to analyze the optimal allocation of surface and groundwater for the Western regions of the U.S. Vaux and Howitt (1984) developed a regional trade model to predict that water scarcity in California could be addressed with a regional water transfer mechanism. None of these U.S. based models has direct methodological relevance to the PMP calibration based models that have been used to address water policy issues in Southern Alberta.

However, over the past decade, another set of European studies has made further improvement to the standard PMP calibration technique of Howitt (1995b, 2005) adopted in the computational models used for water allocation issues in Southern Alberta (Paris and Arfini, 2000; Röhm and Dabbert, 2003; Iglesias and Blanco, 2008; Blanco et al., 2008; Cortignani and Severini, 2009; Judez et al., 2011). These improvements centered around a couple of stylized

weaknesses of the Howitt's standard PMP calibration technique. First, when a crop is produced with two different irrigation technologies or two varieties of a crop are produced with the same irrigation technology, they are treated as 'different' activities by the standard PMP, which may lead to unsatisfactory estimates of the cost functions used to modify the objective function. Assuming that the elasticity of substitution between variants of the same crop would be higher than between two crops, Röhm and Dabbert (2003) proposed addition of an extra slope parameter to the cost function to represent each variant of the same crop. To recover the extra parameter, an extra calibration constraint on all varieties of the same crop is added to the model.

Second, by design, the calibration constraint in the standard PMP technique ties up the model chosen activity levels to their perturbed base year values. If some crops or activities are not produced in the base year (observed values are zero) growing conditions, they have no chance to emerge (become profitable) in the simulations of different growing conditions when markets or policies change. Cortignani and Severini (2009) addressed this problem by adding another linear parameter to the modified cost function proposed by Röhm and Dabbert (2003) to represent the additional marginal costs of the newly emerged activities. This additional parameter is then recovered by introducing an additive perturbation constant (a very small positive number) to the two calibration constraints, which requires hard to come by data on costs and yields of the unobserved crops or activities from experimental field trials or from other regions.

Following the methodology of Paris and Arfini (2000), Iglesias and Blanco (2008) and Blanco et al. (2008) suggested a 'wide-scope' PMP calibration technique that is applicable to a wide range of approaches aimed at addressing the issue of unobserved base year activities discussed above. For a sub-regional model, this method involves specifying a non-linear



(quadratic) cost-function (and the corresponding average cost-function) for the least-cost sub-region and then adding an additional parameter for the other sub-regions to represent the additional costs in those regions. To recover these parameters, two calibration constraints are needed – one for the total land allocated to the activity and another for the land allocated to the activity in each sub-region. The advantage of this method over the Röhm and Dabbert (2003) approach is that it does not require any additional data from outside as it is always possible to identify the lowest-cost area from the observed data.

Below we describe the structure and composition of the specific model used in the present study by utilizing the methodological insights learned from the literature review above.

### **3. Specific model in this study**

Our approach in this study is to adopt the already existing economic optimization models in Southern Alberta by taking advantage of the methodological advancements of the PMP calibration technique proposed by some of the European studies above. Specifically, our model in this study builds upon the modeling structure of the most recent studies (He and Horbulyk, 2010; He et al., 2012), but adapts and improves them in four aspects. First, we augment the scope of the analysis by incorporating water demands from the non-irrigation sectors (municipal, industrial, and commercial sector demands) so that the augmented model can inform on allocative efficiency gains through between (and within) sector water trading under different allocation policies and water shortage scenarios. Second, we adopt an improved calibration technique known as the ‘wide-scope PMP’ method suggested by Iglesias and Blanco (2008) and Blanco et al. (2008) to ensure that unobserved base-year activities have the chance to emerge in the simulations of potential water shortage scenarios. Third, we include one new water allocation strategy, the 'People First' policy, in addition to the two previously studied policies (FITFIR and

proportional allocation). Fourth, we improve model results by using a more recent (2008) crop production and evapotranspiration data of all major crops produced in Southern Alberta. The present model thus addresses the implications of the *Water for Life* strategy through the gains from between and within sector allocations in a more comprehensive manner than before since the non-irrigation sector users compete for the same surface water sources as the irrigation districts do for crop production.

Mathematically, the objective of the specific model in this study is to maximize a net benefit (NB) or surplus function which is composed of two distinct parts as shown in Equation (1). The first part in the first square bracket represents a producers' surplus or net return function for the irrigation sector. It is specified as the producers' total revenues minus total costs resulting from a very detail crop production sub-model. The choice variable for the irrigation sector is the water demand resulting from the areas (measured in hectares) cultivated  $A_{d,x,l,m}$  in three irrigation districts  $d$  ( $d = \text{WID, EID, BRID}$ ) with 32 crops  $x$  ( $x = 1, 2, \dots, 32$ ; 21 irrigated and 11 dryland) on three types of land  $l$  ( $l = \text{irrigated, non-irrigated, and land with no irrigation infrastructure}$ ; the latter two types are referred to as 'dryland' in the text) by eight irrigation methods  $m$  ( $m = \text{gravity-developed-controlled, gravity-developed-no control, gravity-undeveloped, micro drip-trickle, sprinkler-linear-high pressure, sprinkler-linear-low pressure, sprinkler-hand move, and sprinkler-volume gun}$ ). Total revenue is calculated by multiplying the hectares cultivated  $A_{d,x,l,m}$  by the tonnes per hectare yield ( $Y_{d,x,l}$ ) and 2008 Canadian dollar (C\$) per tonne crop price ( $V_x$ ). Total cost is calculated by multiplying the hectares cultivated  $A_{d,x,l,m}$  by the C\$ per hectare input costs ( $c_{i,x,l}$ ) of nine inputs ( $i = \text{seed, fertilizer, chemicals, insurance, fuel, machinery, pumping, labor, and other inputs}$ ).

$$\text{Max}_{\{A_{d,x,l,m}, Q_u\}} \text{NB} = \left[ \sum_{d,x,l,m} A_{d,x,l,m} Y_{d,x,l} V_x - \sum_{i,d,x,l,m} c_{i,x,l} A_{d,x,l,m} \right] + \left[ \sum_u \left( \int_0^{Q_u} a e^{-Q_u/b} dQ_u - c Q_u \right) \right] \quad (1)$$

The second part in the second square bracket represents a consumers' surplus or net benefit function for the three non-irrigation sector users  $u$  ( $u$  = City of Calgary, Shell Canada, University of Calgary). It is specified as the consumers' total benefit from water usage evaluated by the integral measuring the area under the aggregate inverse water demand curve<sup>1</sup> ( $P = a e^{-Q/b}$ ,  $a \geq 0$ ) up to the quantity of water  $Q$  demanded minus the total supply cost of water assuming a constant marginal cost of supply ( $c$ ) that includes both treatment and distribution costs. The choice variable for the non-irrigation sector users is the aggregate water demand ( $Q_u$ ) except for the municipality sector for which the model chooses water usage per capita per day ( $\text{m}^3/\text{c}/\text{d}$ ). It is then multiplied by the city population to determine the aggregate water demand ( $Q_u$ ) for the municipal users. For all non-irrigation users, the base model is validated for aggregate water demand for 153 days (May to September), not for the entire year, to maintain comparability with the seasonal demand in the irrigation sector.

Equation (1) above is maximized by choosing  $A_{d,x,l,m}$  (which provides water demand for irrigation users) and  $Q_u$  (which provides water demand for non-irrigation users) subject to a set of physical, economic, and regulatory constraints. Equation (2) specifies a land constraint to ensure that total land chosen by the model for each irrigation district and by land types stays within the observed land limits.

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<sup>1</sup> A power function ( $P = a e^{-Q/b}$ ,  $a \geq 0$ ) is chosen to approximate the aggregate demand curve for the non-irrigation users as it allows finite estimate of the total benefits as the integral  $\int_0^Q a e^{-Q/b} dQ$  is bounded by the price axis (quantity falls to zero if price is high enough). Another advantage is that the two parameters  $a$  and  $b$  can be uniquely estimated if only one price-quantity data point ( $P$ ,  $Q$ ) and the price elasticity of demand ( $\epsilon = (\partial Q/Q)/(\partial P/P)$ ) are known (Diaz et al. 2000). Other alternatives such as a constant elasticity function ( $P = (a/Q)^{1/\epsilon}$ , which is the inverse of  $Q = a P^{-\epsilon}$ ,  $a > 0$ ,  $P \neq 0$ ) is undefined at zero prices, does not intersect either axis, and therefore evaluation of the integral could be very sensitive at both extremes of price and quantity, while a linear function requires more information about the elasticity of demand ( $\epsilon$ ) as the demand is elastic for the upper half of a linear demand curve and inelastic for the lower half.

$$\sum_{x,m} A_{d,x,l,m} \leq \sum_m \bar{L}_{d,l,m}, \quad \forall_{d,l} \quad (2)$$

Equation (3) calculates how much water is required ( $Q_U$ ) for all users (a capital  $U$  subscript is used on the left hand side to indicate all users – irrigation districts ( $d$ ) and non-irrigation users ( $u$ )). The amount of water needed for crop production in each irrigation district is calculated as the product of crop evapotranspiration ( $ET_{d,x,m}$ ) and the crop areas chosen ( $A_{d,x,l,m}$ ) by the model. This amount plus the water needed by the non-irrigation users determines the total requirement.

$$Q_U = \sum_{x,m} ET_{d,x,m} A_{d,x,l,m} + Q_u \quad (3)$$

$$Q_U \leq W_U - \sum_{UU} T_{U,UU} + \sum_{UU} T_{UU,U} - SL_U - Ret_U + Rainfall_U \quad (4)$$

Equation (4) balances the requirements calculated in Eq. (3) against how much water is available. The right hand side of this constraint specifies total availability from diversion ( $W_U$ ) adjusted for return flow volumes ( $Ret_U$ ) plus the amounts received as rainfall net of system loss ( $SL_U$ ) due to seepage, percolation, distribution etc. and the traded volumes ( $T_{U,UU}$ ; negative sign indicating a sale, positive sign a purchase). The  $UU$  subscript is used to indicate another element or user in the set  $U$ , i.e., it is just an alias of set  $U$ .

$$W_U + \sum_{UU} T_{U,UU} \leq WR_{UU} \quad (5)$$

Equation (5) is a regulatory constraint which specifies that users' diverted amount ( $W_U$ ) along with the purchased volume, if any, cannot exceed the maximum water designated by their licensed water rights ( $WR_{UU}$ ).

$$\sum_d A_{d,x,l,m} \leq \sum_d \bar{A}_{d,x,l,m} (1 + \varepsilon_1) \quad [\mu_{x,l,m}], \quad \forall_{x,l,m} \quad (6)$$

$$A_{d,x,l,m} \leq \bar{A}_{d,x,l,m}(1 + \varepsilon_2) \quad [\gamma_{d,x,l,m}] \quad (7)$$

Following Howitt (1995b, 2005), Iglesias and Blanco (2008) and Blanco et al. (2008), equations (6) and (7) are specified to implement the ‘wide scope - positive mathematical programming’ (WS-PMP) calibration of the irrigation sector component to ensure that unobserved base year activities have the chance to emerge in the simulation runs of anticipated shortage scenarios. As noted earlier,  $A_{d,x,l,m}$  is the model chosen crop areas. It’s under-bar variant on the right hand side indicates observed areas;  $\varepsilon_1$  and  $\varepsilon_2$  are two very small positive numbers ( $\varepsilon_1 < \varepsilon_2$ ) required for perturbation by the WS-PMP calibration technique;  $\mu_{x,l,m}$  represent the marginal values corresponding to the total activities in all irrigation districts combined and  $\gamma_{d,x,l,m}$  represent the marginal values corresponding to the district specific activity levels. These marginal or shadow values are used to estimate a non-linear (quadratic) cost function for each activity including those that are not observed in the base year. This is accomplished in two steps: first, a general quadratic cost function in the form of Eq. (8) is postulated,

$$C_{d,x,l,m} = \alpha_{x,l}A_{d,x,l,m} + \frac{1}{2}\beta_{x,l,m}A_{d,x,l,m}^2 + \delta_{d,x,l,m}A_{d,x,l,m} \quad (8)$$

where,  $\delta_{d,x,l,m} = 0$  for the least-cost irrigation district (or sub-region) implying that producers incur some additional costs for growing the same crop with the same irrigation technology in all other irrigation districts except for the least-cost district. Second, parameters of Eq. (8) are recovered using the marginal values from the two calibration constraints Eqs. (6) and (7) as follows:  $\beta_{x,l,m} = \mu_{x,l,m} / \sum_d \bar{A}_{d,x,l,m}^*$ , and  $\delta_{d,x,l,m} = \gamma_{d,x,l,m} + \mu_{x,l,m} \left(1 - \frac{\bar{A}_{d,x,l,m}}{\sum_d \bar{A}_{d,x,l,m}^*}\right)$ , where  $\bar{A}_{d,x,l,m}^*$  indicates the observed area in the least-cost district or sub-region (see Blanco et al., 2008, p9). The other parameter,  $\alpha_{x,l}$  is equal to the average cost parameter shown in the objective function, i.e.,  $\alpha_{x,l} = \sum_i c_{i,x,l}$ .

For the non-irrigation component of the model, only the standard PMP calibration suggested by Howitt (1995b, 2005) is sufficient to retrieve a non-linear cost function as there is no such unobserved activity in the base year. It is accomplished by specifying just one calibration constraint, Eq. (9) as below.

$$Q_u \leq \bar{Q}_u (1 + \varepsilon_3) \quad [\theta_u] \quad (9)$$

where, the under-bar variable on the right hand side indicates the observed aggregate quantity of water in the base year,  $\varepsilon_3$  is another small positive number required for PMP calibration and  $\theta_u$  represent the marginal or shadow values of this constraint. A simpler version of the quadratic cost function is postulated in the form,  $C_u = \varphi_u Q_u + \frac{1}{2} \lambda_u Q_u^2$ . The parameters are recovered as,  $\lambda_u = \theta_u / \bar{Q}_u$ , and  $\varphi_u$  is equal to the constant marginal (also average) cost  $c$  in the second part of the objective function (Eq.(1)). As before, the under-bar variable indicates the observed value of the choice variable  $Q_u$ .

With the substitution of the parameters in the two cost functions, the calibrated objective function takes the following form,

$$\begin{aligned} \text{Max}_{\{A_{d,x,l,m}, Q_u\}} \text{NB} = & \left[ \sum_{d,x,l,m} A_{d,x,l,m} Y_{d,x,l} V_x - \sum_{i,d,x,l,m} c_{i,x,l} A_{d,x,l,m} - \frac{1}{2} \sum_{d,x,l,m} \beta_{x,m} A_{d,x,l,m}^2 - \sum_{d,x,l,m} \delta_{d,x,l,m} A_{d,x,l,m} \right] \\ & + \left[ \sum_u \left( \int_0^{Q_u} a e^{-Q_u/b} dQ_u - c Q_u \right) - \frac{1}{2} \sum_u \lambda_u Q_u^2 \right] \end{aligned} \quad (10)$$

This substitution makes the three calibration constraints Eqs. (6), (7), and (9) redundant. The calibrated objective function (Eq. (10)) is then maximized subject to the remaining constraints Eqs. (2)-(5) with the help of GAMS (general algebraic modeling system) software (Brooke et al., 1998).

#### 4. Study area and data

The model is implemented on the three irrigation sector users (WID, EID, and BRID) and three non-irrigation users (City of Calgary, Shell Canada, and University of Calgary) in the Bow River Sub-Basin (BRSB) of Southern Alberta which constitutes the watershed area of the Bow River and its adjoining tributaries (Figure 1). These six users account for bulk of the water in the BRSB as indicated in the pie chart of Figure 1. The BRSB is a semi-arid region with limited precipitation (regional mean is 250 mm year) occurring mostly during May to September. Major source of the surface water in the Bow River and its tributaries is the snowmelt from the Bow Glacier in the Rocky Mountains of Canada. The Bow River is about 587 kilometer long, flows southeast criss-crossing through the foothills, the city of Calgary, and on to the prairies before draining to the South Saskatchewan River. All three irrigation districts are located downstream, east of Calgary. The Bow River is a major source of irrigation, commercial, and industrial needs in Southern Alberta and it is also an important source of drinking water for over a million people of the city of Calgary. The city of Calgary is licensed to divert about 460 million m<sup>3</sup> of water per year while the three irrigation districts are licensed to divert about 1,700 million m<sup>3</sup> of water per year from the Bow River, adjacent lakes and reservoirs to service about 217,000 hectares of irrigated land (roughly 9% by WID, 52% by EID, and 39% by BRID in 2008)<sup>2</sup>. Commercial and industrial users divert only a small fraction of the irrigation and municipality diversions.

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<sup>2</sup> In Southern Alberta, irrigation is mostly (85%) provided through 13 organized irrigation districts and the rest (15%) through small private irrigation projects. Irrigation districts hold organizational large scale water diversion licenses for thousands of water users while private irrigators hold individual small scale water diversion licenses issued by the Alberta Environment. Farmers within the command area of an irrigation district obtain water from the district's conveyance and storage system by paying a one-time capital asset fee plus annual water operation and maintenance fees. Private irrigators do not obtain water from irrigation districts, rather they obtain water directly from the surface water sources (rivers and tributaries) and pay only a one-time license fee to the Alberta Environment (AAF, 2008).

Major crops produced in this region include grains (barley, wheat and cereals), forages (alfalfa, barley silage, hay and tame pasture), oilseeds (canola, soyola, flax and mustard) and specialty crops (potatoes, vegetables, sugar beets, dry peas, dry beans, and confection crops) – mostly irrigated but some rain fed as well. Table 1 provides a few select characteristics of these crops in the three irrigation districts for the 2008 growing season. Note that some crop names represent a single crop (e.g., potatoes and sugar beets) while others represent a group of crops of the same category (e.g., alfalfa includes both two- and three-cut alfalfa hay, and vegetables include carrots, fresh peas and chickpeas). Large variations exist in the percentage of land allocated for different crops across districts. For example, the EID has the highest percentage of land (50%) under forage crops followed by WID (41%) and BRID (22%), while a reverse land allocation pattern is seen for grain crops – BRID has the highest (44%) followed by WID (33%) and EID (29%). The BRID also has the highest percentage of land (17%) under specialty crops, followed by EID (7%) and WID (2%). These are the highest value crops as seen from the last two columns of Table 1. Percentage of land for oilseed crops is the highest in WID (21%) followed by BRID (17%) and EID (14%). All of these data are compiled from AARD (2009).

Dominant method of irrigation in Southern Alberta is the pivot sprinkler system – high and low pressure (69.7%) followed by wheel move – sprinkler and volume gun (17%) and gravity (12.5%) as of 2008 (AARD, 2009, p5). Pivot sprinkler systems are also the most efficient (77%), followed by wheel move (69%) and gravity method (52%) as per AECOM (2009). Only the percentage under pivot irrigation is shown in Table 1, but all other irrigation technologies enter the optimization model. Annual average crop evapotranspiration (ET) estimates for 2008 crop systems in Southern Alberta – weighted by the areas under different irrigation method are also shown separately for each irrigation districts in Table 1. The ET values are non-zero for



each crop, but the zero values in the table appeared due to the weighting by zero cropped areas for some crops not grown in 2008. These estimates were provided by Robert Riewe (2010), a staff member of the AARD, Lethbridge Research Station, through personal e-mail correspondence.

Tables 2 and 3 provide additional information on input data used in the optimization model. Table 2 shows water allocations among all users by their historical license priority dates under the existing (FITFIR or seniority rule) and alternative allocation policies (People First and proportional reduction) for three potential water shortage scenarios (20%, 30%, and 40% from the base year 2008 diversions). The license priority dates and water allocation figures are gathered from the Alberta Environment's (2008) online license viewer system. The diversion figures for irrigation districts are compiled from AARD (2009), while the diversions for the city of Calgary were obtained from Werner Herrera (2011) of Alberta Environment (Southern Region) and the diversions for Shell Canada and University of Calgary were compiled from the Alberta Environment's Water Use Reporting System (WURS) database provided by Janet Yan (2011) of Alberta Environment (Northern Region) through personal e-mail correspondences. Unlike the irrigation sector data, actual diversions of the non-irrigation sector users are never published and difficult to come by. The selection of the three non-agricultural users was primarily driven by the availability of their actual water diversion data over the period from 2003 to 2008. These past allocation data were needed to determine the allocations under the proportional reduction strategy based on the users' past five-year (2003-07) average diversions (PropP5Y, for short)<sup>3</sup>. To maintain comparability with the irrigation users' diversions, the non-

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<sup>3</sup> A proportional reduction strategy can be defined in many ways. As mentioned in the text, we base the reductions from the users' past five-year diversions to smooth out fluctuations in annual diversions. He et al. (2012) used two other definitions – one based on the users' previous year's diversion and the other based on their licensed allocations.

irrigation users' diversions in Table 2 are shown for 153 days only (May to September), not for the entire year.

The bottom-half of Table 2 illustrates how the allocations under the existing (FITFIR or seniority rule) and the alternative allocation strategies (People First and PropP5Y) could be calculated for 20%, 30%, and 40% potential shortage scenarios. For example, if the predicted shortage is 20% from the base year (2008) total of 992.8 million m<sup>3</sup>, that is the total availability is 794.2 million m<sup>3</sup> ( $992.8 \times 0.8 = 794.24$ ) or a short fall of 198.6 million m<sup>3</sup>, then according to the existing seniority rule, University of Calgary and Shell Canada will receive no water at all, city of Calgary's water will be restricted to 5.55 million m<sup>3</sup> and BRID's water will be restricted to 178.86 million m<sup>3</sup> as these users possess junior licenses. With these cuts, the shortfall of 198.6 million m<sup>3</sup> is mitigated so that the two senior licensees (EID and WID) are able to divert the same amount of water in the 20% shortage scenario as they diverted in the base year. Notice that the city of Calgary's allocation remains steady at 5.55 million m<sup>3</sup> even for the most severe shortage (40%) scenario. This is because that 5.55 million m<sup>3</sup> was designated by its most senior license dated back to 1895. Also notice that even though the WID and EID have the same license dates (September 04, 1903), WID's license is deemed senior as it has the earliest priority sequence number (01). Therefore, even if there is a 40% shortage, WID's full allocation will remain secured and protected while EID will take the necessary cut. In other words, hierarchy of the licence priority dates are preserved and respected in determining the allocations under the seniority rule.

Under the 'People First' policy, as discussed in Section 1, human and livestock needs are protected so that the same total 794.2 million m<sup>3</sup> will be allocated differently with this policy. The municipal sector users, only the city of Calgary in this study, will get full base year

allocation of 85.59 million m<sup>3</sup>, and the shortfall will be mitigated by the other junior licensees (no water for University of Calgary and Shell Canada, and a restricted amount of 98.82 million m<sup>3</sup> for BRID). In this case, hierarchy of the license priority dates still maintained except the highest priority is temporarily assigned to the needs of the municipal sector users.

A yet another allocation pattern emerges if the shortfall is mitigated in proportion to the users' average diversions in the past five years (2003-07) regardless of their licence priorities. For example, the WID's average diversion in the past five years is 124.01 million m<sup>3</sup>, which is  $124.01/970.5 = 0.1278$  or 12.78 percent of the total. Now, if WID has to share the 20% reduced total with other users, then its allocation will be  $0.1278 \times 794.2 = 101.49$  million m<sup>3</sup> under the proportional allocation strategy (PropP5Y). All other users' allocations could be calculated in the same manner. The process is repeated to calculate the allocations for 30% and 40% shortage scenarios. All allocation values in Table 2 are then entered the optimization model to estimate their marginal or shadow values, and the resulting cropped areas, crop mixes, net surpluses, etc.

Table 3 shows the data used to estimate the parameters of the inverse demand and cost functions which are then utilized to estimate the consumers' surplus for the non-irrigation sector users. Water price is taken from the city of Calgary's web-site. Price elasticity of demand for municipal, industrial and commercial water usage for various years and cities in Canada are taken from Renzetti (1992a, 1992b, 1993) and Tate et al. (1992). Production and distribution costs for municipal water are taken from Mahan (1997, p102) and the same costs are applied to commercial and industrial users due to unavailability of sector specific water supply costs.

## **5. Results**

The initial model was validated with the base year 2008 data to ensure that model outputs in terms of cropped areas, total land under each district, water demands for irrigation and non-

irrigation users, etc. match the corresponding inputs available for 2008. This model was then calibrated and used for simulating three potential water shortage scenarios for four different allocation policies. Results are presented in several sub sections below.

### 5.1. *New activities*

Table 4 shows a sample of activities (cropped areas) that were not observed in the base year (2008) but emerged in several water shortage simulation runs. On average, about 30 new activities emerged for each policy when different water shortage scenarios were simulated. These results attest the validity of the wide-scope PMP calibration implemented in this study.

### 5.2. *Water allocations*

Table 5 shows water demands and marginal values for the four-policy (including Trading) simulations under the three potential water shortage scenarios. Water demands in this table refer to the same allocations calculated in Table 2 except for the ‘Trading’ policy, for which the demands are determined by the optimization model when users engage in a costless trading of water in the model. Marginal values (or shadow prices) and net surpluses shown in Table 5 are also determined by the optimization model – non-zero marginal values results from the binding constraints, i.e., when (pre-trade) allocations determined by a policy falls short of the users' base year values and zero marginal values results if there is no shortfall. These marginal values represent users' willingness to pay (WTP) for an additional cubic meter of water when trading is not allowed (i.e., when the two terms  $\sum_{UU} T_{U,UU}$  and  $\sum_{UU} T_{UU,U}$  in Eq. (4) are set to zero). As expected, the non-irrigation users exhibit higher WTP compared to the irrigation users. Municipal users (city of Calgary) seem to have the highest marginal value of water followed by the industrial users (Shell Canada) and commercial users (University of Calgary) under allocations by the seniority rule as these users are most disadvantaged by this policy. Within the

irrigation sector, the BRID shows the highest marginal value of water as it possesses the most junior licenses and consequently gets the biggest cut during water shortage years under seniority rule and People First policies.

Water allocations under trading policy result when users are allowed to trade water in the model (Eq. (4) is fully activated) starting with their (initial or pre-trade) allocations established by any of the three policies above. Regardless of the starting allocations, the model converges to the same optimal allocations of water and marginal value (trading price) for any given shortage scenario. Conceptually, when trading is allowed, high value users gain through purchases and low value users gain through sales of water until the market reaches to an equilibrium trading price. At that price, there is no further incentive for users to engage in further trading as there is no further economic gains from trading to be exploited. That is all economic gains are captured from reallocation of water across users and the value of the objective function reached its unrestricted maximum. With regard to the equilibrium marginal values, the model shows that if there were 20% shortage in the BRSB, water would be traded at 3.3 Canadian cents per cubic meter. More scarcity would lead to higher market price – a 6.7 cents/m<sup>3</sup> would be expected in a 30% shortage scenario and an 8.1 cents/m<sup>3</sup> would be expected in a more severe 40% shortage scenario.

### 5.3. *Water trading*

Table 6 provides a summary of the results on trading activity – how much water would be traded and who would buy or sell. Negative numbers in this table indicate sales (corresponding to the term  $-\sum_{UU} T_{U,UU}$  in Eq.(4)) and positive numbers indicate purchases (corresponding to the term  $+\sum_{UU} T_{UU,U}$  in Eq.(4)). Analytically, the numbers represent the difference between the water demands for the trading policy and the (initial or pre-trade) water demands established by

any of the other three policies as shown in Table 5. For example, for the 20% shortage scenario case, WID is entitled to divert 104.85 million m<sup>3</sup> under the existing (seniority rule) allocation policy. However, most of its water remains unutilized. The model determines that WID can maximize its net returns or surpluses by using only 20.20 million m<sup>3</sup> for its production activities and selling the balance 84.65 million m<sup>3</sup> at 3.3 cents/m<sup>3</sup> to other users. This sale as well as other sales is indicated with negative signs in Table 6 while the purchases are indicated with positive signs.

Clearly, WID and EID are the major sellers while BRID and other non-irrigation users are the major buyers. However, EID also buys some water under the proportional allocation system as it suffers bigger cuts under this system. On the other hand, the city of Calgary sells some small volumes under the People First policy as its entire volume is protected by that policy. Shell Canada and University of Calgary buy water in all scenarios as they have the most junior licenses – but they are relatively better off under the proportional allocation policy as they have to buy smaller volumes under this policy.

#### *5.4. Cropping patterns*

Tables 7 and 8 provide a summary of the total irrigated land and cropping pattern under the seniority rule and how they would have changed under the alternative allocation policies. The last column in Table 7 shows that with the same total amount of water, more land could be irrigated if the water were allocated differently by a proportional reduction method or by allowing trading than with the existing allocation (seniority) method. This is due to the fact that large volumes of water held by senior licensees remain underutilized when allocation is determined with the seniority rule. However, district specific results show that this overall trend applies to the BRID only, WID and EID show the opposite trend. This is not surprising as from

Table 5, we have seen that WID and EID have surplus water and are better off by selling it rather than using it for irrigation purposes while BRID has shortage and is willing to pay high price for extra water. In fact, for 40% water shortage scenario, BRID does not get any water at all under the seniority rule. From Table 7, we see that it still has 277 hectares of land under irrigated crops. This is partly due to some fallow land and some rain fed vegetable crops in the BRID. The huge percentage increase in the irrigated land for the allocations by proportional and trading policies is simply due to the very small denominator (277 hectares) from which the changes are calculated.

Table 8 shows the land-use pattern of a broad group of crops – cereals (barley, wheat, and other grain crops), forages (alfalfa, barley silage, fallow, hay and pasture), specialty crops (alfalfa seeds, dry beans, dry peas, confection crops, essential oils, potatoes, sugar beets, vegetables and other crops), and oilseeds (canola, hyola and flax) under the seniority rule and the change that would have been resulted if the water were allocated following the three alternative policies. A very clear pattern is observed for low value crop – forages – more land is allocated for forages under seniority based allocation than under any of the three alternative policies. Cereal crops show similar pattern for less severe (20%) water shortage scenario but the pattern is reversed as the severity of shortage increases. On the other hand, land allocated for high value crops (specialty crops and oilseeds) show significantly increasing trend for the proportional and trading policies – most increasing trend is noticed for oilseeds for the 20% to 30% shortage scenarios. But for the 40% shortage scenario, most increasing trend is noticed for the most valuable specialty crops.

### *5.5. Economic gains*

The value of the objective function measuring the net returns or benefits are presented in Table 9 for all users together as well as for the six individual users. As discussed in Section 3,

these values represent the producers' surplus for the irrigation users and consumers' surplus for the non-irrigation users. The last column of Table 9 shows that among the first three policies, the existing allocation policy (seniority rule) provides the lowest basin-wide aggregate net benefits. Net gains for the 'People First' and proportional allocation policies are very similar and about 80% higher than the net gains of the allocations based on the existing policy. However, as expected, the largest basin-wide net surplus is achieved when users are allowed to trade water in a costless way to capture additional economic gains from reallocation of water from the low value applications to the high value applications. The maximized net economic gains for trading policy are found to be \$222 million for 20%, \$217 million for 30%, and \$210 million for 40% water shortage scenario. Relative to the existing (seniority rule) allocation policy, these net surpluses are 88%, 103%, and 126% higher for the 20%, 30%, and 40% water shortage scenarios respectively.

The disaggregate results in Table 9 show who are the winners and who are the losers with the alternative policies vs. the status quo. Users with most senior licenses are usually better off with the existing allocation policy while users with the most junior licenses are better off with proportional allocation or trading policies. The People First policy is designed to favor the municipal users – so the city of Calgary is the most beneficiary with this policy at the cost of other junior licensees. Since BRID has the most junior licenses among the three irrigation districts, it benefits the most with the proportional and trading policies. The city of Calgary also benefits from trade as it has the highest marginal value of water. Consumers' surpluses for Shell Canada and University of Calgary are zero for the allocations based on the seniority rule and People First policy as these two users do not receive any water under these two policies (see



Tables 2 and 5). These two users also benefit the most with the proportional allocation and trading policy.

## **6. Discussion**

Economic implications of allocating water following the existing (FITFIR or seniority rule) and three other alternative (People First, proportional reduction, and trading) strategies during scarcity in the BRSB of Southern Alberta have been investigated in this study through a mathematical programming model. The model expands and improves upon the existing irrigation district scale mathematical programming models (He and Horbulyk, 2010; He et al., 2012) to address water allocation issues in Southern Alberta in several ways: (i) it incorporates water demands from previously missing non-irrigation sectors (municipal, industrial, and commercial sector demands) so that the present model can inform on allocative efficiency gains through between (and within) sector reallocation of water through trading; (ii) it adopts an improved calibration technique known as the ‘wide-scope PMP’ method suggested by Iglesias and Blanco (2008) and Blanco et al. (2008) to ensure that unobserved base-year activities have the chance to emerge in the simulation of water shortage scenarios; and (iii) it improves model results by updating the crop production and evapotranspiration data (for 2008) of 21 irrigated crop/crop groups in Southern Alberta. The present model is thus better equipped to address the issue of potential allocative efficiency improvements from between and within sector reallocations of water – a core strategy of achieving the goals of Alberta’s *Water for Life* policy.

Even though it is expected that allocations based on the existing (seniority based) policy will be favoured by the senior licensees (mostly irrigation districts) and allocations based on the People First policy will be favoured by the municipal users, similar statements cannot be made in advance for allocations based on the proportional reduction strategy or if the users have a chance

to participate in a costless trade of water during shortage years. Empirical results from this model help us reflect on this issue. Specifically, model results indicate that large scale users are the most affected with the proportional allocation policy even though it affects all users across-the-board. However, irrigation users are relatively better-off with this policy as an alternative to the seniority based allocations during drought years as it affords them more irrigation opportunity with the same amount of water leading to higher net returns. Further, if users can participate in a costless trade, a completely different allocation profile develops across users in which cities and commercial users tend to buy as they have much higher marginal values of water than the irrigation users. In such idealistic market setting, some irrigation users find it more profitable to engage in temporary sale (short-term trade) of their water to the non-irrigation users rather than utilizing it for crop production activities. However, it should be acknowledged that this is the only way non-irrigation users can have some water to keep their water economies alive during scarcity as the existing policy is likely to deny or severely restrict their allocations.

Regarding land use and cropping patterns, model results show that proportional allocation policy has the highest irrigation expansion potentials among all four policies considered in this study. This expansion is likely to occur in favour of the high value crops such as oilseeds and specialty crops from the low value forage crops produced more heavily under the existing allocation policy. In case of a severe shortage scenario, proportional and trading policies also increase allocations for cereal crops compared to the seniority based allocations. Overall, compared to the seniority-based allocations, economic gains are the highest under seasonal trading, followed by the proportional shortage sharing and People First policy. Allocations based on the existing policy yield the lowest aggregate economic returns for all three shortage scenarios considered in this study.

A key contribution of this research is the incorporation of the water demands from the non-irrigation sectors alongside the irrigation sector in the modeling framework as they all compete for the same aggregate pool of water. This has been repeatedly identified by the previous studies as one major areas of future research. However, these sectors' representation in the model could be further improved with better accessibility and reliability of their water diversion data. Consideration of storage water would be another area of future research as some irrigation districts have access to the water stored in lakes and reservoirs to mitigate shortages. Also, even though the proportional allocation policy appears to be more equitable and economically viable alternative to the seniority based allocation policy during scarcity, its implementation is likely to face tremendous opposition from the irrigation districts as they have contributed over the years toward the improvement of irrigation infrastructure solely for the security and protection of water afforded by the historic license priorities. A very strong political will to change the historic licensing system, public support, and institutional shake-up would be necessary to implement the proportional allocation policy. Alternatively, keeping the FITFIR system unchanged, institutional and regulatory adjustments could be made to promote low-cost trading during shortage years. But it has significantly different welfare distribution implications.

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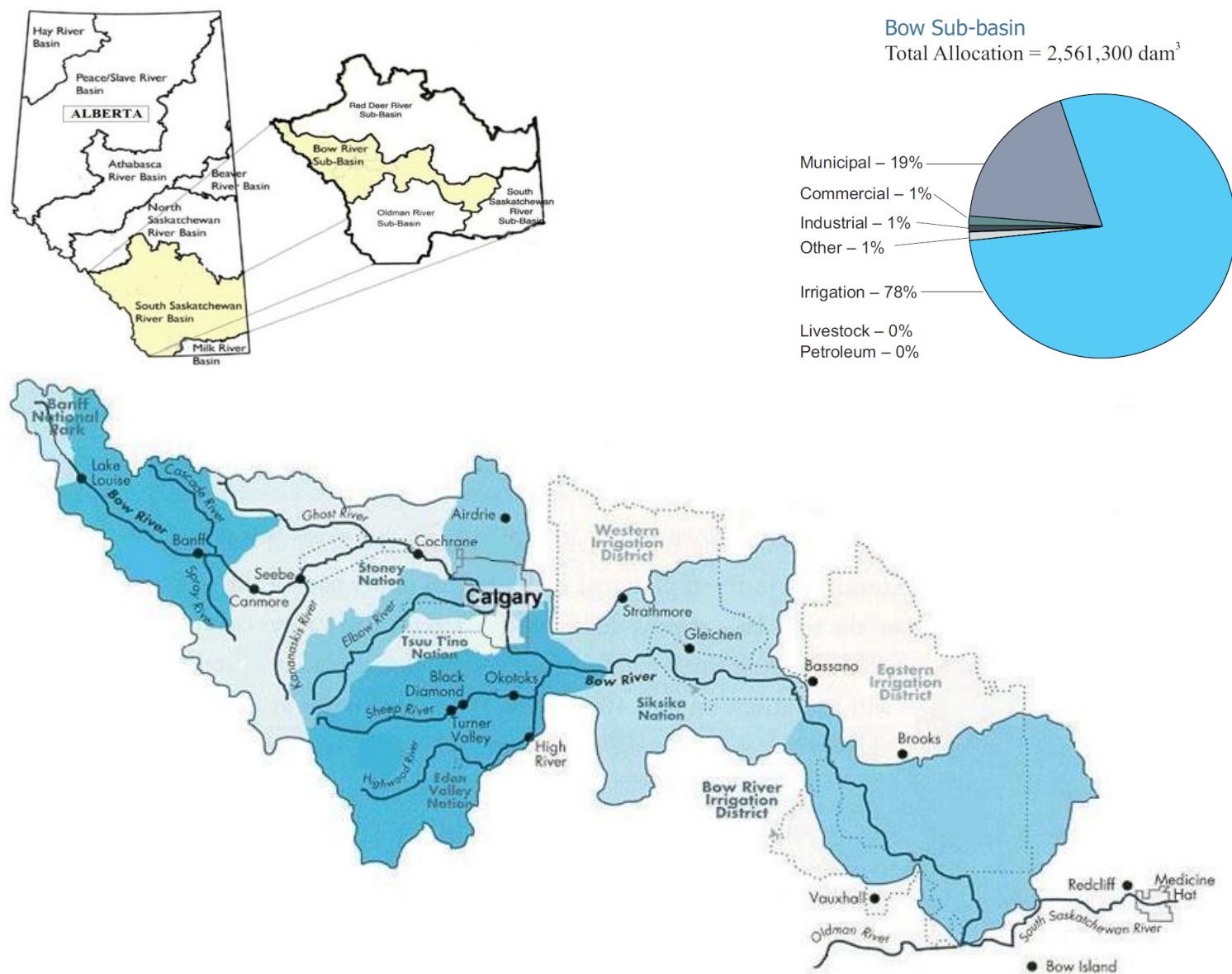


Figure 1: Study Area – Bow River Sub-Basin (BRSB) of Southern Alberta and its major users

Table 1: Summary crop characteristics, 2008

Crops/crop groups	Western Irrigation District (WID)			Eastern Irrigation District (EID)			Bow River Irrigation District (BRID)			Average net returns (\$/ha/year)	
	% land under	% pivot irrigation	ET (m <sup>3</sup> /ha)	% land under	% pivot irrigation	ET (m <sup>3</sup> /ha)	% land under	% pivot irrigation	ET (m <sup>3</sup> /ha)	Irrigated land	Dryland
Alfalfa seed	0.3	100	4006	4.9	61	4363	2.3	0	4248	1058	597
Alfalfa	10.2	91	5774	18.2	49	6395	8.7	60	6241	539	130
Barley	16.1	77	3182	8.3	61	3483	8.0	73	3447	769	288
Barley silage	15.2	92	2961	5.6	80	4255	3.8	89	3689	290	214
Dry beans	0.0	0	0	0.6	97	3134	5.4	0	3167	529	285
Oilseeds	23.5	94	3408	12.2	79	3711	15.2	90	3646	442	372
Confection crops	0.0	0	0	0.2	72	4885	0.0	0	0	463	-
Cereals	1.0	100	3524	2.6	76	4022	1.3	84	4013	1006	325
Essential oils	0.0	0	0	0.0	0	0	0.0	0	3241	2158	-
Summer fallow	0.0	0	0	0.0	0	0	0.1	0	1621	0	0
Flax	0.6	100	3622	1.9	71	4021	1.7	64	3972	479	273
Hay	0.7	90	3987	6.4	47	3807	2.0	60	4019	485	168
Other specialty crops	0.5	0	3728	0.2	21	4121	0.1	88	3492	10568	5284
Pasture	14.6	48	2875	19.7	35	3182	7.8	39	3324	434	168
Dry peas	0.8	100	3050	0.4	69	3400	1.1	84	3322	288	185
Potatoes	0.3	100	4089	0.9	99	4592	4.6	100	4496	1991	1352
Sugar beets	0.0	0	0	0.1	74	4609	3.4	0	4559	915	499
Vegetables	0.0	0	0	0.0	100	2927	0.3	100	2559	3297	351
Durum wheat	0.0	0	0	1.2	77	4058	9.3	0	3949	927	300
Hard spring wheat	5.1	67	3772	14.7	66	4122	17.6	87	4035	725	338
Soft wheat	11.0	93	3788	2.0	76	4074	7.5	81	3973	867	327
Total area (hectares)	19,476	-	-	113,592	-	-	83,557	-	-	-	-

Notes: Crop groups represent similar other crops in each category. For example, cereals include grain corn, oats, rye and triticale. Details are available upon request. Pivots include sprinkler-high pressure and sprinkler-low pressure irrigation systems. ET represents average crop evapotranspiration weighted by the areas under different irrigation methods. All monetary values in this table are 2008 Canadian dollars.

Table 2: Water allocation (in million m<sup>3</sup>/year) by historical license priority dates and potential shortage scenarios

Users	WID	EID	BRID	City of Calgary	Shell Canada	University of Calgary	Total (million m <sup>3</sup> /year)
License priority dates yyyymmdd(ss)	19030904(01) (2007)	19030904(02)	19081027(02) 19130325(01) 19530625(01) 19920205(10)	18950802(01) 19291024(01) 19711125(01) 19711129(02) 19811102(03)	19500823(01) 19540804(01)	19660615(01) 19770117(01) 19810129(01)	
Water allocation under each license (million m <sup>3</sup> /year)	197.85 - 2.47	939.91	185.02 185.02 98.68 86.34	5.55 66.67 41.98 135.07 210.93	0.43 0.29	4.93 2.47 3.08	
Total licensed water	195.38	939.91	555.07	460.18	0.72	10.48	2161.8
<b>Base year (2008) diversion</b>	<b>104.85</b>	<b>504.99</b>	<b>293.57</b>	<b>85.59</b>	<b>0.15</b>	<b>3.66</b>	<b>992.8</b>
Past 5-year average div.	124.01	480.59	286.34	75.77	0.17	3.64	970.5
<b>20% shortage</b>							
Seniority rule	104.85	504.99	178.86	5.55	0	0	794.2
People First	104.85	504.99	98.82	85.59	0	0	794.2
PropP5Y	101.49	393.30	234.33	62.01	0.14	2.98	794.2
<b>30% shortage</b>							
Seniority rule	104.85	504.99	79.58	5.55	0	0	695.0
People First	104.85	504.52	0	85.59	0	0	695.0
PropP5Y	88.80	344.14	205.04	54.26	0.12	2.60	695.0
<b>40% shortage</b>							
Seniority rule	104.85	485.29	0	5.55	0	0	595.7
People First	104.85	405.24	0	85.59	0	0	595.7
PropP5Y	76.12	294.97	175.75	46.51	0.11	2.23	595.7

Notes: WID = Western Irrigation District, EID = Eastern Irrigation District, BRID = Bow River Irrigation District.

Priority sequence number is shown in parenthesis (ss) in the license priority dates.

In 2007, the WID sold 2.47 m<sup>3</sup> of its licensed water to the Municipal District of Rocky View to provide water for a shopping complex.

PropP5Y = Users' diversions are reduced in proportion to their past 5-year's (2003-07) average diversion.

Allocations for the non-irrigation users are shown for the months of May to September of 2008 to make them comparable.



Table 3: Parameter estimates of the inverse demand and cost functions for non-irrigation sector users

Users ( $u$ )	Water price $P$ (\$/m <sup>3</sup> )	Observed demand $\bar{Q}_u$ (million m <sup>3</sup> /yr)	Price elasticity of demand $\varepsilon_{P,Q}$	$a = P/e^{1/\varepsilon}$	$b = -\varepsilon\bar{Q}_u$	Production cost $c_1$ /m <sup>3</sup>	Distribution cost $c_2$ /m <sup>3</sup>	Marginal cost $c = c_1 + c_2$
City of Calgary	1.3067	85.59	- 0.650	6.086	48.96	0.067	0.066	0.133
Shell Canada	1.3067	0.15	- 1.415	2.649	0.21	0.067	0.066	0.133
University of Calgary	1.3067	3.66	- 1.910	2.206	6.64	0.067	0.066	0.133

Notes: Water price refers to the General Service Metered Usage Rate for 2010 available at,

<http://www.calgary.ca/UEP/Water/Pages/Customer-service/Water-and-wastewater-rates/Water-and-Wastewater-Rates.aspx>

Price elasticity of demands are taken from Renzetti (1992a, 1992b, 1993), and Tate et al. (1992).

Production and distribution costs are taken from Mahan (1997, p102) and used for cost estimation.

Sector demands are for the months of May to September of 2008, so that they are comparable to the irrigation season demands.

Parameters  $a$  and  $b$  of the inverse demand function  $P = ae^{-Q/b}$ ,  $a \geq 0$  are used to estimate the benefits of non-irrigation users.

Table 4: A sample of new activities emerged in the water shortage simulation runs

Irrigation districts	Crops	Irrigation technology	Observed hectares	Simulated hectares		
				20% water shortage	30% water shortage	40% water shortage
Western Irrigation District	Pasture	Sprinkler-volume gun	0	5.70	7.86	12.81
Eastern Irrigation District	Dry Beans	Gravity-controlled	0	10.03	10.82	12.08
Eastern Irrigation District	Vegetables	Sprinkler-low pressure	0	5.35	5.89	6.76
Eastern Irrigation District	Dry Beans	Gravity-developed	0	0.77	1.59	0.77
Bow River Irrigation District	Hays	Sprinkler-volume gun	0	12.65	12.65	14.07
Bow River Irrigation District	Flax	Sprinkler-volume gun	0	4.44	3.18	3.18
Bow River Irrigation District	Essential oil	Gravity-undeveloped	0	160.06	-	-
Bow River Irrigation District	Pasture	Micro-drip	0	83.99	83.99	83.99

Table 5: Water demand (million m<sup>3</sup>/year) and marginal values (\$/m<sup>3</sup>)

Scenarios	WID		EID		BRID		City of Calgary		Shell Canada		Univ. of Calgary		Total water demand
	Water demand	Marginal value	Water demand	Marginal value	Water demand	Marginal value	Water demand	Marginal value	Water demand	Marginal value	Water demand	Marginal value	
2008 diversion	<b>104.85</b>		<b>504.99</b>		<b>293.57</b>		<b>85.59</b>		<b>0.15</b>		<b>3.66</b>		<b>992.8</b>
2003-07 av. div.	124.01		480.59		286.34		75.77		0.17		3.64		970.5
<b>20% shortage</b>													
Seniority	104.85	0.000	504.99	0.000	178.86	0.085	5.55	2.447	0.00	1.678	0.00	1.505	794.2
People First	104.85	0.000	504.99	0.000	98.82	0.118	85.59	0.000	0.00	1.678	0.00	1.505	794.2
PropP5Y	101.49	0.000	393.30	0.052	234.33	0.076	62.01	0.721	0.14	0.123	2.98	0.280	794.2
Trading	20.20	0.033	431.17	0.033	254.62	0.033	84.52	0.033	0.15	0.033	3.58	0.033	794.2
<b>30% shortage</b>													
Seniority	104.85	0.000	504.99	0.000	79.58	0.130	5.55	2.447	0.00	1.678	0.00	1.505	695.0
People First	104.85	0.000	504.53	0.000	0.000	1.360	85.59	0.000	0.00	1.678	0.00	1.505	695.0
PropP5Y	88.80	0.001	344.14	0.075	205.04	0.085	54.26	0.958	0.12	0.317	2.60	0.433	695.0
Trading	1.76	0.067	368.77	0.067	237.41	0.067	83.39	0.067	0.15	0.067	3.49	0.067	695.0
<b>40% shortage</b>													
Seniority	104.85	0.000	485.29	0.006	0.000	1.360	5.55	2.447	0.00	1.678	0.00	1.505	595.7
People First	104.85	0.000	405.24	0.046	0.000	1.360	85.59	0.000	0.00	1.678	0.00	1.505	595.7
PropP5Y	76.12	0.003	294.98	0.081	175.75	0.085	46.51	1.195	0.11	0.512	2.23	0.586	595.7
Trading	1.51	0.081	291.67	0.081	215.96	0.081	82.95	0.081	0.15	0.081	3.46	0.081	595.7

Notes: WID = Western Irrigation District, EID = Eastern Irrigation District, BRID = Bow River Irrigation District.

PropP5Y = Users' diversions are reduced in proportion to their past 5-year's (2003-07) average diversion.

Trading implies short-term or temporary transfer of water for the irrigation season, not the permanent transfer of licensed water rights.

All monetary values in this table are 2008 Canadian dollars.

Table 6: Water trading volumes (million m<sup>3</sup>/year) and directions (purchases > 0; sales < 0)

Scenarios	WID	EID	BRID	City of Calgary	Shell Canada	Univ. of Calgary
Base year 2008 (no shortage)				No trading		
<b>20% shortage</b>						
Seniority	-84.64	-73.82	75.77	78.97	0.15	3.58
People First	-84.64	-73.82	155.81	-1.07	0.15	3.58
PropP5Y	-81.29	37.87	20.30	22.51	0.01	0.60
<b>30% shortage</b>						
Seniority	-103.08	-136.22	157.83	77.83	0.15	3.49
People First	-103.08	-135.76	237.41	-2.21	0.15	3.49
PropP5Y	-87.04	24.63	32.37	29.13	0.02	0.89
<b>40% shortage</b>						
Seniority	-103.34	-193.62	215.96	77.39	0.15	3.46
People First	-103.34	-113.57	215.96	-2.65	0.15	3.46
PropP5Y	-74.61	-3.30	40.21	36.44	0.04	1.23

Notes: WID = Western Irrigation District, EID = Eastern Irrigation District, BRID = Bow River Irrigation District.

Table 7: Percentage change in total irrigated land from existing allocation policy (seniority rule)

Scenarios	Western Irrigation District	Eastern Irrigation District	Bow River Irrigation District	Total
Base-year (2008) hectares	19,476	113,592	83,557	216,625
<b>20% shortage</b>				
Seniority (hectares)	19,476	113,592	60,717	193,786
People First (%Δ)	0.0	0.0	-47.5	-14.9
PropP5Y (%Δ)	0.0	-0.1	31.6	9.8
Trading (%Δ)	-72.9	0.0	34.8	3.6
<b>30% shortage</b>				
Seniority (hectares)	19,476	113,592	25,196	158,265
People First (%Δ)	0.0	0.0	-98.9	-15.7
PropP5Y (%Δ)	-4.6	-6.3	179.2	23.5
Trading (%Δ)	-98.0	-1.5	219.3	21.8
<b>40% shortage</b>				
Seniority (hectares)	19,476	113,592	277	133,345
People First (%Δ)	0.0	-0.1	0.0	-0.1
PropP5Y (%Δ)	-12.8	-18.2	21388.0	27.1
Trading (%Δ)	-98.5	-19.0	26593.2	24.7

Table 8: Percentage change in cropping pattern from existing allocation policy (seniority rule)

Scenarios	Cereals	Forages	Specialty crops	Oilseeds	Total
Base-year (2008) hectares	75,550	83,086	23,155	34,833	216,625
<b>20% shortage</b>					
Seniority (hectares)	69,643	76,849	24,643	22,650	193,785
People First (%Δ)	-15.0	-12.9	-27.0	-8.1	-14.9
PropP5Y (%Δ)	-5.1	-14.2	4.7	142.6	9.8
Trading (%Δ)	-7.7	-19.2	0.7	118.3	3.6
<b>30% shortage</b>					
Seniority (hectares)	55,477	64,116	16,724	21,948	158,264
People First (%Δ)	-29.5	-3.1	-45.7	5.0	-15.7
PropP5Y (%Δ)	14.2	-10.1	51.1	124.1	23.5
Trading (%Δ)	7.6	-18.7	50.9	153.9	21.8
<b>40% shortage</b>					
Seniority (hectares)	36,608	61,387	9,549	25,802	133,345
People First (%Δ)	-5.2	-17.0	4.4	45.6	-0.1
PropP5Y (%Δ)	69.9	-10.0	160.9	5.2	27.1
Trading (%Δ)	56.0	-24.2	159.7	46.8	24.7

Notes: Cereals include barley, wheat, and other grain crops; Forages include alfalfa, barley silage, fallow, hay and pasture; Specialty crops include alfalfa seeds, dry beans, dry peas, confection crops, essential oils, potatoes, sugarbeets, vegetables and other crops; Oilseeds include canola, hyola and flax.

Table 9: Economic gains (in million 2008 Canadian \$/year)

Scenarios	WID	EID	BRID	City of Calgary	Shell Canada	Univ. of Calgary	Total
<b>20% shortage</b>							
Seniority	9.56	44.99	49.02	14.05	-	-	117.62
People First	9.56	44.99	41.08	111.96	-	-	207.58
PropP5Y	9.56	42.29	53.58	103.47	0.13	2.66	211.68
Trading	8.63	43.89	54.66	111.95	0.13	2.75	222.01
<b>30% shortage</b>							
Seniority	9.56	44.99	38.69	14.05	-	-	107.29
People First	9.56	44.99	24.39	111.96	-	-	190.90
PropP5Y	9.55	39.11	51.25	96.96	0.12	2.52	199.52
Trading	7.85	40.83	53.81	111.89	0.13	2.74	217.25
<b>40% shortage</b>							
Seniority	9.56	44.94	24.39	14.05	-	-	92.94
People First	9.56	42.87	24.39	111.96	-	-	188.79
PropP5Y	9.52	35.26	48.76	88.62	0.12	2.33	184.61
Trading	7.83	34.99	52.16	111.86	0.13	2.74	209.72

Notes: WID = Western Irrigation District, EID = Eastern Irrigation District, BRID = Bow River Irrigation District.