PROJECT FINAL REPORT

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List of Acronyms and Glossary of Terms

Acronym	Meaning
AMO	Atlantic Multi-decadal Oscillation, a climate index
ANN	Artificial Neural Network, a machine intelligence method
AO	Arctic Oscillation, a climate index
BRID	Bow River Irrigation District, in the Bow River Basin
EID	Eastern Irrigation District, in the Bow River Basin
ELM	Extreme Learning Machine, a machine intelligence method
MAE	Mean Absolute Error, a statistical measure of “goodness of fit” (m^3/s)
MLR	Multiple Linear Regression, a statistical technique to model the relationship between input variables and an output variable
MTO	Multiple Time-step Optimization, the proposed basin modelling approach
NAO	North Atlantic Oscillation, a climate index
NINO	El Niño Southern Oscillation, a climate index
NOAA	National Oceanic and Atmospheric Administration of the U.S.
NP	North Pacific Index, a climate index
NSE	Nash-Sutcliffe Efficiency, a statistical measure of “goodness of fit”
PCA	Principal Component Analysis, a statistical procedure
PDO	Pacific Decadal Oscillation, a climate index
Q	Streamflow (m^3/s)
R^2	Coefficient of determination, a statistical measure of “goodness of fit”
RID	Raymond Irrigation District, in the Oldman River Basin
RMSE	Root Mean Square Error, a statistical measure of “goodness of fit” (m^3/s)
SMRID	St. Mary River Irrigation District, in the Oldman River Basin
SOI	Southern Oscillation Index, a climate index
STO	Single Time-step Optimization, the standard river basin modelling approach
SWE	Snow Water Equivalent, equivalent depth of water in snow pack (mm)
TID	Taber Irrigation District, in the Oldman River Basin
WEB.BM	Online prototype Multiple Time-step Optimization model developed with Alberta Innovates funding support
WID	Western Irrigation District, in the Bow River Basin

Executive Summary

This project developed a prototype tool to optimize seasonal operations of reservoirs within irrigation districts. Irrigation districts manage water licenses, internal reservoir storage and canal flows, and influence annual crop demands. Their shares of water licenses account for 77% and 87% of the total allocations in the Bow and Oldman River Basins, respectively. Although the districts have substantially reduced their gross diversions over the last two decades through increased water-use efficiency, further increases in efficiency are possible with a computer modelling approach called "Multiple Time-Step Optimization" (MTO). The resulting "water savings" offer the opportunity to 1) increase river flows, providing important environmental benefits, 2) deliver significant economic benefits by making greater volumes of water available to irrigated agriculture to reduce drought risks, and 3) support irrigation sector expansion that meets all water licenses and in-stream water-quality objectives.

Our prototype MTO model, WEB.BM, developed through this project is now complete for the Bow River Basin, and is available as an online decision support tool. It provides weekly operational guidance for reservoir operators based on current storage levels and crop demands, using 1) seasonal runoff predictions based on snow pack observations, global climate indices and historical runoff patterns; 2) multiple time-step optimization over an operational horizon of up to 12 weeks; and 3) a self-correcting mechanism that takes into account actual reservoir storage each time the model is run, such that the previous forecast obtained in the previous week is corrected by using the actual storage level at the time the model is run. Six of the major irrigation districts in Alberta participated as project partners. The Bow River (BRID), Eastern (EID), and Western (WID) Irrigation Districts will be using the model as of October 25 and December 17 after attending workshops to introduce them to all model features. Work will continue in the next several years to prepare a similar tool for the Oldman River Basin districts: St. Mary River (SMRID), Taber (TID), and Raymond (RID).

A number of our academic journal and conference papers (either published or in preparation) demonstrate the advantages of the MTO modeling approach. One applies the MTO approach to the Western Irrigation District. The second compares results from seven different models for a test problem created in collaboration with the Government of India, and provided as part of a World Bank tender. This is the first time a numerical test problem has been included as part of the tender. No other vendors were able to match the benchmark solution provided by our WEB.BM. The results of the numerical tests will be presented at an international conference in Pune, India, and will also be submitted to a major technical journal in the coming months.

Seasonal and monthly streamflow predictions for the growing season are necessary as input to the MTO seasonal operational model, since it simultaneously optimizes water allocation over the entire Spring-Summer season (May-July). As such, it requires reliable predictions of streamflow volume over that period by no later than the end of April of a given year. We have therefore developed a model that predicts streamflow accurately for up to three months in advance of the start of the irrigation season. The development of these streamflow predictions was a difficult, complex, and time-consuming component of the project; however, the resulting monthly and seasonal streamflow predictions for the Bow River at Calgary have relatively low error (seasonal RMSE of 24 m^3/s for a mean streamflow of approximately 190 m^3/s), and are of interest to a wider audience, including members of Alberta Environment and Parks, Agriculture and Forestry, and the irrigation districts.

Also completed was a set of 904 years of stochastic weekly Bow River and tributary flows for use by the City of Calgary based on 1) tree ring data from the University of Regina (produced with Alberta Innovates funding), 2) 100 years of weekly naturalized flow records at the City of Calgary, and 3) a new algorithm for in-filling missing data. These flows were used to model water supply for the City of Calgary, based on the current level of water demand in the three major irrigation districts and Calgary, as well as existing TransAlta Corporation operating rules. The study was well received by the City of Calgary, and the in-filling algorithm has been published in the academic literature.

In summary, we successfully completed all major proposed components, 1) developed seasonal flow forecasting methods and tools for use by Irrigation Districts and other groups in the Bow River Basin, 2) set a new standard for river basin modelling based on MTO, 3) developed a benchmark solution for MTO and, 4) introduced the WEB.BM model to the irrigation districts and modelling practitioners worldwide. We propose additional work to prepare streamflow predictions and the WEB.BM model for use by three irrigation districts in the Oldman River and Southern Tributaries Basins, SMRID, RID, and TID.

1. Project Description

The aim of this project was to develop a prototype tool to optimize seasonal operations of irrigation reservoirs. Irrigation districts manage water licenses, internal reservoir storage and canal flows, and influence annual crop demands. Although the districts have substantially reduced their gross diversions over the last two decades through increased water-use efficiency, further increases in efficiency are possible with a computer modelling approach called “Multiple Time-Step Optimization” (MTO). The resulting “water savings” offer the opportunity to 1) increase river flows, 2) make greater volumes of irrigation water available to reduce drought risks, and/or 3) support irrigation sector expansion.

Our completed online MTO model, WEB.BM, uses seasonal runoff forecasts developed for the irrigation season (May-July) and an operational horizon of up to 10 weeks to provide updated operational guidance to irrigation districts throughout the season based on current storage levels and crop demands. Six of the major irrigation districts in Alberta participated as project partners. The Bow River districts – WID, BRID, and EID – will being to test and evaluate the prototype tool this autumn, and work is ongoing to complete a model version for three districts in the Oldman River Basin, SMRID, RID, and TID.

The overall project objectives were to,

- Find the best way to manage internal district storage and licensed diversion within an irrigation season, and
- Extend results from planning studies to real-time operation.

The first goal addressed drought management, and in addition to the six participating irrigation districts, the City of Calgary was an important stakeholder that contributed to this study. The project also had secondary goals, which were implicitly included in the above goals, and were to,

- Establish the utility of the Multiple Time Step (MTO) solution approach,
- Develop river basin optimization benchmark tests,
- Develop an algorithm for in-filling the missing data in hydrologic series, and
- Develop reliable streamflow predictions with up to three months of lead time.

2. Results and Discussion

We focus here on two key components of the project: 1) the development of the MTO model for use by Irrigation Districts in decision support, 2) the development of stand-alone streamflow predictions for input to the Multiple Timestep Optimization (MTO) model or for more general use by multiple stakeholders throughout the Bow River Basin, and 3) the 904 years of stochastic weekly Bow River flows produced for Calgary. All three components have been completed successfully. In addition to this, WEB.BM is also available as a promising web-based river basin management model that may be of interest to many practitioners around the world.

2.i. MTO Modelling for Irrigation District Operations

Our MTO model, WEB.BM, has been designed with a seasonal operational option to be used by irrigation districts in Alberta, in combination with the seasonal forecasting model. However, WEB.BM can also be used as a planning model with a range of capabilities, and it is the first and so far the only model of its kind that is freely available as a web application. The online model WEB.BM has been tested by Optimal Solutions Ltd. for the WID, EID, and BRID irrigation districts, while a PC version has also been used for a Narmada River Basin, India, benchmark test. In meetings with the three districts in the summer of 2019, it was agreed that all three will be included in a single model of the Bow River Basin. All three districts will then be able to run the model and gain insight into the water supply operation within each district. The model will also include the new operating rules on the Ghost reservoir which have caused recent difficulties for water supply to the Districts at the end of June and in the first 10 days of July.

A technical paper on the benefits of MTO for irrigation district operations has been completed. The material outlined in the paper was presented at the Alberta Water Resources Association annual conference in Red Deer in April 2019, and has since been submitted for publication in the Canadian Water Resources Journal. Prior to submission, the paper was reviewed by the WID District Manager, since a numerical example related to the WID district was used in the paper. The paper addresses previous modelling work done by Alberta Environment and Parks, and reveals that the previous limit on the WID diversions from the Bow River as determined by AEP could have been 20% higher on average if different assumptions were made in the process. This point is better explained in the paper.

We are also preparing a paper containing a broadly useable benchmark test problem. The intents are to demonstrate the benefits of the MTO approach, and to establish testing standards for the industry that would permit comparison of the quality of existing modelling tools. Benchmark preparation was conducted in collaboration with the Government of India, through a World Bank tender published on India's National Hydrology Project web site. It focused on the Narmada River Basin, one of the most prominent basins in India, which straddles five states and includes a number of large reservoirs and diversion structures. The total storage in five major dams is 27.8 billion m^3, which amounts to roughly three times the volume of Lake Diefenbaker, Saskatchewan. The Narmada Control Authority has so far used spreadsheets to carry out water accounting, and wants to develop planning simulations and seasonal modelling with better tools. The use of a technical test problem was suggested as a step in the selection of the best model for the basin, and the World Bank tender invited all existing model vendors to provide their solutions.

The Narmada River Basin MTO test has been compiled and results will be presented at an International Technical Conference (http://nhp.mowr.gov.in/conference-2/) in Pune, India, on Nov. 6, 2019 – the conference paper is attached. After that, a revised version of the paper will be submitted to a high impact water resources journal. The test problem was of moderate difficulty. Yet, the only correct solution was obtained from the WEB.BM model, despite the fact that well-known model groups including OASIS (Hydrologics Inc.) and Mike-Basin (Danish Hydraulic Institute) also submitted solutions. We believe that the forthcoming publications will generate interest for WEB.BM among practitioners around the world.

2.ii. Seasonal and Monthly Streamflow Predictions

Seasonal and monthly streamflow predictions for the growing season are necessary as input to the MTO seasonal operational model, since it simultaneously optimizes water allocation over the entire high river-flow period critical for irrigated agriculture (May-July). As such, it requires reliable predictions of streamflow volume over that period by no later than the end of April of a given year, and ideally up to three months in advance. The development of these streamflow predictions was a difficult, complex, and time-consuming component of the project. The subsections below provide first details of the input data and processing, then model development, and finally streamflow projection model results.

a) Input data and processing

In developing the seasonal and monthly streamflow prediction models, we have used both local and large-scale climate data. At a local scale, historical records of average monthly precipitation, minimum, maximum, and mean temperatures and local snow cover have been collected, as well as stream flow data generated as monthly-averaged naturalized historical flow records from the Upper Bow River watershed in Southern Alberta. Data from mountainous, upstream areas of the Bow River Basin are critical, because a substantial portion of the runoff comes from this area. However, such data are difficult to obtain because only a few stations exist there, and records are short and sometimes incomplete. In particular, snowpack data are limited and have the shortest historical records. We have therefore compiled all the available historical data sets for the variables listed above, including records from Environment Canada, Alberta Agriculture and Forestry, and Alberta Environment and Parks. We devoted significant time to this work during the project, and it has resulted in substantial improvements to model values.

At a larger scale, previous studies have found that using climate indices (also called “teleconnections”) as predictors improves the streamflow forecasting skill. However, no single climate index can explain all climate variability within a river basin, and climate indices are therefore typically used in groups. We selected eleven large-scale climate indices for our study based on their linkage, by previous studies, to streamflow, precipitation, and temperature variability in the winter and summer months over Canada or North America, while others have been used to develop streamflow forecasting models in Canada or North America. The selected indices are NINO 1+2, NINO 3, NINO 3.4, and NINO 4 (Rayner et al., 2003), which are a time series of sea surface temperature (SST) anomalies in the Pacific Ocean; SOI (Ropelewski & Jones, 1987); PDO (Mantua et al., 1997); AO (Zhou et al., 2001); NAO (Hurrell et al., 1997); AMO (Enfield et al., 2001; Rayner et al., 2003); North Pacific (NP) Index (Trenberth & Hurrell, 1994), which is the area-weighted sea level pressure anomalies over 30°N–65°N, 160°E–140°W; and the Darwin SLP (Allan et al., 1991; Ropelewski & Jones, 1987). Monthly time series of these eleven indices were downloaded from NOAA’s Global Climate Observing System Working Group on Surface Pressure website (www.esrl.noaa.gov/psd/gcos_wgsb/Timeseries/); their values are regularly updated.

The climate indices were used, in conjunction with local-scale variables, as input to the seasonal streamflow forecasting model. Once potential predictors were identified and their values were prepared, the local and global predictor variables were grouped into three input datasets similar to those used for seasonal streamflow forecasts. The first set (S1) represents conditions from 1981 to 2014 and uses a combination of local observations and climate indices. The second set (S2) has a longer record than S1, from 1970 to 2014, but has a lower number of predictors (because of data limitations) in the forecasting model. The third set (S3) has only climate index predictors (i.e. no local predictor variables), which provides a longer data record, and therefore extends from 1950 to 2014. In order to partition the data into the model development (training) and model evaluation (testing) parts, each of the three full sets was split into ≈70% for model calibration and validation and ≈30% for the model testing. Table 1 summarizes the statistical characteristics of the streamflow for the full-time span of each input dataset. Input datasets were used in both monthly and seasonal-average forms and were lagged by 12 months and 4 seasons, respectively, to represent the antecedent conditions up to the end of the previous year.

Table 1: Descriptive statistics for Bow River seasonal streamflow

Partition	Period	No. records	Average Seasonal Streamflow (m^3/s)				
			Mean	St. Dev.	Median	Minimum	Maximum
Input Data Set 1							
Training	1981-2003	21	550	117	521	377	781
Testing	2004-2014	11	633	166	658	404	883
Input Data Set 2							
Training	1970-1999	30	536	116	524	330	781
Testing	2000-2014	15	596	160	609	400	883
Input Data Set 3							
Training	1950-1992	42	547	114	529	330	781
Testing	1993-2014	22	588	136	584	400	884

b) Forecasting Model Development

Having identified potential input variables, we next chose three different models for seasonal and monthly streamflow prediction: Multiple Linear Regression (MLR), Artificial Neural Networks (ANN), and Extreme Learning Machines (ELM). While MLR was chosen for its simplicity and ease of interpretation, ANN and ELM were chosen because several recent studies have shown their superiority over other streamflow forecasting models in some regions of North America. In training MLR models, the coefficients of the independent variables represent the local behaviour and were estimated by the least-squares methods. For ELM models, many configurations were tested, including ten different activation functions and a range of values for the number of hidden neurons. As in the case of Artificial Neural Network model, a feed-forward back-propagation network with three layers and one hidden layer was used.

In developing MLR, ANN, and ELM models, and because of the high-dimensional nature of our input datasets of predictors, not all of which were used by each model, an essential step in developing data-driven prediction models is the selection of a reduced number of input variables for the different models (i.e., MLR, ELM, and ANN). Variable selection allows the machine learning algorithm to train in shorter time, having simpler network structure, with better accuracy by reducing the potential of overfitting and makes the model easier to interpret. For this purpose, we used four variable selection techniques: high correlation (Pearson), forward stepwise selection, backward stepwise elimination, and we tested the use of a preprocessing technique, namely, principal component analysis (PCA).

For model training, we used ≈70% and employed a k-fold cross-validation technique to avoid overfitting, with ten folds and random sampling of data in each fold. Root-Mean-Square Error (RMSE) was calculated for each of the ten folds and then averaged over them. The MLR, ANN, and ELM models were optimized based on a minimum RMSE criterion. To investigate the model prediction accuracy, we used ≈30% of the data that were unseen by the model during any stage of model training. Model forecasting skill was evaluated using the following metrics: mean absolute error (MAE), root mean square error (RMSE), the coefficient of determination (R^2), Nash-Sutcliffe model efficiency coefficient (NSE), and the index of agreement (d). Figure 1 summarizes the steps for developing the ELM and ANN models.

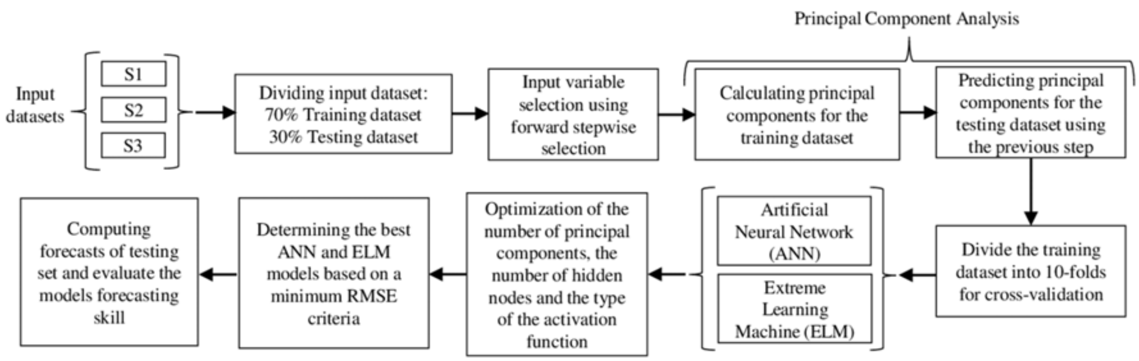

Figure 1: Flowchart summarizing the steps for developing the Extreme Learning Machine (ELM) and Artificial Neural Network (ANN) models.

c) Streamflow Projection Model Results

We tested a number of streamflow model configurations, including regression approaches and machine learning methods. In general, the nonlinear machine learning approaches, Extreme Learning Machines (ELM) and Artificial Neural Networks (ANN), outperformed multiple linear regression (MLR), which tended to underestimate the peak values. Figure 2 shows the performance of the ELM model over the testing period (2000-2014). More generally, ELM always outperformed ANN except for the May streamflow (Table 2), and the prediction accuracy for June and July was better than for May (Table 2 and Figure 2). Further, coupling the ELM and ANN models with PCA improved model performance and the quality of the predictions. Using ELM coupled with PCA permitted seasonal streamflow predictions to be issued in April with NSE = 0.79, RMSE = 24 m^3/s, and R^2 = 0.84. The three most important predictors of the spring to summer runoff in the Bow River Basin were the Atlantic Multi-decadal Oscillation (AMO) in November, the Pacific Decadal Oscillation (PDO) in December, and the measured snow-water equivalent (SWE) in April.

Several groups in Alberta Environment and Parks as well as the irrigation districts are interested in longer lead-times for monthly and seasonal streamflow predictions. Therefore, we investigated the effect of increasing lead time on prediction accuracy and found that the forecasting skill decreased as the lead time increased. The degree of decrease depended on a number of the important predictor variables becoming unavailable to the model as the lead time increased. Importantly, while monthly prediction accuracy decreased with lead time, seasonal predictions experienced little decrease as early as February of the same year. These results also have important implications for flooding and drought forecasts. For dry conditions, drought classes were determined through the streamflow drought index (SDI) (Vincente-Serrano et al., 2012). The streamflow prediction model can provide reliable warning of below normal condition (0.33 quantile) with 74% accuracy. Further, the model can reliably predict high streamflow conditions (above 0.8 quantile) with 80% accuracy.

Table 2: Summary of evaluation measures for the better May, June, July streamflow prediction models

Model	Mean absolute error (MAE) m^3/s	Root mean square error (RMSE) m^3/s	Coefficient of determination (R^2)	Nash-Sutcliffe coefficient (NSE)	The index of agreement (d)
ELM					
Seasonal	21	24	0.84	0.79	0.95
May	15	17	0.76	0.75	0.92
June	30	34	0.89	0.87	0.96
July	13	15	0.9	0.88	0.97
ANN					
Seasonal	34	41	0.53	0.54	0.76
May	23	27	0.53	0.28	0.75
June	47	54	0.55	0.64	0.77
July	31	39	0.49	0.70	0.75

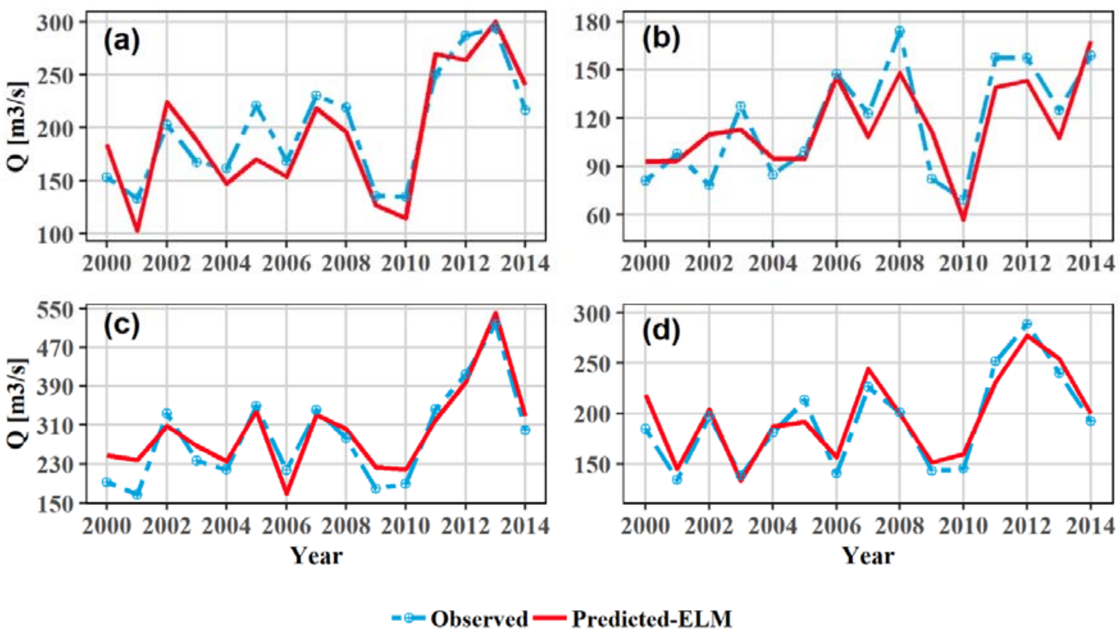

Figure 2: Extreme Learning Machine (ELM) predictions and observed streamflow for input dataset S2 (a) Seasonal, (b) May, (c) June, and (d) July for the testing period (2000-2014).

2.iii. Stochastic Weekly Bow River Flows for 904 Years and City of Calgary Water Supply

An earlier Alberta Innovates project led by the PARC institute at the University of Regina and co-funded by the City of Calgary generated weekly flow estimates for a long historic period (1111-1911) based on decomposition of annual flows derived from tree ring data. The tree ring signal helped to generate annual flow estimates. However, annual flows alone are not sufficient input into complex water resources models, and so decomposition of annual into weekly flows was conducted for a single location at the City of Calgary. This work was previously published in Water Resources Research (Sauchyn and Ilich, 2017). Weekly flows at the Bow River near Calgary are thus a mix of flows from the historical record, and estimated weekly flows dating back to 1111 derived from a decomposition of the tree ring-based annual flow estimates. The generated series 1) exhibits weekly statistics that are similar to the weekly statistics of the historical naturalized flows, and 2) conforms also to the annual means obtained from the tree rings proxy.

In addition to weekly hydrologic input, water allocation models also require a breakdown of a larger river basin into smaller sub-basins, along with runoff values for each sub-basin as a unique continuous hydrological series. We therefore used weekly flow estimates of the Bow River below the Bearspaw Dam for the 1111-2014 period, developed as described above, as a reference point to fill missing data from 14 hydrometric stations on the main stem and the tributaries of the Bow River, as well as for precipitation and evaporation estimates at Calgary. The result was a 904 year record of weekly time series for 15 locations as inputs available for input to a water allocation model. The in-filling of the missing data required development and testing of an algorithm for this purpose. A technical paper describing this work was published in the Hydrological Sciences Journal (2018).

These 904 years of weekly flows were then input to a river basin model which was used to examine flows through existing infrastructure, focusing on the performance of the Bearspaw and Glenmore Reservoirs in meeting water demands of the City of Calgary. The model is based on the existing water licensing system, where the three senior irrigation licenses for the BRID, EID, and WID, have the highest priority, followed by Transalta's licenses for their reservoirs and the City of Calgary's licenses for municipal withdrawals. Other junior licenses were also modelled, as well as their interaction with the in-stream water conservation objectives (WCOs), to which many licenses issued after 1990 have been subjected. Both the irrigation demand for senior irrigation licenses as well as water conservation objectives had to be estimated in relation to the generated flows in this study. Stochastic generation of flows also involved generation of precipitation series, which were used in the assessment of net irrigation demands. Similarly, water conservation objectives flow targets for selected river reaches were created in relation to generated natural flow estimate in a similar way that was done in previous studies by Alberta Environment and Parks.

Results showed that supply deficits from the Bearspaw Reservoir were encountered less than 10% of the time and only within the period between weeks 19 and 44. Such deficits were primarily caused by insufficient conveyance capacity at the Glenmore Dam, which has maximum of release of 4.63 m^3/s in open water season months, of which half can be used to augment the targeted Bearspaw supply. Hence, if deficits at Bearspaw Reservoir are above 2.315 m^3/s in some years, a supply deficit for the city is inevitable, and the deficit reduction is equal to the Bearspaw demand reduced by the total supply that can be provided by both Bearspaw and Glenmore. In contrast, Glenmore Reservoir deficits are very rare, and happened in only 7 out of 904 years, when there was a total depletion of storage.

3. Overall Conclusions

We have completed all major components of the study. Specifically, the project has successfully, 1) developed seasonal flow forecasting methods and tools for use by irrigation districts and other groups in the Bow River Basin, 2) set new standards for river basin modelling based on MTO, 3) developed a benchmark solution for MTO, and 4) introduced the WEB.BM model to irrigation districts and basin modelling practitioners worldwide.

Of the three methods tested for predicting streamflows, the ELM model provided the most accurate results. Our flow forecasting methods will be detailed in a number of academic publications currently under preparation, and an online streamflow prediction tool has been developed for use by the irrigation districts (available at https://amrgharib.shinyapps.io/seasonalForecastingModelBowRiverBasin/).

MTO should be considered the new modelling standard for river basin modelling. An argument to this effect is presented in a paper submitted to the Canadian Water Resources Journal. The paper demonstrates superior results of MTO as compared with the traditional single time-step optimization (STO) approach for the Western Irrigation District. Further, a benchmark test for the basin modelling community has been prepared based on the Narmada River Basin, India, with results to be published in an upcoming conference and a technical paper. Finally, three irrigation districts in the Bow River Basin, WID, BRID, and EID, are currently testing the new WEB.BM model.

In addition to these four main components, it is possible to develop very long data series of streamflows based on tree ring data and historical flow records. We developed a set of 904 years of stochastic weekly river flows on the Bow River and upstream tributaries for use by the City of Calgary based on 1) tree ring data provided by the University of Regina from a project previously funded by Alberta Innovates, 2) historical records of 100 years of weekly naturalized flows at the City of Calgary, and 3) a new algorithm for in-filling missing data. These 904 years of weekly flows were used as input to model water supply for the City of Calgary. This study assumed the current level of water demand at the three major irrigation districts and the City of Calgary, as well as the existing TransAlta Corporation operating rules. The study was well received by the City of Calgary, and the in-filling algorithm has been published in the academic literature.

4. Next Steps

4.i. Communications Plan

Two workshops on the WEB.BM model are scheduled for the three irrigation districts in the Bow River Basin for October 25 in Strathmore and on October 29, 2019 in Brooks. These workshops will also be attended by representatives of the three Oldman River Basin districts that participated in the project as well as the Provincial and Federal government employees interested in using WEB.BM**.**

4.ii. Future Research

Although the WEB.BM model is complete for the Bow River irrigation districts, WID, BRID, and EID, we continue to work on the Oldman River Basin and Southern Tributaries version. Over the next year, streamflow projections for the Southern Tributaries, which are the source of water for SMRID, TID, and RID, will be developed with funding support from Optimal Solutions Inc. and Mitacs. We are searching for funding sources to support WEB.BM updates for the three Oldman River Basin districts.

4.iii. Commercialization Plan

The potential market for the MTO approach proposed here is significant, particularly because there are currently no real-time models for irrigation district operation with its planned capabilities. If successfully implemented in Alberta, the project may lead to the development of a growing community of on-line users, who would be willing to fund fee-based technical support services; these would eventually constitute a return on investment to Alberta through charges for these services. The principal vehicle for revenue is separation of the solver component of the model from the database and graphical user interface, with installation of the solver on a separate server that can be accessed by other modeling platforms. Optimal Solutions is currently engaged with two model vendors who are interested in being able to access the solver in this manner. After successful implementation and testing, this could lead to various licensing agreements.

4.iv. Environmental and Economic Benefits

The project did not focus on the larger economic and environmental benefits of an operational model for irrigation reservoir management; however, the following discussion addresses its potential use for these purposes.

Application of the WEB.BM model may yield potentially significant economic benefits. As the model is tested and implemented by irrigation districts and other stakeholders over the next several years, it is likely to 1) permit greater water supply to support irrigation and potentially agri-food processing expansion, 2) reduce the effects of water shortages during dry years, and 3) provide a return on investment through fee-based technical support services to help to implement and run MTO models in other jurisdictions. Such benefits may prove economically valuable both to the agricultural producers and communities of southern Alberta, and to the province as a whole.

A recent study conducted for the Alberta Irrigation Projects Association by Paterson Earth and Water Consulting Ltd. (2015; hereafter Paterson Earth and Water) found combined annual sales of irrigation crop and livestock products generated $1.7 billion dollars for the Alberta economy, and nearly $1.7 billion from the associated agricultural processing industries. Approximately 90% of this economic value accrued to the province and region, and 10% to the irrigation producers themselves.

To determine potential economic benefits of an increased irrigation supply from use of the WEB.BM model, we use representative figures from Paterson Earth and Water (2015) to calculate possible additional revenues from irrigation expansion. The resulting monetary value is large. An application of the Multiple Time-Step Optimization (MTO) approach to the Western Irrigation District (WID) showed that it is possible with perfect foresight of seasonal runoff to divert 20% more water from the Bow River per year, on average, to the WID (Ilich et al., *CWRJ*, under revision). Further, this greater diversion is socially and environmentally benign, as it was accomplished without any negative effects to in-stream flows, apportionment, or other stakeholders with senior license priorities.

These larger diversion volumes can be connected with 1) an average net irrigation value of $2,070 per hectare (Paterson Earth and Water, 2015), 2) an actual irrigated area of 491,000 ha per year from 2000-2011, and 3) the possible greater supply of irrigation water permitted by the MTO approach. To take a conservative approach, rather than the possible 20% increase in diversion to the Western Irrigation District, we use a 10% increase in the supply for all the irrigation districts together. This increase would permit an additional irrigation area of 50,000 ha. Combining this irrigation area with the net value of irrigated production yields an additional $102 million per year in irrigation revenues. These figures are clearly approximate and omit the necessary investments in new irrigation infrastructure (reservoirs, conveyance works, and on-farm equipment), but also the potential increases in agricultural processing industries. Therefore, even a one-tenth expansion made possible by the project would yield large and continuing economic benefits for both southern Alberta and the Province as a whole.

The project will also reduce the number of dry years with irrigation deficits. Drought is economically damaging, with lengthy and wide-spread droughts among the costliest natural disasters (Bonsal et al., 2013). Further, the situation may worsen world-wide, as drought frequency and severity are both projected to increase with climate change throughout the 21st century (Prudhomme et al., 2013). Therefore, the potential role of the project in improving production in dry years and reducing the economic risks faced by irrigation farmers and agri-foods processing industries is important. Further, this reduced risk of irrigation deficits – along with the potentially greater water supply as a result of greater irrigation efficiency – may provide incentive for increasing production of value-added agricultural goods and increasing numbers of value-added agri-foods industries in the South Saskatchewan basin, as recommended by the South Saskatchewan Regional Plan (AEP, 2014). In this regard, note that the irrigated area for potatoes increased from 8,700 ha in 1995 to over 18,000 ha in 2012 with the expansion of world-class agri-food processing companies in Southern Alberta, including Lamb-Weston and McCain Foods.

In terms of environmental benefits, the project will make greater volumes of water available for stakeholders, for the environment, or for both. Specifically, the greater agricultural water-use efficiency made possible by the model would present opportunities to 1) increase river flows, providing clear environmental benefits and without detrimental effects for the irrigation sector, 2) boost irrigated production while still meeting all licenses and water quality objectives, or 3) provide a combination of each: both higher environmental flows and higher irrigation production.

The WEB.BM model should also help partner groups and the Province to deal with a decreased water supply into the future. According to recent studies, the *"*future water availability in Southern Alberta does not look encouraging, even without considering the expected increasing water demands of a growing economy and population" (St. Jacques et al., 2010: 4). In fact, some of the projected changes in hydrology, with higher winter flows, but reduced spring peak flow and summer flows, are actually already apparent relative to the historical record (Rood et al., 2008; Burn et al., 2010). Recently, Philipsen et al. (2018) found a slight decline in the summer and annual flow from 1912 to 2016 by 0.13%/year. Over the next 25 years, the South Saskatchewan River basin may experience both increased temperatures and significantly decreased mean annual and maximum streamflow with climate change (Islam and Gan, 2014), and although precipitation is actually predicted to rise into the future, the projected increase in evaporative losses due to increased temperatures will offset its increase (Tanzeeba and Gan, 2011). In contrast, recent projections using Global Circulation Models indicate a decrease in streamflow from the mountain headwaters and an increase of streamflow from the foothills, resulting in an overall increase of streamflow +0.1%/year (Philipsen et al., 2018). Operational support for reservoir management in this context of decreasing supply, increasing demands, and overall uncertainty will become increasingly important.

5. References

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Appendix A: List of Project Outputs

HQP Trained

Gharib, Amr, PhD candidate in Civil and Environmental Engineering at University of Alberta. Research topic: streamflow projections with machine intelligence methods for Bow River

Journal Articles

Ilich, N., A. Gharib, and E. G. R. Davies, (2018). Kernel distributed residual function in a revised multiple order autoregressive model and its applications in hydrology. *Hydrological Sciences Journal* 63(12):1-14.

Ilich, N., A. Gharib, and E. G. R. Davies. New Modeling Paradigms in the Assessment of Future Irrigation Storage Requirements with a case study of the Western Irrigation District in Alberta. *Canadian Water Resources Journal* (under revision, 09/19).

Ilich N., M. Sinha, N. Manglik, J. Quebmann, and N. Kumar. Comparison of River Basin Model Solutions on the Narmada River Basin Test Problem. To be submitted to *Water Resources Research*.

Ilich, N., A. Gharib, E. G. R. Davies. Reservoir Optimization Model for Irrigation Districts. To be submitted to *Journal of Water Resources Planning and Management-ASCE*.

Gharib A., E. G. R. Davies, and N. Ilich. Streamflow prediction for the Summer Months and Season in the Bow River Basin, Alberta, Canada. To be submitted to *Hydrology and Earth System Sciences* (HESS).

Gharib A., E. G. R. Davies, and N. Ilich. On the variable selection techniques for data-driven streamflow prediction models. To be submitted to *Journal of Hydrology*.

Conference Presentations

Ilich N., M. Sinha, and N. Manglik, (2019). Comparison of River Basin Model Solutions on the Narmada River Basin Test Problem. *2nd International NHP conference on Sustainable Water Management*, Nov. 6–8, 2019, Pune, India.

Gharib A., E. G. R. Davies, and N. Ilich, (2019). Streamflow Forecasting for the Summer Months and Seasons with Machine Learning Models in the Bow River Basin, Alberta, Canada. paper 95. *8th International Conference on Water Resources and Environment Research*, Jun. 14-18, 2019, Nanjing, China.

N. Ilich, E. G. R. Davies, and A. Gharib, (2019). New Modeling Paradigm for the Assessment of Future Reservoir Storage Requirements: a case study of the Western Irrigation District", Alberta, *2019 CWRA Alberta Conference*, Apr. 14-16, 2019, Red Deer, AB.

Gharib A., E. G. R. Davies, and N. Ilich, (2019). Reliable Summer Streamflow Forecasting in the Bow River Basin Using Machine Learning Techniques, *2019 CWRA Alberta Conference*, Apr. 14-16, 2019, Red Deer, AB.

Davies, E. G. R., N. Ilich, and A. Gharib**,** (2019). Seasonal Operational Model for Water Management within Irrigation Districts. *Alberta Irrigation Districts Association Water Conference*, Feb. 5, 2019, Calgary, AB.

Reports

Optimal Solutions Inc., (2017). 904 Years of Weekly Modeling of the Bow River Basin. A report submitted to the City of Calgary, Dec. 8, 2017. 21 pages.

Software Products

Seasonal Flow Forecasting
(https://amrgharib.shinyapps.io/seasonalForecastingModelBowRiverBasin/**)**

WEB.BM (to be linked to the optimal-solutions-ltd.com web site before Oct. 25, 2019)