

An integrated approach for the assessment of water availability for irrigation in semi-arid regions

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Abstract

An integrated approach to water availability assessment for irrigation is presented and illustrated through examples from Canada's South Saskatchewan River Basin (SSRB). It is based on the integration of irrigation and non-irrigation water demands at the basin level, and accounts for the seasonal and annual variation in water supply and water demand. Irrigation water demands are derived from a detailed simulation model which estimates irrigation water diversion and return flow based on physical, climatic and operational parameters and management practices. By integrating the time varying demand and supply, water availability can be expressed in terms of probability or a risk-management context. The impact of any long-term climatic changes on water availability is determined through integration of the resulting changes in water demand and water supply. The paper explains the modelling framework used and its application to SSRB, with special emphasis on irrigation. The importance of accounting for the temporal variability of demand and supply when assessing water availability is demonstrated through several examples, including sensitivity analysis of the irrigation sector and the overall basin water resources to climatic changes.

The views expressed in this paper are those of the authors and do not necessarily represent the views of their employer.

Keywords: irrigation water demand, water availability, IWRM, climate variability, climate change, P, ETP, risk, GCM, WATFLOOD.



1 Introduction

While Canada is a water-rich country, water is not always available in sufficient quantity when it is most needed. This is particularly true for the semi arid Prairie region of Western Canada which contains much of Canada's irrigated agriculture. Water availability in this region represents significant challenges to present and future irrigation.

The assessment of water availability for irrigation requires the evaluation of not only water supplies but also of water demands. Both are subject to significant seasonal and annual variation. It also requires consideration of all competing demands on the water resources such as socio-economic uses, maintaining a healthy ecosystem, and potential implications of climate change.

This paper describes a planning model which analyses irrigation water demands using physical and climatic data, integrates these demands with non-irrigation water demands at the river basin level for the quantified assessment of water availability under any number of future development scenarios. The model application is illustrated through examples from Canada's South Saskatchewan River Basin (SSRB). The paper shows how water availability can be represented in terms of probability or a risk-management context through the integrated assessment of the impacts of climate variability, and climate change, on water demands and water supplies.

2 Framework for the assessment of water availability for irrigation

The modelling framework for the assessment of water availability for irrigation is depicted in fig. 1. In this framework, irrigation water demands are first evaluated on the basis of irrigation areas. These demands are then integrated with non-irrigation water demands at the basin or sub-basin level and compared against available supplies for basin water budget assessment. Water availability is viewed as the surplus water after satisfying all water demands. The assessment of water availability also takes into consideration the effect of structural measures such as reservoir storage. This modelling framework is the basis of a comprehensive water supply and demand planning model described by Kassem [2] which allows the analysis of water availability under any number of, user-defined, future socio-economic, climatic and other scenarios. The model has been evolving and has had many applications in Canadian studies [e.g., 1,3,5,7].

2.1 Irrigation water demands

Irrigation water demands are calculated using a soil moisture balance simulation sub-model. Each irrigation area is defined by size, crop types/mix, soil types/parameters, irrigation methods and on-farm application efficiency, and delivery efficiency. Precipitation (P) and potential evapotranspiration (ETP) data drive the irrigation water demands simulation. Crop-specific irrigation level parameters, which represent the ratio between actual and potential



evapotranspiration, are utilized to simulate sub-optimal irrigation conditions prevailing in the Prairie region. The basic calculations are performed on a monthly basis within the cropping season. The irrigation sub-model is explained in detail by Kassem [2]. The required irrigation water diversions (and return flows) are, in turn, assigned to the basin (or sub-basin) based on the location (river reach) of water supply and discharge point(s) of return flow.

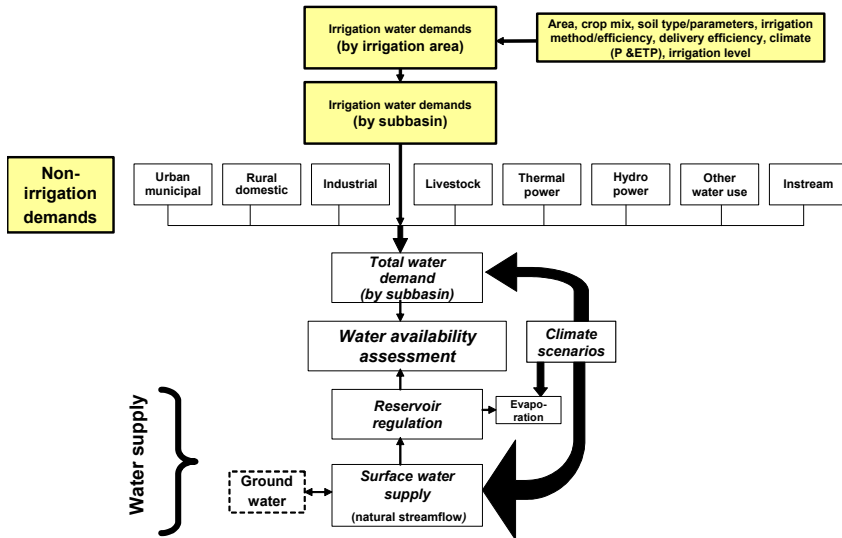


Figure 1: Framework for the assessment of water availability for irrigation.

2.2 Non-irrigation water demands

Non-irrigation water demands are broadly classified into urban-municipal, rural-domestic, industrial (manufacturing and mining), livestock, power generation (thermal and hydro), evaporation and other water uses. Non-withdrawal or instream water uses are simulated based on minimum flow requirements. Non-irrigation water demands are calculated from physical, socio-economic and other data and water use rates, rather than input directly into the model. This allows forecasting of future water demands given projections of future socio-economic conditions and activities. Any changes in water use practices (e.g., water conservation) can be accounted for based on knowledge of the impacts of such changes on the water use rates.

2.3 Water supply

Surface water supplies are represented by natural streamflow data at or near each sub-basin outlet. A long period of hydrologic record is required in order to account for the temporal variability in supply. At present, approximations are

used for groundwater supplies. A distributed hydrologic model, WATFLOOD [4], has also been calibrated for SSRB and is used as a means of projecting future water supplies under climate change scenarios.

2.4 Calculation details

A river basin is represented by nodes, denoting subbasins and links, representing the flow path between nodes. The calculation detail at each node is illustrated in fig. 2. First, water use projections are made based on the user assumptions about the future. Two main water use parameters are calculated: water intake, and water consumption which is the difference between water intake and return flow. The difference between the available supply at the node and water consumption is passed onto the downstream node. A user-defined priority system is employed for the analysis of water allocation issues when available supplies are exceeded.

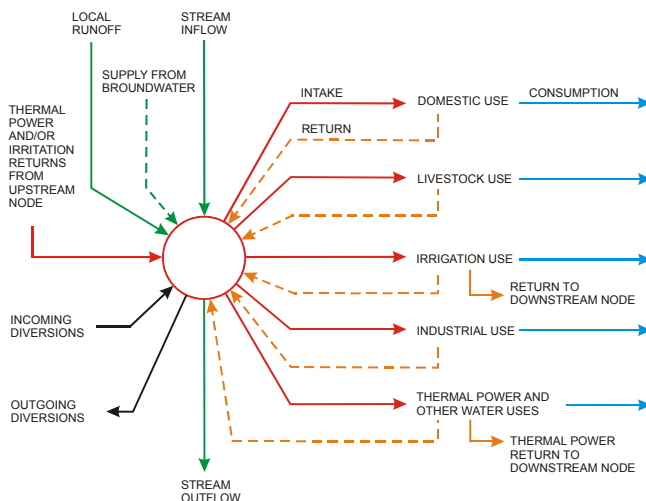


Figure 2: Schematic presentation of water balance calculation at a node.

3 Climate variability and climate change

Climate variability and climate change will affect water availability in two ways. First, they will affect water demands, particularly for irrigated agriculture due to changes in P and other climatic parameters. Secondly, they will impact water supplies.

3.1 Impact of climate variability

The variability of water demands is accounted for through the use of historical (or projected) time series of climatic data in simulating irrigation water requirements. Likewise, the variability of water supplies is analysed from historical (or simulated) natural streamflow data.

3.2 Climate change

The modelling framework allows the examination of climate change impacts on water availability through the integrated assessment of changes to water demand and water supply. Using temperature and precipitation scenarios derived from global circulation models (GCM's), the impacts on irrigation water demands can be directly assessed. Hydrologic modeling employing the same climatic scenarios is used for the assessment of changes in water supply (Pietroniro *et al* [6]). Regional averages of future annual and seasonal mean temperature and precipitation were calculated using GCM data described by Töyrä *et al* [8]. The 2050 annual results are shown in fig. 3. The results show that the range of predicted change is very large. For example, the spread of predicted annual change in temperature and precipitation was 3.4°C and 18.6%, respectively, when all models are considered. Winter and spring show the largest variation between the models.

3.3 Projected changes in water supply

The changes in precipitation and temperature derived from the scenarios shown in fig. 3 were applied to hourly observation gridded precipitation and temperature files. The meteorological forcing represents an average change in monthly precipitation for a 30 year period. The results shown in Table 1 represent the average change in mean annual flow for the major tributaries of the SSRB as predicted by the hydrologic model.

4 Case study: South Saskatchewan River Basin (SSRB)

The modelling framework presented above has been applied to Canada's SSRB. The basin is located in the semi-arid Prairie region of southern Alberta and south-central Saskatchewan in Western Canada. Irrigated agriculture is the dominant water use in the basin which is home to more than 1.5 million people. Water availability represents the primary constraint to future irrigation expansion which has to compete with the increasing water demands caused by population expansion and industrial growth. There are also stringent requirements for instream flow which limit the amount of water that can be withdrawn. Climatic changes can further exacerbate water use conflicts within the basin and present new challenges to the irrigation sector.

4.1 Basin configuration

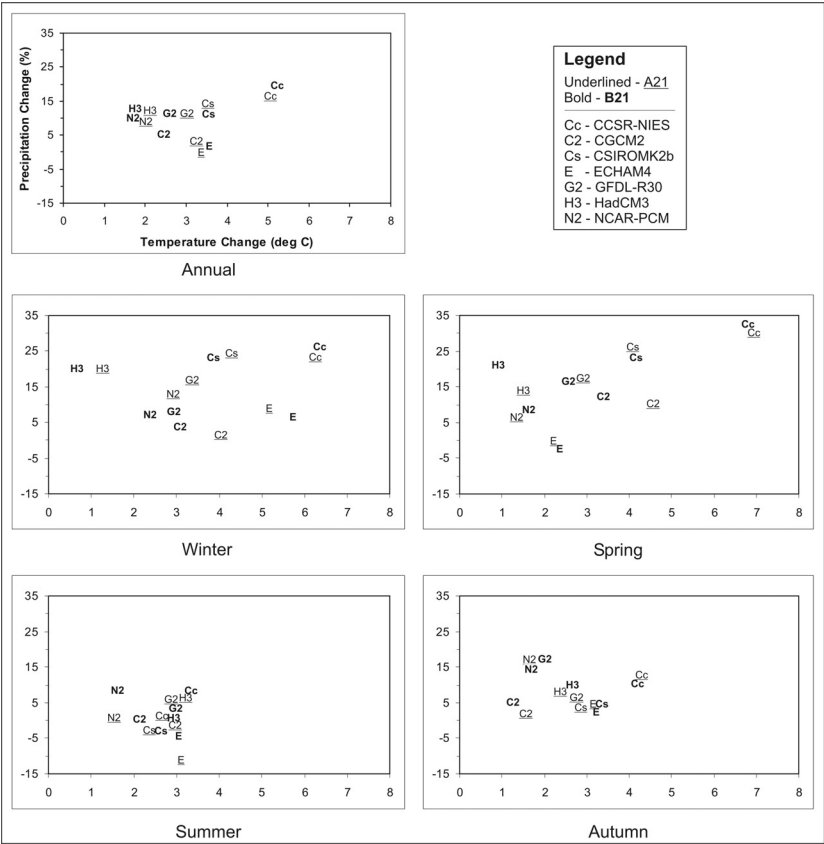
The SSRB includes four main sub-basins: Oldman, Bow, Red Deer and the lower SSRB. There are five main reservoirs in the basin used to support a vast irrigation network, as well as for flood control, recreation and other purposes. Surface water is the main source of water supply in the basin. Extractions from groundwater sources are limited at present. The SSRB is represented by the network shown schematically in fig. 4. The network shows the irrigation areas and their spatial locations. The irrigation areas have been aggregated into 30



units. P and ETP data are assigned to each irrigation area by defining the climatic station(s) nearest to the area. The network also shows existing inter-basin and intra-basin water diversions.

4.2 Model calibration/verification

The model has been calibrated in order to a) reproduce recorded irrigation water diversions and return flows, and b) reproduce recorded streamflows throughout the system, given the simulated water demands and natural streamflow data. Assessments were also made to ascertain the model’s ability to reproduce the actual operations of reservoirs, by comparing simulated reservoir levels and releases against recorded data.



Scenarios: A21 = High emissions scenario, **B21** = Low emissions scenario.
GCM Models: CCRS = Japanese Center for Climate Research Studies; CGCM2 = Canadian Centre for Climate Modeling and Analysis; CSIROCMK2b = Australian Commonwealth Scientific and Industrial Research Organisation; ECHAM = German Climate Research Center; GFDL = Geophysical Fluid Dynamics Laboratory; HadCM3 = Hadley Center for Climate Prediction and Research.

Figure 3: Regional averages of predicted annual and seasonal changes in mean temperature and precipitation for the 2050 climate.



Table 1: Projected changes in flow for the SSRB tributaries.

Station	% change as estimated by GCM scenario						Avg.
	ECHAM (b21)	ECHAM (b21)	HAD (a21)	HAD (b21)	NCAR (a21)	NCAR (b21)	
Oldman River at Lethbridge	-13.5	-13.3	1.5	-4.4	7.0	2.4	-3.4
South Saskatchewan River at Medicine Hat	-16.7	-15.6	-2.1	-8.6	6.1	1.0	-6.0
Bow River at Calgary	-18.7	-17.4	-6.5	-11.9	0.1	-3.0	-9.6
South Saskatchewan River at St. Louis	-22.1	-19.3	-5.3	-13.9	8.3	1.1	-8.5

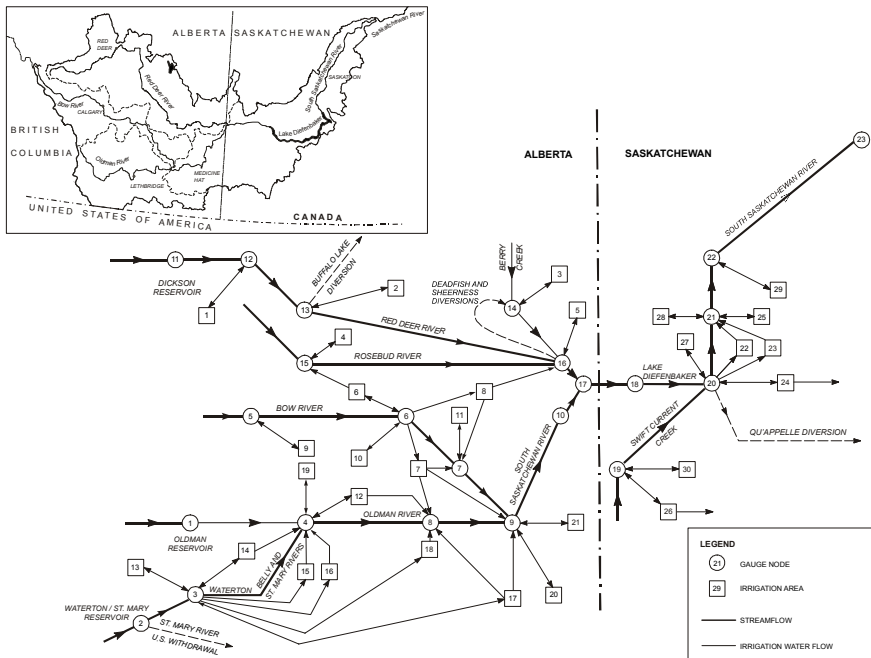


Figure 4: Schematic representation of South Saskatchewan river basin.

The hydrologic model, WATFLOOD [4], used for the projection of future water supplies under climate change scenarios, has been calibrated for SSRB using 30 years of available historical temperature and precipitation data at climatic stations. The simulated hydrographs were compared against natural streamflow data derived from recorded flows throughout the basin (fig. 5.)

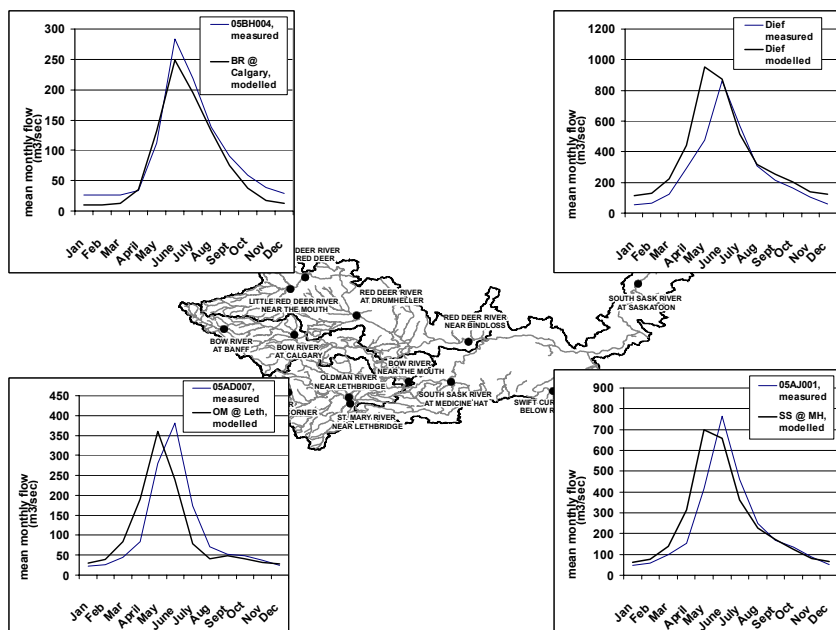


Figure 5: Observed and simulated mean monthly hydrographs for the 1961-1990 time period at selected locations.

5 Impact of climate variability on irrigation water demands

Using 92 years (1912-2001) of historical P & ETP data, fig. 6 shows an example of the variation of irrigation water demands, due to only climate variability, presented in a frequency diagram. Highlighted on the diagram are irrigation water withdrawals for a number of recent climatic years. These analyses have been further extended to investigate the sensitivity of the irrigation sector to climate change, given projections of P & ETP under climate change scenarios. Analyses of the impacts of climate variability on water availability are presented below.

6 Climate variability and water availability

The importance of incorporating climate variability in the assessment of water availability is demonstrated in fig. 7. The figure presents 92 years of historical natural streamflow data and the corresponding water demands simulated using historical climatic data for the same time period. The figure clearly shows that while average supply and demand values may indicate ample water availability, a year-to-year analysis shows many occurrences of water shortages or critical water availability. This observation highlights the need to incorporate climate variability when assessing water availability for irrigation since critical water

availability would generally coincide with dry periods when irrigation demands are the highest. From such analysis, irrigation water demands and water availability can be presented in terms of probability, or a risk-management context, as illustrated below.

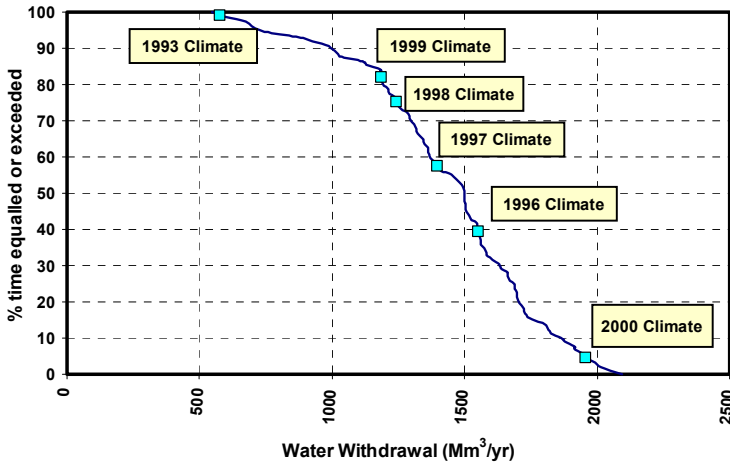


Figure 6: Example of variation of irrigation water demands due to climate variability.

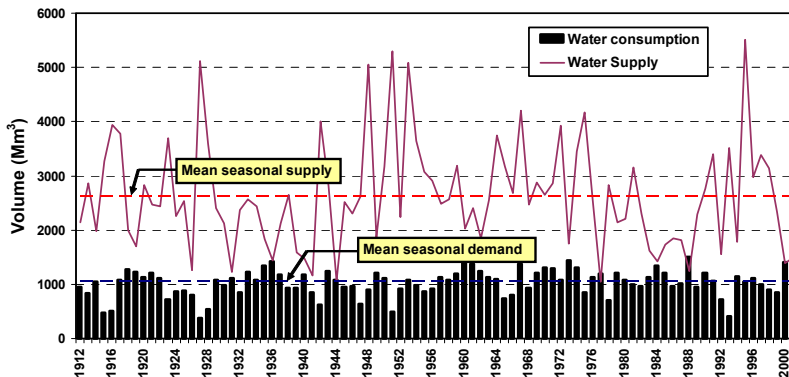
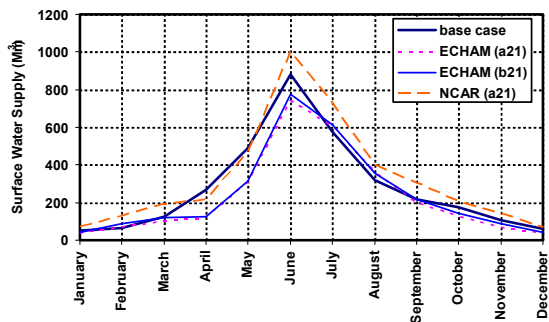
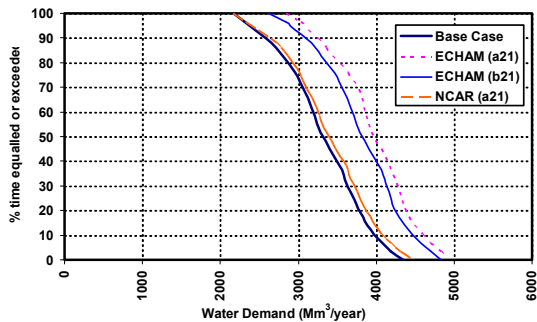


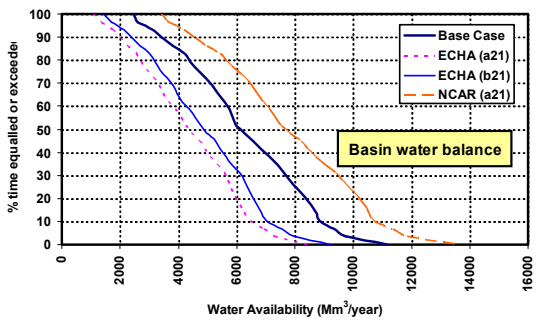
Figure 7: Example of annual variation of water demand and water supply due to climate variability.



a) 30-year mean monthly supply – historical climate and climate change scenarios.



b) Impact of climate change scenarios (P & ETP) on water demands.



c) Water availability - historical climate and climate change scenarios.

Figure 8: Irrigation water demands and water availability in a risk management context.



7 Water availability in a risk-management context

By analysing the time varying water demands and water supplies, it is possible to represent water availability in terms of probability. This is demonstrated in fig. 8, under two climate assumptions: a) a static climate (base case), i.e., assuming that past climate will be repeated in the future, and b) using a number of climate change scenarios. In these analyses, climate change scenarios, obtained from GCM's, were used for the prediction of water supply (fig. 8a) using a hydrologic model calibrated for the basin (Pietroniro *et al* [6]), as well as to calculate the corresponding water demands (fig. 8b). From the integrated analysis of water supplies and water demands, water availability can be expressed in terms of probability or a risk-management context (Fig. 8c).

8 Conclusions

The assessment of water availability for irrigation in semi-arid regions requires consideration of both water demands and water supplies and fully incorporating the impact of climate variability and possible climatic changes. The modeling presented in this paper can provide policy makers with the foundation upon which to base management strategies for the irrigation sector under a changing climate and help develop appropriate policy responses when and where needed.

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