Environmental Modelling & Software 58 (2014) 12–26

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

# Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada

Elmira Hassanzadeh [a,b,*], Amin Elshorbagy [a,b], Howard Wheater [b,c,a], Patricia Gober [d,b]

[a] Department of Civil and Geological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada
[b] Global Institute for Water Security, University of Saskatchewan, National Hydrology Research Centre, 11 Innovation Boulevard, Saskatoon, Saskatchewan, SK S7N 3H5, Canada
[c] School of Environment and Sustainability, University of Saskatchewan, 117 Science Place, Saskatoon, SK S7N 5C8, Canada
[d] Johnson-Shoyama Graduate School of Public Policy, 101 Diefenbaker Place, University of Saskatchewan, Saskatoon, SK S7N 5B8, Canada

ARTICLE INFO

*Article history:*
Received 25 October 2013
Received in revised form
30 March 2014
Accepted 30 March 2014
Available online 8 May 2014

*Keywords:*
Integrated water resource management
SWAMP1.0
System dynamics
Scenarios
Irrigation
Economic evaluation

ABSTRACT

Using a system dynamics approach, an integrated water resources system model is developed for scenario analysis of the Saskatchewan portion of the transboundary Saskatchewan River Basin in western Canada. The water resources component is constructed by emulating an existing Water Resources Management Model. Enhancements include an irrigation sub-model to estimate dynamic irrigation demand, including alternative potential evapotranspiration estimates, and an economic sub-model to estimate the value of water use for various sectors of the economy. Results reveal that the water resources system in Saskatchewan becomes increasingly sensitive to the selection of evapotranspiration algorithm as the irrigation area increases, due to competition between hydropower and agriculture. Preliminary results suggest that irrigation expansion would decrease hydropower production, but might increase the total direct economic benefits to Saskatchewan. However, indirect costs include reduction in lake levels and river flows.



## 1. Introduction

Water resources globally are under pressure, mainly due to population growth, intensive socio-economic development and warming climate (Vörösmarty et al., 2000). The transboundary Saskatchewan River Basin (SaskRB) in western Canada is a key resource for the prairie provinces of Alberta, Saskatchewan and Manitoba, and an example of a complex water resources system that is facing these water security challenges (Gober and Wheater, 2013). The main river flows in the province of Saskatchewan are dominated by flows generated in the Rocky Mountains in Alberta, which provide water to industry, agriculture and urban centers. Recent years have seen severe extremes of both flood and drought (Wheater and Gober, 2013), and due to the impacts of climate change and intense human regulation in Alberta, the future characteristics of these flows might change (Nazemi et al., 2013). Increasing demands in the Province stem from population growth, large economic investments in mining, and agriculture. Agriculture is currently the major water demand, accounting for more than 56.3% of water withdrawal in Saskatchewan (Martz et al., 2007). The Saskatchewan Ministry of Agriculture has proposed a 400% increase in irrigated area to address global food security and stimulate economic development (Saskatchewan Ministry of Agriculture (2012)). This proposal presents potentially significant challenges for the maintenance of healthy ecosystems downstream, including the Saskatchewan River Delta (SRD), the largest inland river delta in North America, which includes multiple wetlands and lakes that have high ecological and cultural values for the resident First Nation communities (Partners for the Saskatchewan River Basin, 2008). In addition, Saskatchewan has inter-provincial commitments. The 1969 interprovincial Master Agreement on Apportionment requires Alberta to pass half of the natural flows to Saskatchewan, which is in turn required to pass half of that flow and other natural flows in Saskatchewan to Manitoba (Prairie Province Water Board, 2013). Dealing with these problems and planning for the future of Saskatchewan needs an integrated water resources model that estimates agricultural water demand, includes impacts of climate change, and helps to investigate the economic benefits of policy decisions.

* Corresponding author. Department of Civil and Geological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada.
*E-mail address:* elmira.hassanzadeh@usask.ca (E. Hassanzadeh).

http://dx.doi.org/10.1016/j.envsoft.2014.03.015
1364-8152/

Various object-oriented simulation environments (e.g. Bayesian networks; system dynamics; agent-based models) are available to develop an integrated water resources model. These modeling approaches have many common points and model selection depends on the main purpose of the model application. Among these available approaches, System Dynamics (SD) explicitly captures the feedback loops among system components, and can be used by people with minimum technical background, due to the capability of SD models to include different communication layers from user-interface to programming codes (Kelly et al., 2013). Thus, SD models are suitable for social-learning and understanding the modeling processes as well as involving dynamic feedback loops among the underlying components. SD has had wide application in environmental and water resources studies (e.g. Ahmad and Simonovic, 2006; Elshorbagy and Ormsbee, 2006; Winz et al., 2009; Hassanzadeh et al., 2012). For example, Simonovic and Fahmy (1999) used an SD approach to assess the long-term effect of alternative socio-economic development policies on a water resources system in the Nile River basin in Egypt. Saysel et al. (2002) developed an SD model for southeastern Anatolia, Turkey to evaluate long-term environmental sustainability under alternative socio-economic and environmental scenarios. Ewers (2005) developed an SD model for the San Juan watershed in northwestern New Mexico (with extensions into Colorado, Utah and Arizona), including agricultural, municipal, and energy components and evaluated the effect of increasing power production on the required environmental flows in the system. Gastélum et al. (2009) used an SD approach in the Conchos Basin in Mexico to consider the effect of different water allocation scenarios on water delivery to the United States and agricultural production within the Basin. SD provides a simulation environment for place-based models that must be custom-built for the study area under consideration.

The objective of this study is to use SD to develop an integrated water resources management model for Saskatchewan that includes irrigation demand, and economic evaluation sub-models, and has the capability to investigate alternative environmental flow conditions. Furthermore, the model can be used in practice by decision makers. In a broad sense, the proposed model allows for Sustainability-oriented Water Allocation, Management, and Planning, and thus we refer to it as SWAMP1.0. The paper begins with an overview of the SaskRB water management concerns in Section 2, followed by a description of the SWAMP1.0 model in Section 3, including water resources model construction in 3.1, development of several irrigation sub-models in Section 3.2; and cost-revenue analysis to inform policy makers about the productivity and economic value of water for various use sectors in Section 3.3. Model calibration and performance assessment are outlined in Section 4. Section 5 reports on the results of various growth and policy scenarios and final conclusions are given in Section 6.

## 2. Case study

The SaskRB covers a large portion of the populated area in the Province of Saskatchewan (Fig. 1). The schematic diagram of the water resources system in Saskatchewan is shown in Fig. 2. The South Saskatchewan River (SSR) (bottom-left) after meeting a few demands in the South West of the province flows to Lake Diefenbaker. Water is allocated from Lake Diefenbaker to various water use sectors and a group of small reservoirs and delivers the regulated SSR flow through the major Coteau Creek Hydropower station towards Saskatoon (center). The SSR after meeting multiple demands on its way, confluences with the North Saskatchewan River (NSR) (top) and produces the Saskatchewan River (SR). The SR after meeting water for Codette and Tobin reservoirs flows to the SRD, and ultimately to Manitoba.

Lake Diefenbaker, the largest water body in the region, was built in 1959. Its maximum capacity is 9400 million cubic meter (MCM). Lake Diefenbaker is a multiuse reservoir for hydropower production, supporting water for municipalities, irrigation, mining, recreation, and flood control and downstream flow regulation (WSA, 2012b). The main discharge from Lake Diefenbaker is for the 186 MW Coteau Creek hydropower and subsequent downstream uses, accounting for 94% of water withdrawal, followed by evaporation from the lake (3%), water-use for irrigation, industrial, mining and municipal uses (2%) and the supplementation of flows in the Qu'Appelle River System (1%) (WSA, 2012b), which supplies water for municipal requirements of the Cities of Regina and Moose Jaw, industrial requirements, irrigation in the Qu'Appelle Valley and the maintenance of the eight lakes in the Qu'Appelle River Valley for recreational uses. The management philosophy for this reservoir is to fill it during the high flow season of the spring Prairie snowmelt and the later runoff from ice melt at higher elevations combined with rainfall in Alberta headwaters, then deplete the stored water in fall and winter until the following spring, when the chance for refill returns (WSA, 2012b). This annual operation supports flood control but does not support water supply capacity over a multi-year drought (WSA, 2012b). The downstream Codette and Tobin Lakes mainly supply water for the 255 MW Nipawin and 288 MW E.B. Campbell hydropower stations, respectively.

Irrigated agriculture and hydropower use are the major users of water in the Province (Government of Saskatchewan, (2013)). Irrigation is seen as essential to diversify the rural economy and to stabilize crop production in this semi-arid Prairie region. Almost 25 percent of Saskatchewan's electricity comes from hydropower. Hydropower consumes little water but significantly changes the flow patterns of the river; reducing summer flows and increasing winter flows (Saskatchewan Electricity, 2013). Saskatchewan potash mines use a considerable amount of the Province's industrial water (Halliday, 2009).

The province has a set of targeted objectives that relate to environmental flows during key seasons and at set locations. (1) Lake Diefenbaker is a crucial point in the system. The targeted water level in Lake Diefenbaker is above 551 m on May 1 to enable pumping water for irrigation areas, and between 555 and 555.3 on July 1 to support recreational use and prevent flooding of the nests of Piping Plover, an endangered bird species; (2) environmental flow requirements stipulate that SSR flows toward the City of Saskatoon must maintain a minimum of 42.5 ($m^3$/s) to support downstream ecosystems and adequate sewage effluent dilution (Blackwell, 1963); (3) there should be adequate flow to support ecosystem and human health in the SRD, although precise figures are not provided; and (4) the Master Agreement on Apportionment to deliver half of natural flow and any flows that originate in Saskatchewan to Manitoba.

The water system is confronted by deep uncertainties about future water supply and demand. Canada's climate is changing (Zhang et al., 2000). As an example, Hao et al. (2013) showed that Canada has experienced concurrent increase in temperature and a decrease in precipitation which means significant change in river flows. Since more than 80 percent of flows in the SSR and NSR in Saskatchewan originate in Alberta (Pomeroy et al., 2009), any changes in the upstream SSR and NSR flows can significantly affect Saskatchewan's water resources system. Various studies have attempted to use different climate models as well as various hydrological models to project the NSR (e.g. Shepherd et al., 2010; North Saskatchewan Watershed Alliance, 2008) and SSR flows (e.g. Lapp et al., 2009; Pomeroy et al., 2009). However, the wide band of uncertainty associated with these studies' predictions