Final Report to the Alberta Land Institute:

Systems modelling for sustainable land and water policy in Alberta's irrigation sector

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A Statement on the Approach/Methodology

The project addressed topic 3 of ALI's 2012 Call for Proposals: a synthesis of current information on economic, environmental and social linkages associated with irrigation, development and analysis of future scenarios, and an evaluation of strategies to address challenges in the sector. Our work focused on modelling connections among land and water, irrigated and dryland agriculture, population growth, economic development, public policy and climate change; such connections are complex and poorly understood, and their effects are unpredictable. Further, because the "mental models" researchers and policy makers typically use to understand cause and effect in such systems have been shown repeatedly to be flawed, and the available physical models, while often quite detailed, have limited applicability and their coupling to other physical models can be technically and philosophically complicated, the project aimed to develop a set of numerical models to integrate information from various disciplines into more comprehensive decision-support tools.

The project was undertaken in three phases. Phase 1 focused on foundational research to support Phases 2 and 3, and was conducted through a combination of a literature review with a workshop involving an advisory panel and stakeholders in the irrigation areas of southern Alberta. Specifically, its aims were to research, develop and deliver a report that 1) identifies and examines the current and the future challenges and opportunities for expanding the irrigation sector in southern Alberta, and specifically in the South Saskatchewan River Basin over the next 25 years; and 2) identifies land-use, water management, agricultural, and financial policies that should help to ensure a sustainable expansion of the irrigation sector. Further, a cost-benefit analysis (CBA) was conducted, using input-output multipliers to estimate economic impacts of major irrigation activities on the provincial and national economies. Four irrigation activities were considered in the CBA – crop production, livestock production, agricultural food processing, and irrigation infrastructure rehabilitation and maintenance – and their direct and secondary economic impacts were then estimated in terms of value-added. Finally, the aggregate value-added impact of irrigation was estimated and the distribution of the aggregate benefits of irrigation among the producers, the province and the nation was determined. The foundational research was completed in August, 2014, while the CBA was completed in October, 2016.

Phases 2 and 3 focused on model development and data analysis, and consisted of two groups of projects. Project 1 of Phases 2 and 3 was the development of systems models for irrigation district-level land and water management. One methodology applied is called system dynamics, which is an interdisciplinary methodology that assembles information from various disciplinary frontiers into single, comprehensive system models. These models function in a "what if" sense for scenario analysis, while also facilitating sensitivity analysis through Monte Carlo simulations. System dynamics models allow stakeholders including researchers, policy-makers, managers, and the public to evaluate proposed management actions, identify trade-offs and improve their understanding of system behaviour. Because these models simulate quickly, with multiple-decade simulations complete in seconds, and Monte Carlo sensitivity analyses in minutes, they are useable by decision-makers and stakeholders for scenario exploration and analysis in real time. They can also be played in a gaming mode with policy choices made at regular intervals (annually or sub-annually), so that decision-makers can adapt to simulated basin conditions and iteratively explore the consequences of their choices. The system dynamics models we developed operate on a weekly time-step and include: 1) an agricultural model as the core of the systems model, with particular attention given to simulation of crop water demands and yield for six major crops of southern Alberta, and 2) a municipal water demand and use model for combination with the agricultural model that represents the effects of socio-economic development, climatic conditions, and water conservation policies on ten different municipal water "end-uses". Finally, to mimic economic and hydrological decisions of irrigators along the Oldman River in southern Alberta, a second type of systems model, called an agent-based model, was constructed. Agent-based models simulate the individual actions and group interactions of multiple autonomous agents, and are used to assess the collective behaviours of groups of agents that all follow simple sets of rules. Each agent in this case represented one of five types: riparian crop farmers, riparian livestock farmers, an irrigation district, non-riparian crop farmers who access water through the irrigation district, and all other license holders. The agent-based model functions at a monthly time scale for the six months of a growing season and simulates six consecutive years. It is comprised of four blocks that represent and compute aspects of crop mix selection, the water market, irrigation decisions, and economic returns to irrigators. The model was simulated under two water allocation regimes, the current first-in-time-first-in-right (FITFIR) and an alternative regime that shares rights equally in times of water shortages. Also, the model was simulated under the contexts of both adequate and inadequate irrigation water supply. Six scenarios were simulated with thirty iterations for each scenario, yielding one hundred and eighty simulations of the model with an average runtime for each scenario of approximately sixty hours.

Project 2 comprised supporting work for the systems model of Project 1, and had two parts. The land-use change component of Project 2 used GIS data at the Alberta Township System level (9.7 km x 9.7 km) and land-use raster images (30 m x 30 m) with spatial autocorrelation (SAC) models to identify the effects of environmental and socio-economic trends that drove land-use conversions over 12 years throughout the agricultural "white zone" of Alberta. Further, water supply was not simulated in this project – in terms of a dynamic hydrology or water balance model component – but a set of water demand scenarios was prepared as input to the systems model, using the Water Resources Management Model (WRMM) of Alberta Environment and Parks and stakeholder interviews with AEP and irrigation district personnel.

Results and Assessment

The first task in Phase 1 of our project was to identify the nature of, and information available on, key linkages between land and water resources, irrigated and dryland agriculture, population growth, economic development, public policy and environmental and climate change. This report brought together and interpreted a variety of literature on current and future challenges and opportunities associated with irrigation expansion in southern Alberta along with the insights from a workshop discussion with multi-sectoral stakeholders in southern Alberta. Furthermore, a set of potential policy and management strategy options that have received local attention, both in literature and in workshop discussions, was also provided, including background on each option and its potential contribution to addressing challenges and improving opportunities for the irrigation sector over the next 25 years. This first stage of the research was intended to aid in the subsequent development of modelling tools and analyses for evaluation of alternative management strategies, and their risks and trade-offs.

The input-output multiplier analysis indicated that Alberta's irrigation-related activities, directly or indirectly, added around $3.2 billion to the national GDP in 2011, or about one per cent of the province's total GDP. The distribution of the benefits was 17% for producers and 83% for the province and the rest of Canada. These estimates suggest that the benefits of irrigation have almost tripled from 1980s estimates, while the share of those benefits accruing to producers has not significantly changed. A second part of the CBA study examined the potential profitability at the producer level in constant 2011 Canadian dollars of expanding the irrigated area in southern Alberta by 10% (59,225 hectares) over the next 16 years. The costs included capital costs for replacing the existing old canals with pipelines, both with and without government subsidies, and the purchase of new low-pressure pivots required for expansion. The benefits include the incremental net benefits of irrigated crops, calculated as the difference between the gross margins of irrigated and dryland crops. The benefits and costs were then discounted and used to calculate a net present value (NPV), and the level of government subsidization required for pipeline construction was calculated from this net present value model. Finally, sensitivity analysis was undertaken for parameters where there was significant uncertainty concerning likely values. The results revealed that the profitability of irrigation expansion for crop producers is subject to the government subsidy provided for the investment in pipeline replacement. With the governments' contribution of 75% to irrigation rehabilitation program, the investment for irrigation expansion would be profitable for producers. It would generate a NPV of $78 million or $1,324 per hectare at the baseline discount rate (10%). However, absent this effective subsidy, expansion would be economically unattractive for producers, because the net benefits obtained from converting the dryland crops into irrigated crops are insufficient to cover the full investment costs required for irrigation expansion, in present value terms. Without the subsidy, expansion would be economically viable to producers only for discount rates (i.e., opportunity costs of capital) of 6.6% or lower.

The first step of Project 1, the development of a systems model, involved the reproduction of the FAO's AquaCrop model in system dynamics form. This step took longer than we had anticipated at the beginning of the project, but has ultimately proved successful – producing results that are very close to AquaCrop's, with significantly lower input data requirements and greater expandability – and the resulting model, called CropSD, now forms the core of the systems model. In addition to simulation of crop biomass and yield for the six crop types, CropSD also calculates irrigation water demand for each crop based on on-farm irrigation technologies, gross irrigation water demands based on the conveyance network, and reservoir releases to satisfy irrigation demands. Further, the model calculates crop production costs and revenues. Work continues on expanding the model to include more the feedbacks identified in the project report of August, 2014, such as the effects of economic factors on the annual crop mix and social considerations related to irrigation expansion. One publication on the effect of model time-step on the accuracy of results will be submitted to an academic journal before the end of the summer, and the writing of a second publication on the systems model is underway. Further, a municipal water demand and use model for Calgary, called the Calgary Water Management Model (CWMM), was completed this spring with data and in-kind support from the City of Calgary, and an academic paper on the model is currently in review. The CWMM was validated (with $R^2 = 0.99$) against historical water demand data for Calgary, Alberta. A series of scenario simulations showed (1) potentially large changes to both seasonal and non-seasonal water demands with climate change and population growth, with population growth a significantly larger driver of water use increases, (2) a need to enhance historical water management policies with new policies such as xeriscaping and greywater reuse to achieve water management goals, and (3) the value of an end-use based model in simulating management policy effects on municipal water demand and use. Its development was necessary because municipal water licenses comprise the second largest water allocation, after irrigated agriculture, in the Bow River Basin. The CWMM was designed to be linked to CropSD. Finally, the agent-based model was used to investigate how the form of the water rights regime affects water market participation, how water market price and volatility affect water market participation, and how the FIT-FIR ("first-in-time first-in-right") regime versus a water-sharing regime affect farmer profitability under adequate and inadequate water supply. Model results indicate that the FITFIR system is neither superior nor inferior to a water sharing system. Instead, a flexible system is required that accommodates a FITFIR regime with no trade in periods of adequate water supply and a trading platform for water-rights sharing during water shortages. If stable water markets are the policy objective, then a water sharing regime would be best regardless of the adequacy of the water supply. Such a flexible system will increase the welfare of licenced crop producers, livestock producers, the irrigation district and its members.

The land-use change component of Project 2 used spatial autocorrelation (SAC) models to identify the comprehensive effects of environmental and socio-economic trends that drove land-use conversions over 12 years. Results from the SAC models indicated that, overall, the impacts of key environmental and socioeconomic factors on land-use changes varied in intensity depending on the type of land-use conversion involved. Further, although environmental factors such as land suitability for agriculture and certain weather conditions were related to land conversion, socioeconomic influences were the dominant forces behind land-use changes in Alberta. Thus, land suitability for agricultural uses, road density, elevation, and population growth were found to be significant predictors of land-use changes. More specifically, high land suitability, low elevation, and moderate road density were associated with land conversion for agricultural purposes. In terms of quantitative results, the assessment of land-use conversions revealed that cropland areas expanded by 14.9%, while pasture areas decreased by 37.5%, with nearly 40% of the pasture converted into cropland within the agricultural class. Further, a 6.1% net decline in the province's agricultural land base occurred over the 12-year period, and the expansion of developed land was substantial, although its overall proportion remained relatively small (1.55 % in 2012). Irrigation was found to be beneficial to agricultural preservation but it favours annual crops over pastures. Thus, pasture and developed land located within irrigation districts was more likely to be converted into cropland.

For the water supply and demand component, in-person interviews were conducted with twelve stakeholders, including irrigation district personnel, provincial dam operators, and government personnel, to gain a greater understanding of water management decisions in irrigation districts under different climatic and hydrological conditions. The interview results on reservoir operations practices were compared with current reservoir optimization models, which typically use a Single Time-step Optimization (STO) approach, to provide guidance for future model development, particularly in terms of a newer Multiple Time-step Optimization (MTO) approach. Interview data were also used to modify the rule curves of AEP's Water Resources Management Model (WRMM) to develop water supply scenarios as input to the systems model. Two papers have been published based on this component of the project: one journal paper, and one conference paper.

A Listing of Papers arising from this initiative presented at Professional Conferences

1. Wang, K., and Davies, E. G. R. "Participatory integrated river basin management: A simulation gaming approach", Poster presentation at *Canadian Water Network Annual Conference*, Toronto ON, May 2016.
2. Davies, E. G. R., Dyck, M., Jeffrey, S, Qiu, F., Ammar, M. E., Brown, B., Wang, K., and D. Amsalu. "Systems modelling for irrigation in Alberta", Presenter and panelist (Davies) at *Land Use 2016 Conference*, Edmonton AB, May 2016.
3. Ammar, M.E., and E. G. R. Davies. "Modelling Irrigated Agriculture Policy Alternatives in Alberta using System Dynamics", Poster presentation at *Land Use 2016 Conference*, Edmonton AB, May 2016.
4. Amsalu, D.W. and S.R. Jeffrey. "Who benefits from irrigation and who should pay for it? A case of southern Alberta's irrigation", Poster presentation at *Land Use 2016 Conference*, Edmonton AB, May 2016.
5. Ammar, M. E., and E. G. R. Davies. "Modelling the irrigated agriculture sector of southern Alberta using system dynamics", *CWRA Alberta Branch Conference*, Edmonton AB, April 2016.
6. Amsalu, D.W. and S.R. Jeffrey. "Cost-benefit analysis of Alberta's irrigation rehabilitation program", Poster presentation at the *Sixth Annual Canadian Agri-Food Policy Conference*, Ottawa ON, January 2016.
7. Ammar, M., and Davies, E. G. R., "A process-based agricultural model for the irrigated agriculture sector in Alberta, Canada", Poster presentation at *AGU Fall Meeting*, San Francisco CA, December 2015.
8. Amsalu, D.W., S. Jeffrey and J. Unterschultz. "Cost-Benefit analysis of Alberta's Irrigation Rehabilitation Program", Poster presentation at the *2015 CANSEE/USSEE joint biennial conference*, Vancouver BC, October 2015.
9. Ammar, M., Davies, E.G.R., Dyck, M., Jeffrey, S., Qiu, F., and Unterschultz, J. "A system dynamics approach to long-range irrigation sector planning for Southern Alberta", Poster presentation at the *2015 Canadian Water Network conference*, Ottawa ON, March 2015.
10. Ammar, M. E., and Davies, E. G. R. Investigation of process-based crop modelling under daily, semiweekly, and weekly simulation time steps. *Agricultural Water Management* (submitted 08/17)

11. Amsalu, D.W., S. Jeffrey and J. Unterschultz. 2015. Economic impact of Alberta's Irrigation Rehabilitation Program. Poster presentation at the *2015 Canadian Water Network conference*, Ottawa ON, March 2015.
12. Ammar, M. E., Ruan, X. F., Davies, E., Dyck, M., Qiu, F., and Jeffrey, S. "Systems modelling for sustainability in Alberta's irrigation sector", *CWRA 2014 Canadian Water Resources Congress*, Hamilton ON, June 2014.
13. Ruan, X., Qiu, F., and Dyck, M. "Effects of climate change and expanding irrigation networks on agricultural land use: A case study of Alberta, Canada". *Canadian Agricultural Economics Society (CAES) Joint Annual Meeting*, Vancouver BC, May 2014.
14. Ammar, M. E., Ruan, X. F., Davies, E., Dyck, M., Qiu, F., and Jeffrey, S. "Systems modelling for sustainable land and water policy in Alberta's irrigation sector", Poster presentation at *Land Use 2014* conference, Edmonton AB, May 2014.
15. Ruan, X. F., Qiu, F., and Dyck, M. "Effects of changing environmental and socio-economic factors as well as expanding irrigation networks on agricultural land use: A case study of Alberta, Canada", Poster presentation at *Land Use 2014* conference, Edmonton AB, May 2014.

Statement on Possible Future Work

Our original aim was to develop a single, comprehensive tool to support decision-making. Thus, the agricultural and municipal components of the systems model of Project 1 were intended to be linked together, and with the ABM of Project 2, so that changes in physical and socio-economic variables influenced one another dynamically. The model coupling was not completed primarily because of time constraints, but also because of methodological differences – in terms of modelling software, simulation time-steps, and dynamic coupling – between systems model and agent-based models. If such a dynamic, linked systems model were completed, it would represent a significant step forward, both theoretically and as a practical decision-support tool, and would have value both for agricultural modelling and river-basin modelling.

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A Listing of Publications (please append in electronic format, publications relevant to the mandate of the Institute):

1. Wang, K., and Davies, E. G. R. Municipal water planning and management with an end-use based simulation model. *Environmental Modelling and Software* (submitted 05/17).
2. Jean, M.-È. and Davies, E. G. R. (2016). Towards best water management policies: How current irrigation reservoir operation practices compare with theory in Alberta. *Water International* 41(7): 948-965. doi: 10.1080/02508060.2016.1210562.
3. Ruan, X., F. Qiu and M. Dyck. (2016). "The Effects of Environmental and Socio-Economic Factors on Land-Use Changes." *Environmental Monitoring and Assessment* 188 (8): 1-31.
4. Jean, MÈ., and Davies E. G. R. Water managers' perspectives on reservoir operations for sustainable irrigation in Alberta. *WIT Transactions on Ecology and the Environment* 197, A Coruña, Spain, June 2015. 12 pages. doi: 10.2495/RM150151.
5. Ammar, M., Ruan, X., Davies, E., Dyck, M. Jeffrey, S., Qiu, F., and Unterschultz, J. "Challenges and opportunities associated with expanding the irrigation sector in Southern Alberta". Report for the Alberta Land Institute, Edmonton AB, September 2014. 47 pages.

Please note that two additional papers by Ammar and Davies, and one paper by Ammar, Wang and Davies, are in preparation for submission to academic journals.

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A Listing of Other Forms of Dissemination (relevant to the mandate of the Institute):

Four stakeholder workshops were held in Lethbridge AB, one with the project's advisory panel, and three with groups of stakeholders including irrigators, irrigation district personnel, government personnel, and academics. These workshops were used to refine the research questions to be addressed by the project, and to provide feedback on work completed to date. The first workshop was conducted in December 2013, and the final workshop in December 2015.