Southern Alberta Resource Economics Centre
Department of Economics, University of Lethbridge
4401 University Drive, Lethbridge, Alberta, Canada, T1K 3M4

SAREC Report 2010-3

Water Allocation Models for Alberta: What's Available and what are the Needs?

2010

Md Kamar Ali, Danny G. Le Roy and K. K. Klein

Southern Alberta Resource Economics Centre Publications

The mission of the Southern Alberta Resource Economics Centre (SAREC) is to study resource issues that affect growth and development of Southern Alberta. Multi-disciplinary research is required on the impacts of human activity on water quality, water quantity, climate change, impacts of biotechnology, growth of the bio-economy, manure disposal from intensive livestock production, and other agricultural and resource issues. These resource-based issues provide the motivation for socio-economic research in this dynamic region of Canada.

While SAREC is centred in the Department of Economics at the University of Lethbridge, SAREC is informally organized and includes researchers in several disciplines, including, but not limited to, economics, geography, management, and public health. The purpose of SAREC publications is to provide a forum for the exchange of information on all aspects of resource issues in Southern Alberta and related areas. The research reports published in this series may be completed research, works in progress or thought-provoking information pieces submitted by academic researchers, graduate students or others with an interest in resource issues in Southern Alberta. SAREC researchers have been supported financially by the Social Science and Humanities Research Centre, the Alberta Water Research Institute (formerly the Alberta Ingenuity Water Research Centre), the Canadian Water Network, SouthGrow Regional Initiative, and other funding agencies.

The opinions expressed in this series of research reports represent those of the authours and not of University of Lethbridge officials or of funding agencies. Prospective authours for this series are invited to submit completed manuscripts or to contact the research leaders regarding proposed topics.

K. K. Klein and Henning Bjornlund, SAREC Research Leaders

Department of Economics, University of Lethbridge

Lethbridge, Alberta T1K 3M4

(klein@uleth.ca; henning.bjornlund@uleth.ca)

Abstract:

Existing water allocation models have been reviewed and evaluated to identify the availability of suitable mathematical models that could be used to evaluate ways to improve water use efficiencies in Alberta. We found that even the most recent economic optimization model in Alberta is too narrow in scope and spatial coverage to represent the intricacies of competing water users in southern Alberta. We identified at least four general areas of improvement that could be made to a recently developed model to improve its analytical capacity – expanding the model structure to include all irrigation districts in southern Alberta, augmenting with modules of other water user sector demands, improving capability to analyze alternative water licensing policies, and developing a field-scale model to help understand the dynamics of micro level decision making on water rights transfers, irrigation technology choices, crop choices, and other decision variables.

Background:

The Government of Alberta's *Water for Life* strategy (announced in November 2003) calls for a 30% improvement in overall efficiency and productivity of water use over the span of 10 years (from 2005 to 2015) to achieve three goals of (1) safe, secure drinking water supply (water for communities), (2) reliable, quality water supplies for a sustainable economy (water for the economy), and (3) healthy aquatic ecosystem (water for nature) (AWC, 2007). In this document, efficiency is referred to the ratio between the amount of water needed to perform an activity to the amount of water actually used or diverted while productivity is referred to the amount of water used to produce a unit of good or service.

Seven major water user sectors have been identified in Alberta that withdraws surface waters from the South Saskatchewan River Basin (SSRB). These are: irrigation, municipal, power generation, oil and gas, mining, chemical and petrochemical, and forestry (AWC, 2008). It is recognized that some of these sectors (e.g., irrigation) have already achieved major improvements in efficiency and productivity. Water use efficiency in Alberta, measured as the fraction of water delivered to the farm that actually reaches the root zone of crops, has improved over time through the gradual movement away from surface irrigation (with an average of 30 percent water use efficiency) to wheel-move and ultimately to low pressure centre pivots (with an average of 80 percent water use efficiency). Under existing irrigation techniques, overall water use efficiency was estimated in 2007 at 72.5 percent across all irrigation districts, compared to only 34 per cent in 1965 (AIPA, 2009). Thus, another 3% per year improvement may be unachievable. However, performance of subsectors within each sector (e.g., irrigation districts) differs and there may still be room for improvement. Within an irrigation district, water use efficiency could be improved at the farm level by employing different water management practices. Also, water use efficiency could be improved in the water head works, distribution canals or water delivery systems to the farms. To assess untapped potentials for improved efficiency and to contribute toward achieving the *Water for Life* strategy objectives, the Alberta Water Council initiated the development of sector specific water conservation and productivity plans by the end of 2010 (AWC, 2008). The approved sector plans would then be implemented over the course of 2010 to 2015 and their progress would be monitored and evaluated by the Council towards meeting the 30% target.

A review of the existing licensing, allocation and transfer of water rights practices and policies in Alberta also is underway with the call of the Minister of the Environment Rob Renner in September 2008. This is because of the need to better understand whether the historical seniority-based volumetric allocation policy is still capable of meeting the challenges of growing demands, unpredictable supplies, and ecosystem needs, or would the “sharing of water” based on *proportional* allocations be a better alternative (Water Matters 2009). Of course, it is hard to predict *a priori* if such alternative policies would be better suited for the water allocation issues and contexts in Alberta even though some have been implemented successfully in other jurisdictions such as in Colorado and Australia. There is also a strong need to assess the potential of economic efficiency gains of existing licensing systems if a full-functioning water trading market were developed in Alberta. Mathematical models that can simulate such alternative policies for Alberta and the experiences from other jurisdictions can provide valuable insights in potential welfare and efficiency gains relative to the status quo or alternative water management policies (Horbulyk and Lo, 1998).

Historically, water licenses and rights in Alberta have been based on a system of *prior allocation* where priority is set by the date of application on the principle of first-in-time-first-in-right (FITFIR) (See AMEC, 2008 for the definition and distinction with the *prior appropriation* principle followed in the western United States). Zilberman and Schoengold (2005) maintain that the FITFIR system is an impediment to water market development, a solution often touted for efficient allocation of water resources during scarcity, since senior rights holders have little incentive to sell the rights to the newer or junior rights holders. However, since the mid-nineties, especially with the inception of the *1996 Water Act*, there is a move toward transforming these historical licences and rights into tradable licences with some government control on the nature of the trade and holdback options[1]. Under this "water transfer" scheme, the door is being opened to the new users even in the context of near-full or full allocation of existing water in many watersheds[2]. Privilege of the senior rights holders is still respected regardless of the trade being temporary or permanent in nature, yet the government can withhold 10% of the water being traded for instream conservation purposes. A permanent transfer involves transferring existing rights for the term of the trade while a temporary transfer involves transferring partial or full allocation of water for the current irrigation season. Regardless of the type of transfer, seniority characteristics of the original licence are preserved. As of 2008, approximately 28 water transfers – mostly between irrigated agricultural use – have taken place in Alberta water market (Water Matters, 2009). A snapshot of the characteristics of the emerging water allocation markets,

---

[1] The *Water Act*, initiated in 1996 and enacted in January 1999, allowed transfers of licences across sub-basins or across irrigation districts or users *within* a river basin and enabled separating water licences from the land entitlements so that transfers of water rights could be independent of the land they are attached to. Inter-basin transfers are subject to the Legislature approval.

[2] As of August 30, 2006, three of the four sub-basins of SSRB – the Bow River sub-basin, the Oldman River sub-basin, and the South Saskatchewan River sub-basin – were closed for new water licences. Only the Red Deer River sub-basin is still open for new licences (Water Matters, 2009).

volumes being traded, and pricing can be found from a field level survey by Nicol and Klein (2006). Analysis of the patterns of the six permanent water rights transfers that have taken place in southern Alberta during the first five years of the enactment of the Water Act can be found in a follow-up study by Nicol et al. (2008).

Given this limited trading experience with a growing water market, the Alberta Water Research Institute (AWRI) recently documented the need for looking at the experiences of more mature water markets in California and Australia where significant time and effort have been invested in creating and assessing the role of markets in reallocating waters in extreme drought conditions (AWRI, 2009). A large volume of literature using a wide range of modeling techniques and methodologies is now available from these locations (Vaux and Howitt, 1984; Booker and Young, 1991,1994; Chatterjee et al., 1998; Chakravorty and Umetsu, 2003; Wurbs, 2003, 2004; Brewer et al., 2008; Grafton et al., 2009; Bjornlund and Rossini, 2007; Zaman et al., 2009; Brooks and Harris, 2008; Cortignani and Severini, 2009; Wheeler et al., 2008). Using limited data from Alberta and utilizing modeling routines from elsewhere, a few models also have been developed for Alberta or western Canada to analyze water allocation policies in this region (He and Horbulyk, 2010; Mahan et al., 2002; Horbulyk and Lo, 1998; Wang et al., 2008; Cutlac et al., 2006; AAFRD, 2002a; AAFRD, 2002b; Alberta Environment, 2002).

With the need to assess changing water allocation policies and procedures in Alberta, an assessment must be made of the usefulness of available mathematical models to provide the analysis. The purpose of this paper is to provide an overview of the literature on water allocation models, the modeling techniques used, their strengths and limitations, and their adaptation and applicability in the context of emerging water policies in Alberta. The primary focus is on basin-scale models since it is at this scale that sectoral competition for water can be adequately analyzed to draw essential information for policymakers in their resource management decisions. Although it is at the farm or field-scale where micro level decision making takes place regarding irrigation equipment purchase, crop choice, and water application, extensive data requirement at such fine levels often thwart modeling efforts. Thus in the following sections, recent applications of basin-scale models in the context of Alberta water are discussed – physical water allocation models are discussed first, followed by the economic optimization models, and then a short discussion follows with the applications and experiences from other international jurisdictions for additional methodological insights. A summary of the most relevant models is presented in the Appendix Table 1.

Physical Allocation Models:

One type of model that has been applied to the water allocation problem in Alberta deals with the physical aspects of water allocation – starting from the diversion of water at the head works, through the networks of storage basins, canals and pipelines, to the distribution of water at the irrigated fields. Two such models are known as the *Irrigation District Model (IDM*) (AAFRD, 2002a) and the *Water Resources Management Model (WRMM)* (Alberta Environment, 2002). The IDM utilizes two integrated modules – the *Irrigation Requirements Module* that contains weather and field level data, and the *Network Management Module* that contains data on canal/pipeline network characteristics in each irrigation districts, storage reservoirs, return flows, and losses. Together, they determine daily farm delivery requirements based on crop growth parameters and translate them into canal flow and diversion requirements. It is the IDM that helps to develop alternative water requirement scenarios depending on the crop mix, irrigation methods, expansion potentials, future demands, and climate predictions.

The WRMM is a basin-scale simulation model that takes the irrigation requirements from the IDM as inputs and determines if those requirements could be met following the license priorities and given other major delivery requirements in the non-irrigation sectors such as municipal, industrial, recreation, wetlands, instream flows, and inter-provincial apportionment commitments in the SSRB. The output of the WRMM informs the frequency and magnitude of the irrigation water deficits on a weekly basis. These deficits form the inputs of a third model, the *Farm Financial Impact and Risk Model (FFIRM)* (AAFRD 2002b) that analyzes the risk and water shortage impacts on the income for representative farms across the basin.

The FFIRM is the only model currently being used by the water managers in Alberta Irrigation (AAFRD 2002b) that incorporates crop yield-water functions and economic parameters (crop prices, labor, capital, repair & maintenance, and energy costs) to help understand how the water availability and climate conditions translate into economic impacts. It includes two components – an optimization component dealing with the optimal allocation of water demand and supply derived from the IDM and WRMM among four typical farm enterprises across the basin. In case of water shortages, this component of the model allocates water to the most profitable farm enterprise on a priority basis. The other component of FFIRM simulates long term financial viability of these farm enterprises considering risk and crop-water management choices. The FFIRM model does a good job of budgeting farm costs and revenues for given situations but since the IDM and WRMM are not based on farmer responses to economic incentives and price signals, the analyses are non-optimizing and thus, may not represent very well actual farmer behavior.

Economic Optimization Models:

Apart from the FFIRM, which involves both economic optimization and simulation approaches, a second type of model applied to the water allocation problem in Alberta involves economic optimization using mathematical programming techniques. Usually, these models have been at the basin scale, involve a high level of aggregation in the input data, have welfare or profit maximization objectives, and assume fully functional water markets in a potential water shortage situation. For example, Horbulyk and Lo (1998) employed a basin-wide optimization model with the objective of maximizing economic welfare gains from alternative water allocations due to short-term (one five-month season) inter-sector water demand (agricultural, urban and industrial, and instream flow) or inter-basin water trading in the four sub-basins (Red

Deer River, Bow River, Oldman River, and South Saskatchewan River) of the SSRB. Model calibration was done by adjusting the vertical intercepts of the aggregate sectoral demand curves to ensure that aggregate water demand meets the supply at zero prices. Four scenarios were simulated: the base scenario (zero prices and therefore no market), within sub-basin rural-to-urban transfer (restricted local market), across sub-basin rural-to-urban transfer (full regional market), and a fourth scenario that relaxed the fixed instream and interprovincial apportionment requirements. Results indicated that more than 90% of the potential short-term welfare gains could be achieved through implementation of the simplest form of the market, i.e., allowing reallocation of water within sub basins only.

Like Horbulyk and Lo (1998), Mahan et al. (2002) also used a welfare maximization model for the same four sub-basins of the SSRB but extended the model by adding six water user categories (irrigation, domestic, general use, industrial, hydro, and total urban), and a sub-model that analyzed the irrigation water demands for six major crops (soft wheat, hard spring wheat, barley, canola, potatoes, and alfalfa). The model network included nine irrigation regions consolidated from the 13 major irrigation districts that manage most of the irrigation water in the Alberta portion of the SSRB. Other major improvements in this model include the use of constant-elasticity inverse water demand functions and choke prices that allow integration of the area under the demand curve, and conversion of untreated water from non-consumptive usage into treated water. Model calibration was done using rigid constraints like the Horbulyk and Lo (1998) study. Allowing trade-in water among irrigation regions for a one growing season period, this study found relative efficiency (welfare) gain for introducing market pricing to be a small 3% for a water surplus season, 6% for an average flow season, and 15% for a drought season. Even though the costs of moving to market pricing are not accounted for in this study, the authors argue that the results are in line to support modifications of the existing water allocation systems in Alberta.

Still within the purview of mathematical programming techniques, Cutlac and Horbulyk (2009) used a pre-packaged software *Aquarius* (Diaz et al., 2000) to simulate 2003-04 level water allocations and provide optimal allocations under four alternative scenarios to derive optimal annual economic benefits in terms of the producers' and consumers' surpluses for the SSRB. The scenarios include 30% higher valuation of urban water use, 30% higher valuation of irrigation water use, 30% decrease in water availability, and a combination of all three scenarios above. Unlike the one growing season time-step in the custom made models discussed above, *Aquarius* uses monthly time steps over a one year time horizon, i.e., it requires specification of the monthly demand curves for each water user category in the model. The modeler has the flexibility to build the basin network as simply or as realistically as possible depending on data availability. In their study, the authors defined approximately forty demand and supply nodes, four user groups (irrigation, municipal use, hydropower, and instream use), and four storage reservoirs that allow diversion for irrigation, hydropower generation, and recreation use. However, *Aquarius* does not allow specification of crops in the irrigation sector. Rather, total water demand for each month for all crops grown across the basin needs to be specified.

Similar to the models discussed previously, *Aquarius* model calibration was done with modification of the constraints rather than modification of the objective function (discussed in detail below). This calibration reproduced "current water allocation". An "optimized base case" allocation was then obtained by allowing the model to reallocate water to the high value users. New allocations for the four scenarios were then generated that follow the model's sequential quadratic programming algorithm. Results indicate that a significant reallocation (agriculture sector withdraws more than double the urban withdrawals) of water is necessary to achieve the greatest short-term economic benefit. In the urban demand increase scenario, urban withdrawals increase about 19% at the cost of 4% decrease in the agricultural withdrawals; in the irrigation demand increase scenario, irrigation withdrawals increase 7% at the cost of 12% decrease in urban withdrawals; in the water shortfall scenario, cut-backs by urban and agricultural users are about 12% and 8%, respectively.

He and Horbulyk (2010) developed yet another mathematical programming model to test the impacts of (i) volumetric water pricing, and (ii) short-term water trading policies among three irrigation districts (Bow River (BRID), Eastern (EID), and Western (WID)) in the Bow River Sub-basin (BRSB) of the SSRB. These two market based policies are implemented in a way that treats water pricing as a substitute for the existing seniority-based (FITFIR) transfer allocations. An artificial market-like condition is created by introducing a water shortfall of 10-30%, in 10% increments, from the observed 2003 usage level. With this scarcity, trading under the status quo scenario resulted in a lower allocation for the BRID while EID and WID still maintain their 2003 level withdrawals. Compared to the allocation by seniority rule, short-term trading and volumetric pricing resulted in a lower water demand in both EID and WID but a higher demand in BRID. The model also provides a comparative picture of the change in crop mix in the three irrigation districts under the three scenarios and three water shortage conditions. In general, irrigated land decreases as the water shortage increases. But more land is irrigated under the short-term trading or pricing scenarios relative to the status quo under a moderate shortage regime. However, some high value dryland crops also increase in acreage under water scarcity. This is especially true for BRID where some irrigated crops switch to dryland cultivation (e.g., non-irrigated soft wheat) under the seniority allocation rule. In terms of welfare change, the two market-based scenarios resulted in a 0.5%, 2%, and 5.8% improvement in producers' surplus when water scarcity is at 10%, 20%, and 30% respectively.

Besides generating some interesting and fairly intuitive results with a rather simple set-up, the He and Horbulyk (2010) model distanced itself from others discussed earlier with regard to its calibration method. While all previous models were calibrated through modifying the constraints, this model was calibrated through modifying the objective function, a procedure commonly known as *positive mathematical programming* or PMP. The PMP utilizes dual values of the calibration constraints to modify the objective function such that the base year observed activities are reproduced without the calibration constraints (Howitt, 1995, 2005; Paris and Howitt, 1998). It is implemented in three steps: first, a set of calibration constraints that bind the activities to the base year level is added to the programming problem; second, the dual values of these constraints are used to modify the objective function; third, the modified model is solved without the calibration constraints added in the first step. This method allows the model to reproduce the base year conditions precisely in terms of input and output values, objective function value, shadow prices and output prices. Without PMP, the base year solution of a mathematical programming problem is likely to contain a set of very specialized activities.

Irrigation districts in this model are treated like representative license holders with BRID holding the junior-most license while EID and WID hold more senior licenses. This representation provides some food for thought if this modeling framework could be adapted to develop a farm-level model to analyze farmers' decision making process on irrigation technology choice, crop choice, water application and trading within a irrigation district (e.g., WID), if farm level data could be generated through surveys.

Models in Other Jurisdictions:

The following studies could be consulted to gather additional methodological insights and experiences from the international context. Tsur (2005) provides an easily accessible theoretical overview and mathematical derivation of different aspects of irrigation water pricing and allocation problem in single or multiple user contexts. How to implement these models in practice also is discussed in this article but no empirical application is presented. Zilberman and Schoengold (2005) and Schoengold and Zilberman (2007) could be consulted for mathematical and graphical representation of economic gains from water trading markets.

United States:

The semiarid southwestern United States has been the subject of numerous studies on interstate water allocation, regional water transfer, third-party effects, transaction costs, etc. with a range of trade models, mathematical programming models, and optimal control models. Over 80% of surface and ground water in this region is used for agriculture and the rest for municipal and industrial use (Gollehon and Quinby, 2000; Chong and Sunding, 2006). Vaux and Howitt (1984) used a regional trade model with nonlinear regional demand and supply functions to show that regional water transfer could be an effective mechanism to deal with water scarcity in California until 2020. Booker and Young (1991, 1994) used a non-linear economic-hydrologic optimization model to estimate economic gain from intra- and inter-state trade of consumptive and non-consumptive uses of fourteen water demand sectors in the Colorado River Basin under two water flow regimes. Results indicate that within state water transfers yield more economic benefit in the short flow regime induced by a severe drought or climate change. Chatterjee et al. (1998) developed a dynamic optimization model for interseasonal allocation of water between irrigation and hydropower for central California. Chakravorty and Umetsu (2003) developed a one-dimensional spatial model to characterize the optimal allocation of surface and ground water (replenished from the return flow) between upstream and downstream users in western U.S. One interesting result of the model is that if on-farm irrigation technology is traditional rather than modern and efficient, basin-wide optimization leads to a significantly higher aggregate economic gain. This is because higher return flow from traditional irrigation technology (e.g., gravity) replenishes groundwater, which appears as a backstop technology for the downstream users. Wurbs (2003, 2004) provide detailed description of the water allocation and river basin management process in Texas. Brewer et al. (2008) has a comprehensive overview of water rights, transfers and prices in major water markets in the American west.

An excellent handbook on setting up the optimization problems, GAMS codes, and illustrative solutions for water allocation among users, optimal management of a single reservoir or a river system, upstream-downstream problems, water rights and markets, etc. is provided by

McKinney and Savitsky (2006). Howe (2005) provides a comparison of water pricing policies in the U.S. and Canada while Grafton et al. (2009) provides a comparison of water rights, markets and trading in the U.S. and Australia.

Australia:

Brooks and Harris (2008) provide estimates of the magnitude of efficiency gains from water markets operating on weekly basis in three trading zones in Australia. Results indicate a substantial gain in economic efficiency can be obtained by reallocation of water from low to high value uses, which could be further improved if trade restrictions are progressively removed. Another recent study on Australian water markets used an integrated economic-hydrologic model to simulate the short and long-term impacts from water trading (Zaman et al., 2009). The authors argue that an integrated model is necessary to improve estimates from market trading as it can induce sudden changes in the demand and/or supply from one region to another that results in significant bottleneck and pressure on the water delivery infrastructure.

Other regions of the World:

An improved PMP calibration technique to allow for activities that are unobserved in the base year but could be adopted in the future is demonstrated by a recent study by Cortignani and Severini (2009). The case in point is the analysis of farm-level adoption of *deficit irrigation* (crops sustain some deficit in water in order to reduce irrigation costs), which was not observed in the base year but included in the simulation runs for three scenarios: increased water cost, reduced water availability, and changes in the price of irrigated produce in the central Italian region. The method is an extension of the Rohm and Dabbert (2003) approach that utilized the fact that elasticity of substitution is larger between varieties of the same crop than across crops.

Rosegrant et al. (2000) used a basin-scale economic-hydrologic integrated optimization model to analyze agricultural, non-agricultural, and environmental interactions in the Maipo river basin in Chile in order to achieve maximum economic gains from improvement in water use efficiency and inter-sector reallocation from trade. Another basin-level linear programming model applied to southern Spain and Italy to test with and without inter-sector market trading allocations confirmed that a water market could significantly improve economic efficiency of water use in times of shortages (Pujol et al., 2006). Qubaa et al. (2002) employed a two-part objective function that represented net returns from agriculture and municipal sector water usage to show the extent of under-pricing of water in southern Lebanon. This model could easily be extended to incorporate other sectors subject to the data availability. A very simple farm-level optimal crop choice model in water surplus and shortage situations is presented by Benli and Kodal (2003) in the context of GAP project region in Turkey.

Conclusions:

The purpose of this study was to identify the availability of suitable mathematical models that could be used to evaluate ways to improve water use efficiencies in Alberta, particularly in irrigation water use. Models that have been developed to address water allocation issues in Alberta and other parts of the world, particularly in the United States, Australia and parts of Europe, were reviewed. We acknowledge that the studies reviewed in this paper are not exhaustive on the subject matter. The literature on water trading and water allocation models is vast – Chong and Sunding (2006) noted that a 1997 review contained more than 200 studies covering a wide range of issues related to water markets. However, our review has determined at least four general areas of improvement that could be made to the existing economic optimization models, particularly to the most recent model in southern Alberta (He and Horbulyk, 2010), to improve analytical capacity.

First, this model has improved upon the earlier models in terms of its calibration technique and simulating reallocation of water among three irrigation districts and crops when trading is allowed in conjunction with the existing seniority-based volumetric licence rights. To make this model representative of the entire irrigation sector in southern Alberta, the model structure could simply be expanded to incorporate the remaining ten irrigation districts in the other three sub basins of the SSRB. Second, the fully expanded irrigation sector model then could be augmented with modules of other water using sector (e.g., municipality, industry, hydro power generation, instream water requirement) demands to analyze the sector competition of surface water in the SSRB. The non-irrigation sector modules could be developed following the network and hydrology of the study by Mahan et al. (2002) and the sector specific water conservation and productivity plans currently being developed for the *Water for Life* strategy objectives. Third, the current version of the He and Horbulyk (2010) model or any of the two expanded versions discussed above could be readily used to analyze the implications of alternative water licensing practices such as "proportional allocation," which has been practiced in Colorado and Australia, against the current "volumetric allocation" licenses in southern Alberta. Under the proportional allocation scheme, the shortage is shared by all users regardless of the seniority of licenses as opposed to the possibility of total denial of water to the junior licensees under the current fixed volume based allocation policies. This exercise could shed light on the ministerial directives of reviewing current and alternative licence policies in meeting the challenges of enhanced future demands under unpredictable supply and drought conditions. Fourth, there is no field-scale economic optimization model or study in southern Alberta to help understand the dynamics of micro level decision making on water allocation or rights transfer, incentives or disincentives to adopt efficient irrigation technologies, crop choices, amounts of water withdrawn and return flow management.

References:

Alberta Agriculture, Food and Rural Development (AAFRD) (2002a): *Irrigation District Model (IDM)*. Edmonton: AAFRD.

Alberta Agriculture, Food and Rural Development (AAFRD) (2002b): *Farm Financial Impact and Risk Model (FFIRM)*. Edmonton: AAFRD.

Alberta Environment (2002): *Water Resources Management Model (WRMM)*. Edmonton: Alberta Environment. http://www3.gov.ab.ca/env/water/regions/ssrb/wrmmoutput/WRMM/index.asp.

Alberta Irrigation Projects Association (AIPA) (2009): Irrigation Sector – Conservation, Efficiency, and Productivity Plan (Draft). Prepared by AECOM Canada Ltd.

Alberta Water Council (AWC) (2007): Water conservation, efficiency and productivity: principles, definitions, performance measures and environmental indicators. Final report prepared by the Water Conservation, Efficiency and Productivity Definitions Project Team. Edmonton, AB.

Alberta Water Council (AWC) (2008): Recommendations for water conservation, efficiency and productivity sector planning. Edmonton, AB.

Alberta Water Research Institute (2009): Towards sustainability: Phase I Ideas and opportunities for improving water allocation and management in Alberta. Edmonton.

AMEC (2008): Comparison of the water allocation process in Alberta to other jurisdictions. Report prepared for the Alberta Environment, Edmonton.

Benli, B. and S. Kodal (2003): A non-linear model for farm optimization with adequate and limited water supplies: Application to the south-east Anatolian project (GAP) region. *Agricultural Water Management*, 62, 187-203.

Bjornlund, H. and P. Rossini (2007): Fundamentals determining prices in the market for water entitlements: An Australian case study. *Water Resources Development*, 23(3), 537-553.

Booker, J.F. and R. Young (1991): Economic impacts of alternative water allocation institutions in the Colorado River basin, Colorado Water Resources Research Institute, Report No. 161. Colorado State University, Fort Collins.

Booker, J.F. and R. Young (1994): Modeling intrastate and interstate markets for Colorado River water resources. *Journal of Environmental Economics and Management*, 26, 66-87.

Brooks, R. and E. Harris (2008): Efficiency gains from water markets: Empirical analysis of Watermove in Australia. *Agricultural Water Management*, 95, 391-399.

Cantin, B., D. Shrubsole, and M. Ait-Ouyahia (2005): Using economic instruments for water demand management. *Canadian Water Resources Journal*, 30(1), 1-10.

Chakravorty, U. and C. Umetsu (2003): Basinwide water management: A spatial model. *Journal of Environmental Economics and Management*, 45, 1-23.

Chong, H. and D. Sunding (2006): Water markets and trading. *Annual Review of Environment and Resources*, 31, 239-264.

Cortignani, R. and S. Severini (2009): Modeling farm-level adoption of deficit irrigation using positive mathematical programming. *Agricultural Water Management*, 96, 1785-1791.

Cutlac, I-M. and T.M. Horbulyk (2009): Optimal water allocation under short-run water scarcity in the South Saskatchewan River Basin. Unpublished manuscript.

Diaz, G.E., T.C. Brown, and O. Sveinsson (2000): *Aquarius*: A Modeling System for River Basin Allocation. RM-GTR-299. Fort Collins, CO: United States Department of Agriculture, Forest Service.

Gollehon, N. and W. Quinby (2000): Irrigation in the American West: Area, water and economic activity. *Water Resources Development*, 16(2), 187-195.

Grafton, R.Q., C. Landry, G.D. Libecap, and R.J. O'Brien (2009): Water markets: Australia's Murray-Darling basin and the U.S. southwest. Paper presented at the Water Economic Consortium Meeting, UC Berkeley, Nov 6-7, 2009. http://www.icer.it/docs/wp2009/ICERwp15-09.pdf

He, L. and T.M. Horbulyk (2010): Market-based policy instruments, irrigation water demand, and crop diversification in the Bow River basin of southern Alberta. *Canadian Journal of Agricultural Economics*, 1-23.

Horbulyk T.M. and L.J. Lo (1998): Welfare gains from potential water markets in Alberta, Canada. Chapter 15 in Easter, K.W., M.W. Rosegrant and A. Dinar (eds.) Markets for Water: Potential and Performance. Norwell, MA: Kluwer Academic, 241-257.

Howe, C.W. (2005): The functions, impacts and effectiveness of water pricing: Evidence from the United States and Canada. *Water Resources Development*, 21(1), 43-53.

Howitt, R.E. (1995): Positive mathematical programming. *American Journal of Agricultural Economics* 77 (2): 329–42.

Howitt, R.E. (2005): *Agricultural and Environmental Policy Models: Calibration, Estimation and Optimization*. Davis: University of California Davis. http://www.agecon.ucdavis.edu/aredepart/facultydocs/howitt/master.pdf.

Mahan, R.C., T.M. Horbulyk, and J.G. Rowse (2002): Market mechanisms and the efficient allocation of surface water resources in southern Alberta. *Socio-Economic Planning Sciences*, 36, 25-49.

McKinney, D.C. and A.G. Savitsky (2006): Basic optimization models for water and energy management. Revision 8. http://www.ce.utexas.edu/prof/mckinney/ce385d/lectures/McKinneySavitsky.pdf,

Nicol, L. and K.K. Klein (2006): Water market characteristics: Results from a survey of southern Alberta Irrigators. *Canadian Water Resources Journal*, 31(2), 91-104.

Nicol, L., K.K. Klein, and H. Bjornlund (2008): A case study analysis of permanent transfers of water rights in southern Alberta. *Prairie Forum*, 33(2), 341-356.

Paris, Q. and R.E. Howitt (1998): An analysis of ill-posed production problems using maximum entropy. *American Journal of Agricultural Economics*, 80(1), 124-138.

Pujol, J., M. Raggi, and D. Viaggi (2006): The potential impact of markets for irrigation water in Italy and Spain: A comparison of two study areas. *The Australian Journal of Resource and Agricultural Economics*, 50, 361-380.

Qubaa, R., M. El-Fadel, and M.R. Darwish (2002): Water pricing for multi-sectoral allocation: A case study. *Water Resources Development*, 18(4), 523-544.

Rohm, O. and S. Dabbert (2003): Integrating agri-environmental programs into regional production models: An extension of positive mathematical programming. American Journal of Agricultural Economics 85(1), 254-265.

Rosegrant, M.W., C. Ringler, D.C. Mckinney, X. Cai, A. Keller, and G. Donoso (2000): Integrated economic-hydrologic water modeling at the basin scale: The Maipo river basin, *Agricultural Economics*, 24(1), 33-46.

Schoengold, K. and D. Zilberman (2007): The economics of water, irrigation, and development. Chapter 58 in Evenson, R. and P. Pingali (eds): Handbook of agricultural economics, Vol 3. Elsevier, B.V.

Tsur, Y. (2005): Economic aspects of irrigation water pricing. *Canadian Water Resources Journal*, 30(1), 31-46.

Vaux, H.J. Jr. and R. Howitt (1984): Managing water scarcity: An evaluation of interregional transfers. *Water Resources Research*, 20(7), 785-792.

Wang, L., L. Fang, and K.W. Hipel (2008): Basin-wide cooperative water resources allocation. *European Journal of Operations Research*, 190, 798-817.

Water Matters (2009): *Share the Water: Building a Secure Water Future for Alberta*. Calgary: Water Matters.

Wheeler, S., H. Bjornlund, M. Shanahan, and A. Zuo (2008): Price elasticity of water allocations demand in the Goulburn-Murray irrigation district. *The Australian Journal of Agricultural and Resource Economics,* 52, 37-55.

Wurbs, R.A. (2003): Modeling river basin management: An institutional perspective. *Water Resources Development*, 19(4), 523-534.

Wurbs, R.A. (2004): Water allocation systems in Texas. *Water Resources Development*, 20(2), 229-242.

Zaman, A.M., H.M. Malano, and B. Davidson (2009): An integrated water trading-allocation model, applied to a water market in Australia. *Agricultural Water Management*, 96, 149-159.

Zilberman, D. and K. Schoengold (2005): The use of pricing and markets for water allocation. *Canadian Water Resources Journal*, 30(1), 47-54.

Appendix Table 1: Summary of the water allocation models at a glance

Study	Area	Scale	Methodology
Southern Alberta:			
IDM, AAFRD (2002a)	SSRB, Alberta	Irrigation districts	Calculation of daily water requirements
WRMM, AENV (2002)	SSRB, Alberta and Saskatchewan	Basin	Calculation of physical allocation and deficits based on IDM needs
FFIRM, AAFRD (2002b)	SSRB, Alberta	Basin	Economic optimization and simulation
Horbulyk and Lo (1998)	SSRB, Alberta	Basin	Economic optimization
Mahan et al. (2000)	SSRB, Alberta	Basin	Economic optimization
Cutlac and Horbulyk (2009)	SSRB, Alberta	Basin	Economic-hydrologic integrated
He and Horbulyk (2010)	BRSB of SSRB	Irrigation districts	Economic optimization with PMP calibration
Australia:			
Brooks and Harris (2008)	Victoria and Southern New South Wales	Region	Econometric analysis
Zaman et al. (2009)	Northern Victoria	Basin	Economic-hydrologic integrated optimization and simulation
United States:			
Vaux and Howitt (1984)	California	Region	Regional trade
Booker and Young (1991, 1994)	Colorado	Basin	Economic-hydrologic integrated
Chatterjee et al. (1998)	California	Basin	Dynamic programming
Chakravorty and Umetsu (2003)	California	Basin	Spatial, optimal control
Wurbs (2003, 2004)	Texas	Basin	Institutional perspective
Brewer et al. (2009)	Western U.S.	Basin	Model comparison
Other regions:			
Cortignani and Severini (2009)	Central Italy	Farm	Economic optimization with improved PMP
Rohm and Dabbert (2003)	Germany	Region	Economic optimization with extended PMP
Rosegrant et al. (2000)	Maipo, Chile	Basin	Economic-hydrologic integrated
Pujol et al. (2006)	Southern Spain and Italy	Basin	Economic optimization
Qubaa et al. (2002)	South Lebanon		Economic optimization
Benli and Kodal (2003)	GAP project, Turkey	Farm	Economic optimization
Other relevant studies:			
Tsur (2005)			Theoretical and mathematical derivation of water allocation and pricing

Zilberman and Schoengold (2005)	Mathematical and graphical overview of water allocation
Schoengold and Zilberman (2007)	Mathematical and graphical overview of water allocation
Howitt (1995, 2005)	PMP calibration
McKinney and Savitsky (2006)	Setting-up water allocation problems, GAMS codes, solutions
Howe (2005)	Comparison of water pricing policies in U.S. and Canada
Grafton et al. (2009)	Comparison of water rights, markets, and trading in southwestern U.S. and Murray-Darling Basin, Australia

Notes: IDM = Irrigation District Model; WRMM = Water Resource Management Model; FFIRM = Farm Financial Impact and Risk Model; AAFRD = Alberta Agriculture, Food and Rural Development; AENV = Alberta Environment; SSRB = South Saskatchewan River Basin; BRSB = Bow River Sub-Basin; PMP = Positive Mathematical Programming; GAP = South-eastern Anatolian Project.